Curriculum Vitae

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Minor: Economics

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University of Maryland, Baltimore, Post Grad Prosthodontics, 2018-2021

University of Maryland, Baltimore, Master of Science, 2018-2021

Honors and Awards:

Dean's List, Union College, 2010-2014

Dean's list attained for all trimesters during four years at Union College; required GPA of greater than 3.5 for the trimester in question

Member of Phi Beta Kappa, Union College, 2014

National academic honor society

Samuel S. Feuer (1925) Prize, Union College, 2014

To a senior premedical student with primary interest in dentistry who has maintained the highest scholastic average over four years.

Hanau Best of the Best Award, University of Maryland, Baltimore, 2018

Awarded to a graduating senior that have demonstrated clinical skill and interest in pursuing additional training in the field or prosthodontics

Best Senior Case Presentation, University of Maryland, Baltimore, 2018

Awarded to a graduating senior in each GP that achieved the highest score on their senior case presentation

Thesis:

Surface Roughness of Zirconia Produced by Additive and Subtractive Manufacturing

Completed for attainment of Master of Science,2021 (Advisor: Dr. Radi Masri, Program Director, Prosthodontics, University of Maryland, Baltimore)

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Perform auxiliary duties around the office including but not limited to cleaning, laboratory deliveries, consulting, and management of office webpage

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Provided clinical instruction to third- and fourth-year students in the Doctor of Dental Surgery program at the University of Maryland, Baltimore

Professional Memberships:

Member of the American College of Prosthodontists, 2018-present

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Extracurricular Activities:

Volunteer, Kennedy Krieger Institute CARD, Achievements Program, 2021

Engaged in discussion with pre-school aged, neurodivergent students about what to expect when visiting a dental office and self-advocacy skills when working with dental health providers

Volunteer, Feminist Collaborative, Family Engagement Programming, 2020-present

Support for family engagement programming i.e. transportation of materials, setup, and handing out fliers

Volunteer, Walter's Art Gallery, Sensory Friendly Programming, 2018-2021

Supported sensory inclusive programming initiative alongside museum educators in partnership with Kennedy Krieger Institute CARD

Volunteer, Kennedy Krieger Institute CARD, Parent's Night Out, 2018-2019

Provided respite care for neurodivergent children and their siblings treated at Kennedy Krieger Institute CARD

Volunteer, Happiness House (Geneva, NY), 2017

Visited with typically developing and neurodivergent preschoolers to increase familiarity with dental health providers as part of a "community helpers" unit

Title of Thesis: Surface Roughness of Zirconia Produced by Additive and Subtractive Manufacturing

Frank Triana, Master of Science, 2021

Thesis directed by: Dr. Radi Masri, Professor and Program Director, Post Graduate Prosthodontics

Abstract

<u>Purpose</u> – The purpose of this in vitro study was to compare surface roughness of full contour zirconia restorations produced by additive and subtractive manufacturing

<u>Materials and Methods</u> – Full contour restorations were designed using 3Shape Dental System. The stl files were exported and utilized to guide production of all specimens. Zirconia samples were manufactured by two methods – additive manufacturing (n=10) and subtractive manufacturing (n=18). A two-step polishing protocol was used following sintering. All specimens were subject to profilometry to measure average Ra values. Ra values for both groups were compared. Statistical analysis was performed using t-test (p=0.05).

<u>Results</u> – The average Ra value for zirconia restorations in the subtractive manufacturing group was 0.35 $\pm$0.07µm while average Ra for additive manufacturing groups was 1.06 $\pm$0.49 µm. Differences were statistically significant ($p < 0.00001$).

<u>Conclusions</u> – Zirconia restorations produced by subtractive manufacturing were significantly smoother than those produced by additive manufacturing even after post-sintering polishing.

Surface Roughness of Zirconia Produced by Additive and Subtractive Manufacturing

by
Frank J. Triana

Thesis submitted to the faculty of the Graduate School of the
University of Maryland, Baltimore in partial fulfillment
of the requirements for the degree of
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Introduction

As new technologies become available, industries are forced to reorganize and adapt. Today, advancements in digital technology have revolutionized the way buyers and sellers interact in the marketplace. The healthcare field, in particular, utilizes many of these advancements to increase availability and efficiency of healthcare for patients. In recent years, the field of dentistry has embraced this trend. Digital dentistry streamlines ways in which dental practitioners acquire and process patient data. The growing market for intraoral scanners, as well as the ability for easy file sharing between dentists, dental laboratories, and other specialists has allowed for more efficient patient care.[1] With respect to manufacturing of indirect dental restorations, digital applications have greatly increased cost effectiveness, quality control, and have reduced labor.[2] The digital workflow in dentistry is based on computer-aided design/computer-aided manufacturing (CAD/CAM). The groundwork for CAD/CAM technology in dentistry was laid by Francois Duret in the 1970s.[3] However, CAD/CAM dentistry did not become a reality until the introduction of the first CEREC system (CEREC 1) in 1985 by Dr. Werner Mörmann and Marco Brandestini.[4] While the original CEREC system was designed to allow practitioners to fabricate inlay restorations chairside, CAD/CAM dentistry has since taken on a much-expanded role. Today, computer-aided manufacturing processes have greatly increased the number of materials available to dentists. The greatest influx of new materials has been dental ceramics.[5] Currently, there are two methods by which computer-aided manufacturing is accomplished ─ subtractive and additive manufacturing.

Subtractive manufacturing

The predominant method by which dental manufacturing is accomplished today is subtractive manufacturing. Subtractive manufacturing (also referred to as computer numerically controlled machining or "milling") begins with a solid block of material. Based on a computer-aided design (CAD), the milling machine uses various cutting instruments to reduce and shape a block of chosen material.[1] Today, subtractive manufacturing is used to produce a multitude of restorations including inlays and onlays, single crowns, fixed partial dentures, veneers, and dental implant restorations. Ceramic restorations produced by this method have been shown to be highly accurate with respect to marginal and internal fit when compared to conventional techniques.[6-7] With respect to surface roughness, while milling does increase surface roughness initially for ceramic restorations, adequate post-milling processing is capable of eliminating any roughness introduced by the milling process.[8]

Subtractive manufacturing has proven to be an efficient and accurate method for fabricating dental restorations. However, it is not without drawbacks. Because the initial block of material is significantly larger than the eventual end product, most of the material goes unused. Because the block cannot be recycled, this remaining material goes to waste. Additive manufacturing attempts to solve this problem.

Additive manufacturing

Additive manufacturing in dentistry

Additive manufacturing, or "3D printing", is defined by the American Society for Testing and Materials (ASTM) as "the process of joining materials to make objects from 3D model data, usually layer upon layer".[1] Because material is added layer by layer, no material goes to waste. Currently, the use of additive manufacturing in restorative dentistry is limited due to lack of experience and inconsistent results. With respect to ceramics, regular use of additive manufacturing is currently limited to production of tissue scaffolds as current methods struggle to regularly produce non-porous ceramic structures.[9] However, as operators gain experience and more resources are devoted to developing new methods, additive manufacturing shows great promise for more consistent use in the production of dental ceramic.[9]

The potential advantages of additive manufacturing in the production of ceramic restorations are obvious. Not only can material be conserved, but the potential to produce highly esthetic restorations is limitless. Ceramists often struggle with layering porcelain in a way to recreate the distribution of shades and textures that occur in natural teeth. With additive manufacturing (which is naturally a layered process) different shades in different layers can be easily accounted for in the computer aided design. This potential in itself justifies consideration for additive manufacturing as a method of producing ceramic restorations. The intricacy of surface detail achievable with milling is also limited by the diameter of burs available. Additive manufacturing has the potential to avoid this issue and produce highly detailed surface characteristics.

Methods of additive manufacturing

There are a multitude of additive manufacturing methods currently available.[11] Historically, only a few have been used in the production of ceramics. These include selective laser sintering (SLS), fused deposition modeling (FDM), stereolithography

(SLA), and ink-jet printing.[9] Selective laser sintering (SLS) uses a computer-controlled CO_2 laser. During production, a layer of powder is placed and the laser lightly sinters or fuses that powder into a solid.[11] Tian et al. 2009 proposed a process of selective laser sintering for the production of ceramic components that utilized a low laser energy density and higher hatching space (i.e. the space between adjacent tracks). With this process, Tian et al. 2009 were able to produce intricate ceramic designs with improved mechanical properties. Maximum flexural strength was measured at approximately 34.0 MPa.[12] However, this method has limited dental applications as 1) maximum strength is significantly less than that seen in leucite-reinforced glass ceramics produced by subtractive manufacturing and 2) the final products were porous.[13] Bae et al. 2016 found selective laser sintering to be more accurate than subtractive methods in fabrication of inlay restorations.[14] The authors, however, did not compare strength or porosity of the final restorations. Fused deposition modeling (FDM) utilizes melted thermoplastic resin which is extruded and subsequently re-solidified.[11] To manufacture dense ceramics such as alumina and zirconia, Scheithauer et al. 2015 proposed a fused deposition modeling process using a high-filled ceramic suspension with a thermoplastic binder system. By lowering the viscosity of the ceramic suspension, Scheithauer et al. 2015 were able to achieve very high densities (approximately 99%) of alumina and zirconia with improved resolution.[15] Stereolithography (SLA) utilizes a computer-controlled laser and a pool of UV-curable photopolymer resin. During printing, the laser cures a portion of the liquid resin at the surface. This layer then solidifies and is submerged. Subsequent layers are cured over the top of the submerged layer as the printing process continues.[11] Based on the current literature, stereolithography seems to have the most promise for regular use in production of dental ceramic restorations. Several articles demonstrate stereolithography as an accurate method for printing ceramic restorations with ideal physical properties. Using 40% Vol.% aqueous zirconia suspension and a scanning speed 1,200 mm/s, Lian et al 2018 were able to produce zirconia ceramic fixed dental prostheses with high density (98.58%), Vicker's hardness of 2.06 µm, and surface roughness of 1,398 HV.[16] Bae et al 2016 found stereolithography to be the most accurate method for fabrication of ceramic inlay restorations when compared to selective laser sintering and two subtractive manufacturing methods.[14] However, lithography based printing is not without limitations. Using a digital light processing method, Conti et al. 2020 showed that, while resolution down to 200 µm could be achieved, there was significant deviation from the original computer aided design for any gaps less than 500 µm.[17] Ink-jet printing involves a conventional ink-jet printer that has been modified to allow for 3D printing. Ebert et al. 2009 used a modified ink-jet printer to assess direct ink-jet printing as a viable method for fabrication of zirconia dental prostheses. Using a 27 Vol% zirconia based ceramic suspension, Ebert et al. 2009 were able to print zirconia (of similar size to a standard posterior restoration) with physical properties similar to those in zirconia restorations produced by conventional methods. The zirconia produced by this method showed an average strength of 763 MPa and fracture toughness 6.7 MPa.[18] While this process shows promise with respect to additive manufacturing of zirconia, issues such as intermittent nozzle clogging requires more advanced machinery to be developed before this process can be used on a large scale.[17]

Additive manufacturing of zirconia

Most recently, two articles produced by Revilla-Leon et al. (2020a, 2020b) looked at fracture resistance, flexural strength, internal and marginal discrepancy of zirconia produced by additive and subtractive manufacturing methods.[19,20] In both articles, the method of additive manufacturing utilized was stereolithography (SLA). With respect to flexural strength and fracture resistance, Revilla-Leon et al. 2020a found that milled zirconia specimens outperformed additive manufactured zirconia significantly. The authors found, on average, fracture resistance of milled zirconia specimens to be almost three times that found in zirconia produced by additive manufacturing.[19] With respect to flexural strength, the trend was the same.[19] Marginal and internal discrepancies of additive manufactured zirconia were also found to be significantly greater than discrepancies seen in milled zirconia specimens. The article concluded that while clinically acceptable marginal and internal discrepancies could be obtained with additive manufacturing of zirconia, there was a positive correlation between restoration volume and marginal discrepancy for anatomic crowns produced by additive manufacturing.[20.] Revilla-Leon et al. 2021 expanded on their findings from 2020 by assessing the effect of porosity on the volumetric shrinkage of zirconia specimens produced by additive manufacturing. For pre-sintered zirconia specimens, post-production sintering is always required. In subtractive manufacturing, each zirconia puck has a specific shrinkage factor which compensates for the shrinkage during the sintering process. However, quantifying this shrinkage factor is difficult for zirconia produced by additive manufacturing. For this reason, Revilla-Leon et al. 2021 sought to determine how post-production sintering affects printed zirconia specimens with differing levels of porosity. The authors found that as porosity decreased, manufacturing accuracy decreased, and manufacturing volume change increased. The authors also note that while the higher porosity, printed zirconia samples exhibit better accuracy following sintering, none of the samples (across all groups) exhibited perfect accuracy when compared to the original computer aided design.[21] Branco et al. 2020 also demonstrated reduced physical properties for printed zirconia versus zirconia produced by subtractive manufacturing. The authors demonstrated that the printed zirconia exhibited reduced density, greater porosity, and lower fracture toughness than milled zirconia specimens. The authors did however demonstrate that the printed zirconia samples showed less antagonistic wear of enamel compared to milled zirconia.[22] There, however, currently appears to be disagreement in physical properties recently reported for printed zirconia. Using a digital light processing (DLP) procedure, Mei et al. 2021 found no statistical difference in fracture toughness of zirconia bars produced by additive and subtractive manufacturing.[23] However, the authors did demonstrate that hardness values were reduced in printed zirconia when compared to milled specimens. This was attributed to greater pore size at the surface of printed specimens.[23] Bergler et al. 2021 also assessed the flexural strength of milled versus printed zirconia using digital light processing (DLP). While the authors did not demonstrate statistically significant differences, they did demonstrate a reduction of flexural strength when comparing milled and printed zirconia as well as comparing thermo-cycled and non-cycled printed zirconia specimens.[24] Ji et al. 2021 using stereolithography and optimizing de-binding with thermogravimetry–differential thermal analysis were able to produce zirconia specimens with favorable physical characteristics. Each specimen was able to achieve a density of 99.95% and flexural strength of greater then 1,000 MPa. While many authors have demonstrated comparable strength characteristics of printed zirconia specimens, the printing process itself may cause printed specimens to fracture more easily. This can occur when inadequate binding during the layering process takes place.[25] Marsico et al. 2020, using vat-polymerization were able to produce zirconia specimens with physical characteristics comparable to those produced by conventional methods. However, the authors did note that a fracture initiated between layer lines occurred with relatively high frequency.[26] Obviously, this observation requires further analysis of the additive manufacturing process used. With respect to marginal fit, Ioannidis et al. 2020 showed that for printed zirconia occlusal veneers, there was no significant differences with respect to marginal fit.[27] However, previous articles have demonstrated the accuracy of marginal and internal fit may be dependent on the volume of the restoration being produced.[20] Also with respect to marginal fit, Li et al. 2021 sought to assess the effect different margin finish lines have on the accuracy of milled and printed zirconia.[28] The authors looked at three different types of finish lines – rounded shoulder, chamfer, and knife-edge. It was found that printed and milled zirconia showed similar margin accuracy for rounded and chamfer margins, while both methods of production exhibited increased incidence of marginal chipping with knife-edge margins. It appears, based on this study, neither milled or printed zirconia adapts well to a knife-edge margin. The use of a knife-edge margin should be avoided for this material regardless of manufacturing method.[28] While a number of articles have addressed the marginal fit and physical properties of zirconia restorations produced by additive manufacturing, few have addressed a third crucial factor – surface roughness. Miura et al. 2021 found promising results with respect to surface roughness of zirconia restorations produced by additive manufacturing.[29] Using stereolithography (SLA), Miura et al. 2021 were able to produce full contour zirconia specimens that exhibited reduced surface roughness when compared to zirconia specimens produced by conventional methods. A contact-free laser microscope was used to quantify surface roughness of each specimen. While the results of this study are promising, the limited number of samples (n=3) in their pilot study certainly warrants further investigation into the surface roughness of zirconia produced by additive manufacturing.

Profilometry

Measurements of surface roughness can be made with the use of profilometry. There are two broad categories of profilometry – stylus profilometry and laser profilometry.[30] While stylus profilometry utilizes a diamond-tipped stylus that measures surface roughness by making physical contact with the sample in question, laser profilometry measures surface roughness indirectly by measuring deflection of the laser beam as it is reflected from the surface of the sample. In both stylus and laser profilometry, the peaks and valleys at the surface level of the sample are measured and recorded.[30] Stylus profilometry has historically been the standard for measuring surface roughness, however it is not without limitations. The primary limitation of stylus profilometry is the use of a stylus of finite size. This can limit the sensitivity of profilometer to peaks and valleys greater than or equal to the size of the stylus. Those smaller than the diameter of the stylus will not be recorded which may give an incomplete picture of the surface topography of the sample in question. In recent years, use of laser profilometry has expanded as technology has improved. Laser profilometry avoids the above-mentioned issue as there is no direct contact of the stylus with the sample. However, unlike stylus profilometry, laser profilometry can be adversely affected by differences in color or transparency of the surface in question.[31] The primary way that surface roughness has been quantified in dentistry is the use of Ra. Ra is the arithmetic mean of the absolute values of peaks and valleys as measured across a surface. Ra has been described as a 2-Dimensional measurement of surface roughness. Sa, on the other hand, represents a 3-Dimensional measurement of surface roughness. Unlike Ra, which represents average surface roughness over a defined distance, Sa takes into account the entire surface area of the sample. Generally speaking, stylus profilometry will produce an Ra value while laser profilometry will produce an Sa value.[31] The use of one or the other in reporting of surface roughness characteristics has largely been a matter of practically (most profilometers, historically, have only been able to provide a measurement of Ra).[31]

Purpose and hypothesis

The aim of this study is to assess additive manufacturing as a viable method of producing indirect ceramic restorations compared to milling, with respect to zirconia. Zirconia has gained popularity in recent years and is used regularly in the fabrication of restorations due its favorable combination of esthetic and physical properties. For this reason, zirconia was chosen for this study. Zirconia, or " yttria-stabilized tetragonal zirconia polycrystal", is a high strength dental ceramic composed of polycrystalline particles in a metastable tetragonal crystal structure.[32] Zirconia has traditionally been used as a core material over which veneering porcelain is applied. However, fractures and stripping of the veneering porcelain has led to increased use of monolithic zirconia. Monolithic zirconia shows considerably higher fracture strength when compared to porcelain veneered zirconia cores.[33] The present study looks to compare additive manufacturing of monolithic zirconia with subtractive manufacturing (i.e. milling). Comparisons are made specifically with respect to surface roughness. Overall roughness of 3D printed products is always a concern due to the use of binders. The additive manufacturing process requires the use of a liquid suspension. This suspension generally is composed of a dispersant, a powder (in this case ZrO_2 ceramic powder), and an organic binder.[34] The binders are added to the suspension as carriers for the powder and facilitate shaping of the final product.[35] These binders are subsequently eliminated during the process of debinding or thermal decomposition. This leaves porosities in the final product. To eliminate these porosities, sintering (a process that uses high temperatures and pressure to compact the ceramic particles into one, unified mass) is often necessary. However, porosities may still remain leading to a rough surface morphology.[35] The clinical implications of surface roughness are well known. While it is clear that rough surfaces promote more biofilm accumulation, it can also influence the wear pattern on opposing dentition and lead to discoloration of restorations. Increased antagonistic surface roughness leads to a significant increase in wear observed in both composite and enamel.[36] For these reasons, it is of great importance to determine the effect of the manufacturing process (additive or subtractive) on surface roughness to adequately assess clinical viability of the procedure. The null hypothesis was that no significant difference would be found in the surface roughness of additive manufactured and milled zirconia restorations.

Materials and Methods

A computer aided design (3Shape, Copenhagen, Denmark) was utilized to create full contour restorations of standardized dimensions. The stl file was then exported and utilized as a guide for computer aid manufacturing. Specimens were produced by two manufacturing methods – additive and subtractive manufacturing (Figures 1 & 2). Specimens produced by subtractive manufacturing represent the control group, while those produced by additive manufacturing represent the experimental group. The control specimens were produced using a Roland DWX-51D 5-axis dental milling machine (Roland, Irvine, CA) (Figure 3). The blocks utilized were monolithic, pre-sintered zirconia (Vericore Unshaded Zirconia, Whipmix, Louisville, KY). Because the sintering process leads to overall shrinkage of the pattern, all blocks of pre-sintered zirconia include an enlargement factor to allow the operator to compensate for this shrinkage in the computer aided design. The pre-sintered milled patterns were sintered according to manufacturer recommendations utilizing a zirconia sintering furnace (Infinity Zr Sintering Furnace, Whipmix, Louisville, KY) (Figure 4). A fast-heating sintering process was utilized. This required that the zirconia patterns be fired at 10°C /minute up to 1000°C (1,832°F). After reaching 1000°C, the patterns were fired a 3-5°C /minute until a temperature of 1,500°C was reached. The patterns were then held at this temperature for 2 hours and subsequently allowed to cool to room temperature prior to removal and post-sintering processing.

Figure 1. Subtractive manufacturing specimen. Specimens were produce using the Roland DWX-51D 5-axis dental mill. All milled specimens were subject to post-production sintering and polished using the 2-step zirconia polishing kit by Brasseler. Type of zirconia used - Vericore Unshaded Zirconia, Whipmix

Figure 2. Additive manufacturing specimen. Specimens were produced by digital light processing (DLP) using the Ember printer from Autodesk. Printed specimens were subject to post-production sintering and polished using the 2-step zirconia polishing kit by Brasseler.

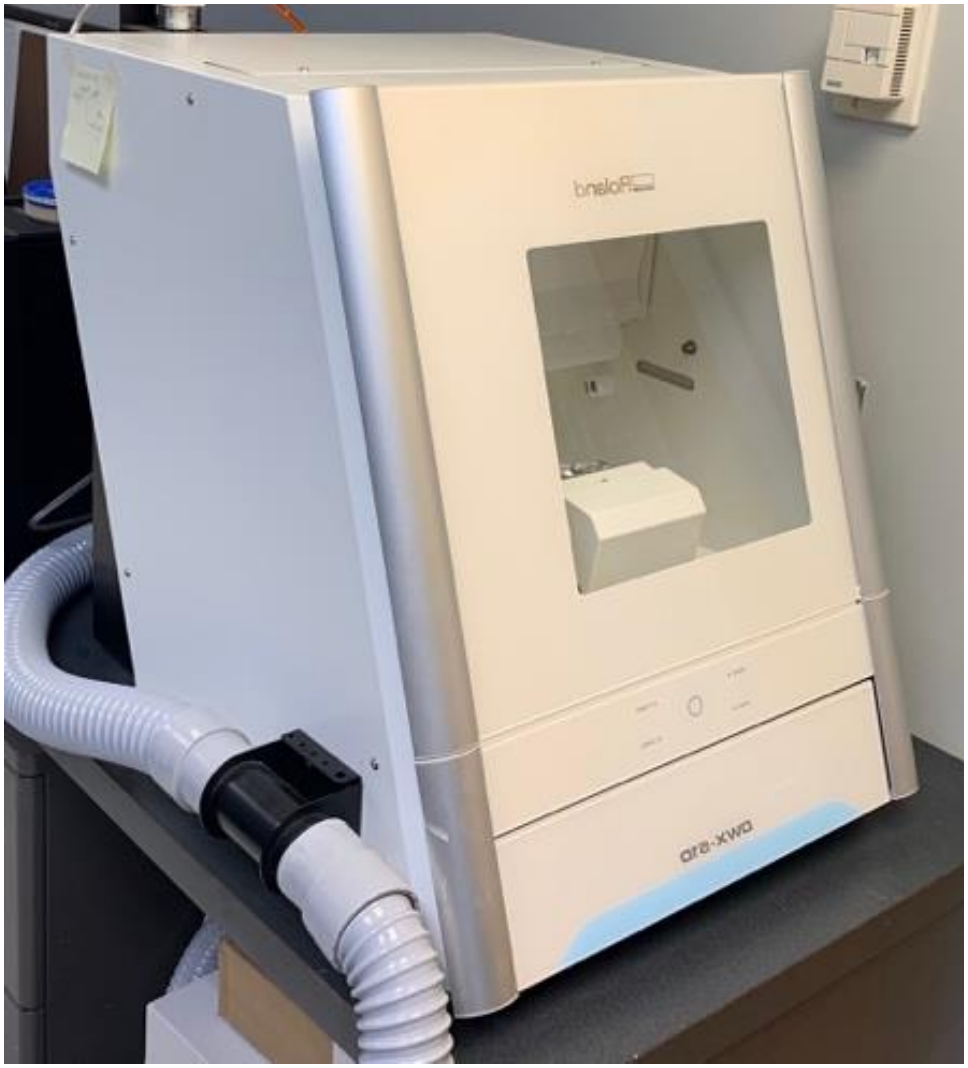

Figure 3. Roland DWX-51D 5-axis dental mill. The milling unit used for production of subtractive manufacturing specimens.

Figure 4. Infinity Zr Sintering Furnace. All specimens were subject to post-production sintering. A fast-heating process was utilized according to manufacturer recommendations. The zirconia patterns were fired at 10°C /minute up to 1000°C (1,832°F). After reaching 1000°C, the patterns were fired a 3-5°C /minute until a temperature of 1,500°C was reached. The patterns were then held at this temperature for 2 hours and subsequently allowed to cool to room temperature prior to removal and post-sintering processing.

Specimens for the experimental group were fabricated by additive manufacturing. All specimens were produced by a digital light processing (DLP) Ember printer from Autodesk (Autodesk, San Rafael, California). This type of printer uses a liquid, photopolymer resin which is able to solidify when subjected to a specific light source. The digital light processing printer is similar to stereolithography (SLA) printers, except for the fact that DLP printers use a single digital light projector screen. To produce zirconia specimens, a sinterable zirconia powder and a photocurable resin must be used. Because the composition of the printed zirconia specimens is proprietary of the company the produced them, the exact composition cannot be known (Tati Incorporated, Annapolis, MD). The printer utilized the same stl file described above to produce full contour, pre-sintered zirconia patterns. After this pattern was produced, each sample was sintered according to the same manufacturer recommendations described above.

Once sintered, both samples (subtractive and additive) were subject to post-milling/post-printing finishing. This was accomplished according to manufacturer recommendations using the 2-step Brasseler zirconia polishing kit (Dialite ZR polishing wheels, Brasseler, USA).

A total of 28 specimens were produced (N=28). 18 specimens were produced by subtractive manufacturing (control group) while 10 specimens were produced by additive manufacturing (experimental group). All specimens were subject to the use of profilometry to assess surface roughness (Mitutoyo Surftest SV-400, Mitutoyo, Kawasaki, Japan) (Figure 5a). A profilometer reflects overall surface roughness by use of a probe or stylus that makes contact with the surface of the sample. Under a constant load, the stylus is moved along the sample (in this study a stylus of 5µm tip radius at a constant force of 3.9mN was utilized). The profilometer traveled at a speed of 0.100 mm/s with a range of 600 µm. As the stylus was pulled across the surface, measurements of the movements across the surface of the sample were made. These movements were recorded and used to produce a profile or line scan of the surface topography. Ra (arithmetic mean roughness) was be used to quantify the surface roughness based off of the measurements taken from the profilometer. Ra is the average of the absolute differences in the microscopic peaks and valleys based off the profilometer measurements. This gives an overall sense of the average roughness of the surface of each sample. The higher the Ra value, the greater the surface roughness of the sample. Each specimen was passed through the profilometer five times to produce five distinct Ra measurements. An average was then obtained to produce an Ra value for each individual specimen in the control and experimental groups. As profilometry is best performed on a flat surface, the flattest surface, closest to the buccal margin, was measured and standardized for each full contour specimen. To ensure consistent orientation of each specimen, a putty matrix was fabricated and secured to the profilometer platform with double sided tape (Lab-Putty, Coltene, Altstätten, Switzerland) (Figure 5b-d). Average Ra values were subject to a t-test for statistical analysis.

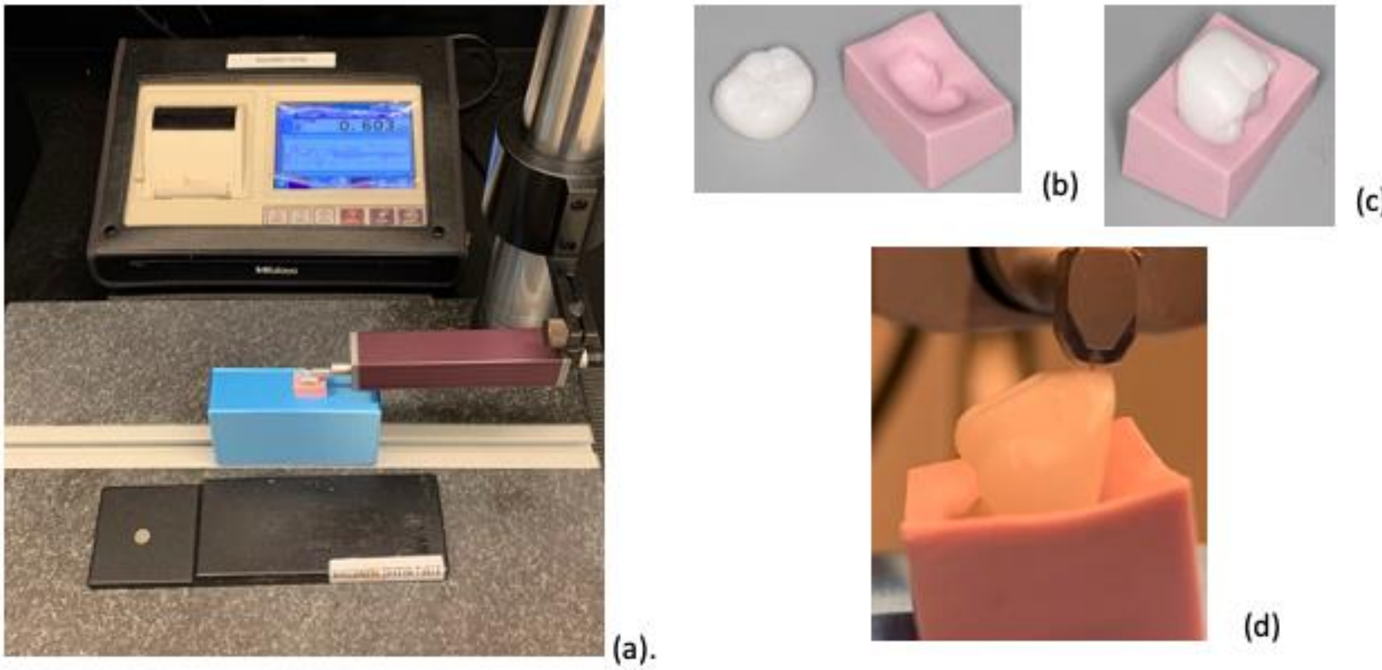

Figure 5. Profilometer. a) Image of the Mitutoyo Surftest SV-400 profilometer. b) Putty matrix fabricated to standardize orientation of specimens within the profilometer (Coltene laboratory putty). c) Specimens oriented within the profilometer to record flattest surface closest to the buccal margin.

Results

Five values for Ra were obtained to produce an average Ra value for each specimen in the subtractive and additive manufacturing groups. For each group, mean, median and range were calculated (Tables 1 & 2). Based on the Ra values for each specimen, standard deviation was calculated for each group and presented in Table 3. A graphical presentation of this data is shown in Figure 6. Statistical analysis was performed using a t-test. Based on the results of the t-test, the null hypothesis was rejected as there was a significant difference between the control and experimental groups with respect to surface roughness ($p < 0.00001$).

The control group (subtractive manufacturing) exhibited significantly lower Ra values (0.3525±0.07301µm) compared to the experimental group (additive manufacturing) (1.059 ±0.4927 µm) (Table 3). This indicates that the surfaces of milled zirconia restorations were on average smoother than those of zirconia restorations produced by additive manufacturing.

Table 1. Average Ra values or each subtractive manufacturing sample

Sample	**Ra (**µm)
M1	0.3926
M2	0.3994
M3	0.3960
M4	0.1960
M5	0.2534
M6	0.2662
M7	0.3818
M8	0.4568
M9	0.3100
M10	0.4122
M11	0.3380

Table 1. Continued

M12	0.4356
M13	0.3336
M14	0.4486
M15	0.3980
M16	0.2824
M17	0.3168
M18	0.3324
Mean	0.3525
Median	0.3599
Range	0.2608

Table 2. Average Ra values for each additive manufacturing sample

Sample	**Ra** (μm)
P1	0.3670
P2	1.1795
P3	0.4648

Table 2. Continued

P4	1.6246
P5	1.1298
P6	0.7320
P7	1.2672
P8	1.6864
P9	1.5548
P10	0.586
Mean	1.059
Median	1.155
Range	1.3194

Table 3. Average Ra and Standard Deviations for subtractive and additive manufacturing groups

Group	**Ra value (μm)** **Mean $\pm$ Standard Deviation**
Subtractive Manufacturing (n=18)	0.35 $\pm$0.07
Additive Manufacturing (n=10)	1.06 $\pm$0.49*

* statistically significant difference p<0.00001

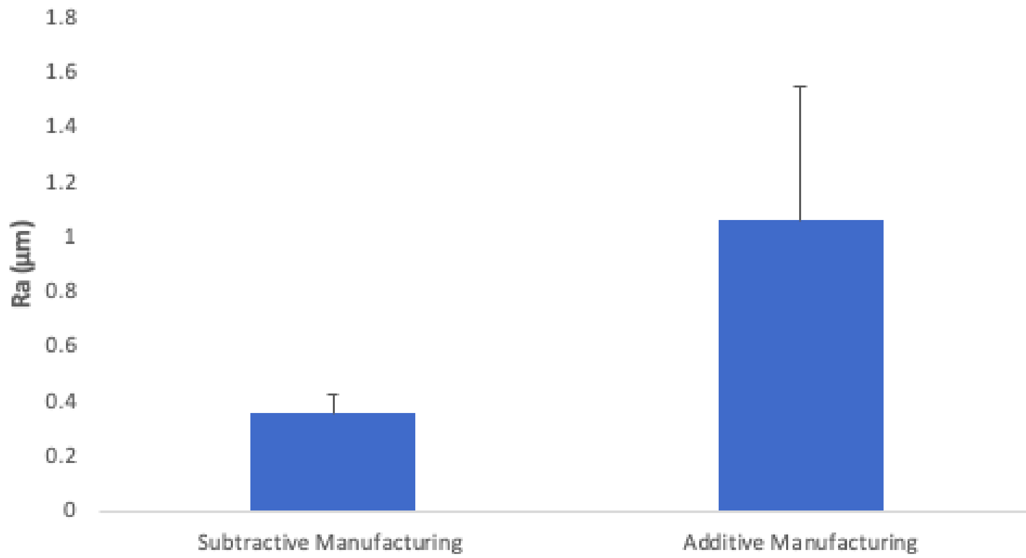

Figure 6. Average Ra and standard deviation for subtractive and additive manufacturing groups

Discussion

Based on the results of this study, the null hypothesis was rejected. The manufacturing process of full contour zirconia restorations had a statistically significant effect on surface characteristics. Zirconia restorations produced by additive manufacturing, even after post-manufacturing polishing, showed significantly higher Ra values compared to restorations produced by subtractive manufacturing. This indicates that the surfaces of zirconia produced by additive manufacturing were significantly rougher than those produced by milling. The clinical implications of rough surfaces in the oral cavity are clear. Restorations with rough surfaces are prone to biofilm accumulation, greater antagonistic wear, and lower color stability.[37-42]

Porosities and rough surface characteristics provide reservoirs for adherence of bacteria biofilms.[37-38] When these roughened surfaces are present at the margins of the restorations (as was assessed in the present study), recurrent caries and thus failure of the restoration can occur. Abdalla et al. 2020, sought to determine the effect surface roughness has on bacterial adhesion for various ceramic restorations. The authors found that roughened ceramic surfaces exhibited a greater percentage of live bacteria and biofilm coverage with respect to *Streptococcus mutans*.[37] As *Streptococcus mutans* is the primary microbe responsible for initiation of dental caries, it is clear, roughened ceramic may allow accumulation of bacteria (especially at the margins) leading to greater risk for recurrent caries and thus greater risk for failure of the restoration. Checketts et al. 2014 assessed the effect dental prophylactic instrumentation has on surface roughness of ceramic restorations as well as the adherence of common microbes associated with dental caries (*Streptococcus mutans, Lactobacillus acidophilus, Actinomyces viscosus*). The authors found that curettage with stainless steel scalers created greater roughness in ceramic restorations. These roughened restorations subsequently showed greater overall bacterial adhesion.[38] While the surface roughness in this study was not inherent of the material itself but rather induced by scaling, the conclusions are the same – rough surfaces promote bacterial adhesion.

The smoothness of restorations can also influence wear patterns. When the restorative material is rough, greater wear of opposing surfaces can be expected. This can result in occlusal instability and irreversible damage to the opposing tooth, requiring additional prosthetic intervention. These effects can be magnified in individuals with parafunctional habits. Janyavula et al. 2013 effectively demonstrated that as surface roughness (measured as Ra) increased, wear of opposing enamel increased significantly.[39] With respect to zirconia restorations subject to different post-processing finishing and polishing procedures, Park et al. 2014 showed a positive correlation between surface roughness and antagonistic wear.[40] However, a recent study by Branco et al. 2020 showed more favorable antagonistic wear for printed zirconia specimens compared to those that were produced by subtractive manufacturing, even though the printed specimens in question were more porous. It is possible that the reduced hardness observed in printed samples offset the increased surface roughness resulting in decrease wear of enamel. With this in mind, further investigation into the various factors that influence antagonistic wear is warranted.

The final characteristic of restorations negatively impacted by surface roughness is color stability. The primary benefit of ceramic restorations has always been the ability to mimic the color characteristics of natural teeth. Long term esthetic success of the restoration is highly dependent on the ability of the restoration to maintain stability of shade and avoid excessive staining compared to natural teeth. It is reasonable to assume that if the surface of a restoration is not adequately polished or is excessively rough, that staining can occur, leading to change in color, which could lead to esthetic failure necessitating the premature replacement of the restoration. This assumption has been supported by current literature. Petropoulou et al. 2020 showed a positive relationship between surface roughness and color instability.[41] While this article supports the assumption that rougher surfaces accumulate stain more readily than smoother surfaces, this article may be less generalizable to the present study as Petropoulou et al. 2020 were studying this effect on gingiva-colored resin composites.[41] Al-Zordk et al. 2020 sought to determine the effect clinical adjustment (i.e. roughening of the surface) had on the color stability of zirconia restorations. The authors found, that while stain accumulation increased for restorations roughened by clinical adjustment, these color changes were not outside the range of clinically acceptable.[42] It appears that while the assumption that greater roughness leads to significant color instability may be correct, the changes expected in roughened zirconia restorations may require further investigation.

The potential benefits of producing ceramic restorations by additive manufacturing are known. An additive manufacturing process conserves material more effectively than subtractive manufacturing, and for this reason could reduce material costs. Additive manufacturing, being a layered process, also provides intriguing advantages related to the fabrication of highly esthetic ceramic restorations as it may allow the layering of different shades to be performed in a more systematic and predictable way. However, the present study shows that the process is limited in its ability to produce a restoration with adequate smoothness. When taken together with other studies that have shown inconsistent results for flexural strength and marginal and internal fit for zirconia produced by additive manufacturing, further advancements in this process are certainly required until it can be used routinely for the fabrication of zirconia restorations. This will require further research and development of additive manufacturing techniques.

It is necessary to discuss limitations of the present study. The primary limitation stems from the use of profilometry to measure surface roughness of the specimens. Profilometry is best suited for measuring roughness on flat surfaces, however the specimens utilized in this study were full contour restorations with various convexities. To combat this, the flattest surface closest to the buccal margin of the specimens was identified and utilized as the region of interest for measuring surface roughness. A putty matrix was fabricated to standardize the orientation of each sample within the profilometer. Because all samples were full contour restorations and the same procedure was utilized for each specimen, the effect of using profilometry to measure Ra values for a non-flat specimen should be negligible. In addition, there are inherent drawbacks of stylus profilometry. For one, sensitivity of the stylus to changes in surface topography is limited by the diameter of the stylus itself.[30] Furthermore, stylus profilometry only provides a 2-dimensional representation of the sample surface. Other methods, such as laser profilometry (which produces an Sa rather than Ra value) are more suited to assess the 3-Dimensional nature of the sample. It has been recommended that using a combination of methods (i.e. stylus profilometry, laser profilometry, and scanning electron microscopy) may provide a more complete picture of surface topography.[30] The use of stylus profilometry in the present study was due to practically and availability of the necessary equipment. The other limitation of the present study is the post-milling/post-printing finishing and polishing. For the present study, a two-step polishing procedure was utilized. Because the printed zirconia specimens were received after polishing had been completed, a comparison of pre- and post-polishing for printed zirconia could not be completed. In addition, utilization of different post-printing processing techniques was not assessed. All samples in the present study were polished using the same procedure. Because of this, no comment can be made on whether a different polishing technique would produce printed specimens with smoother surfaces. This is a question that should be addressed in future studies.

References

1) Van Noort R: The future of dental devices is digital. Dental Materials 2012; 28: 3-12
2) Miyazaki T, Hotta Y, Kuriyama S, et al: A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dental Materials 2009; 28: 44-56
3) Duret F, Preston JD: CAD/CAM imaging in dentistry. Current Opinion in Dentistry 1991; 1: 150-154
4) Mörmann W: The evolution of the CEREC system. JADA 2006; 137(9), 7S-13S
5) Jain T, Porwal A, Bangar BR, et al: Computer-aided design and computer-aided manufacturing ceramic biomaterials in dentistry: past and present. Journal of Dental and Allied Sciences 2018; 7: 18-22
6) Bindl A, Mörmann WH: Marginal and internal fit of all-ceramic CAD/CAM crown copings on chamfer preparations. Journal of Oral Rehabilitation 2005; 32: 441-447
7) Shamseddine L, Mortada R, Rifai K, et al: Marginal and internal fit of pressed ceramic crowns made from conventional and computer-aided design and computer aided manufacturing wax patterns: An in vitro comparison. Journal of Prosthetic Dentistry 2016; 116, 242-248
8) Mota EG, Nunes LS, Fracasson LM, et al: The effect of milling and postmilling procedures on the surface roughness of CAD/CAM materials. J Esthet Restor Dent 2017; 29: 450-458

9) Barazanchi A, Li KC, Al-Amleh B, et al: Additive technology: update on current materials and applications in dentistry. Journal of Prosthodontics 2017; 26: 156-163

10) Li R, Chen H, Wang Y, et al: Three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition. Journal of Prosthodontic Research 2020; 64(4): 478-484

11) Hotz T: Selecting a rapid prototyping process: compare various 3D printing, CNC machining, and injection molding technologies to find a process best suited for your project. Appliance Design 2018; 66: 20-24

12) Tian X, Günster J, Melcher J, et al: Process parameters analysis of direct laser sintering and post treatment of porcelain components using Taguchi's method. Journal of the European Ceramic Society 2009; 29: 1903-1915

13) Byeon S, Song J: Mechanical properties and microstructure of the leucite-reinforced glass-ceramics for dental CAD/CAM. Journal of Dental Hygiene Science 2018; 18: 42

14) Bae E, Jeong I, Kim W, et al: A comparative study of additive and subtractive manufacturing for dental restorations. Journal of Prosthetic Dentistry 2016; 118: 197-193

15) Scheithauer U, Schwarzer E, Richter HJ, et al: Thermoplastic 3D printing- an additive manufacturing method for producing dense ceramics. Int. J. Appl. Ceram. Technol. 2015; 12: 26-31

16) Lian Q, Sui W, Yang F, et al: Additive manufacturing of ZrO2 ceramic dental bridges by stereolithography. Rapid Prototyping Journal 2018; 24: 114-119

17) Conti L, Bienenstein D, Borlaf, M, et al: Effects of the layer height and exposure energy on the lateral resolution of zirconia parts printed by lithography based additive manufacturing. Materials 2020; 13: 1317

18) Ebert J, Özkol E, Zeichner A, et al: Direct inkjet printing of dental prostheses made of zirconia. J Dent Res 2009; 88: 673-676

19) Revilla-Leon M, Al-Haj Husain N, Ceballos L, et al: Flexural strength and Weibull characteristics of stereolithography additive manufactured versus milled zirconia. Journal of Prosthetic Dentistry 2020a; Electronic publication May 17; 1-6

20) Revilla-Leon M, Methani MM, Morton D, et al: Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns. Journal of Prosthetic Dentistry 2020b; 124: 730-737

21) Revilla-Leon M, Mostafavi D, Methani MM, et al: Manufacturing accuracy and volumetric changes of stereolithography additively manufactured zirconia with different porosities. Journal of Prosthetic Dentistry 2021; S0022-3913: 30404-7

22) Branco AC, Silva R, Santos T, et al: Suitability of 3D printed pieces of nanocrystalline zirconia for dental applications. Dental Materials 2020; 36: 442-455

23) Mei Z, Lu Y, Lou, Y, et al: Determination of hardness and fracture toughness of Y-TZP manufactured by digital light processing through the indentation technique**.** BioMed Research International 2021; Article ID 6612840: 1-11

24) Bergler M, Korostoff J, Torrecillas-Martinez, L, et al: Ceramic Printing – Comparative Study of the Flexural Strength of 3D Printed and Milled Zirconia. International Journal of Prosthodontics 2021; 1-15

25) Ji SH, Kim DS, Park MS, et al: Sintering process optimization for 3YSZ ceramic 3D-printed objects manufactured by stereolithography. Nanomaterials 2021; 192

26) Marisco C, Oilo M, Kutsch J, et al: Vat polymerization-printed partially stabilized zirconia: mechanical properties, reliability and structural defects. Additive Manufacturing 2020; 36: 101450

27) Ioannidis A, Park JM, Hüsler, J, et al: An in vitro comparison of the marginal and internal adaptation of ultrathin occlusal veneers made of 3D-printed zirconia, milled zirconia, and heat-pressed lithium disilicate. Journal of Prosthetic Dentistry 2020; 1-7

28) Li R, Chen H, Wang Y, et al: Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs. J Mech Behav Biomed Mater. 2021; 115: 104255

29) Miura S, Fujita T, Tsukada S, et al: Comparative evaluation of the reproductive trueness of zirconia crowns fabricated using additive manufacturing and conventional milling. International Journal of Prosthodontics 2021; doi: 10.11607/ijp.7092

30) Field J, Waterhouse P, German M: Quantifying and qualifying surface changes on dental hard tissues in vitro. Journal of Dentistry 2010; 182-190

31) Stuzikiewicz G, Sioma A: Evaluation of surface roughness and defect formation after the machining of sintered aluminum alloy AlSi10Mg. Materials 2020; 1622

32) Schriwer C, Skjold A, Gjerdet NR, et al: Monolithic zirconia dental crowns. Internal fit margin quality, fracture mode and load at fracture. Dental Materials 2017; 33: 1012-1020

33) Johansson C, Kmet R. Rivera J, et al: Fracture strength of monolithic all-ceramic crowns made of high translucent yttrium oxide-stablized zirconium dioxide compared to porcelain-veneered crowns and lithium disilicate crowns. Acta Odontologica Scandinavica 2014; 72: 145-153

34) Yu T, Zhang Z, Liu Q, et al: Extrusion-based additive manufacturing of yttria stabilized zirconia. Ceramics International 2020; 46: 5020-5027

35) Cano S, Gonzalez-Gutierrez J, Sapkota J, et al: Additive manufacturing of zirconia parts by fused filament fabrication and solvent debinding: selection of binder formulation. Additive Manufacturing 2019; 26: 117-128

36) Ghazal M, Kern M: The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. Journal of Prosthetic Dentistry 2009; 101: 342-349

37) Abdalla MM, Ali IAA, Khan K, et al: The Influence of surface roughening and polishing on microbial biofilm development on different ceramic materials. Journal of Prosthodontics 2020; 0: 1-7

38) Checketts MR, Turkyilmaz I, Asar NV: An investigation of the effect of scaling-induced surface roughness on bacterial adhesion in common fixed dental restorative materials. Journal of Prosthetic Dentistry 2014; 112: 1265-1270

39) Janyavula S, Lawson N, Cakir D, et al: The wear of polished and glazed zirconia against enamel. Journal of Prosthetic Dentistry 2013; 109: 22-29

40) Park J, Park S, Lee K, et al: Antagonistic wear of three CAD/CAM anatomic contour zirconia ceramics. Journal of Prosthetic Dentistry 2013; 111: 20-29

41) Petropoulou A, Dimitriadi M, Zinelis S, et al: Surface characteristics and color stability of gingiva-colored resin composites. Materials 2020; 13: 2450

42) Al-Zordk W, Saker S: Impact of sintering procedure and clinical adjustment on color stability and translucency of translucent zirconia. Journal of Prosthetic Dentistry 2020; 124: e1-e9