





Physical and Mechanical Properties of Dental Ceramic Fabricated by Additive Manufacturing in Accordance with Varying Amounts of Zirconia in Slurry

Ji-Hun Youm

The Graduate School Yonsei University Department of Applied Life Science



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Ji-Hun Youm

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This certifies that the master's thesis

of 'Ji-Hun Youm' is approved.

Thesis Supervisor: Jae-Sung Kwon

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Kwang-Mahn Kim: Thesis Committee Member #1

Eun-Juny Cee

Eun-Jung Lee: Thesis Committee Member #2

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TABLE OF CONTENTS

LIST OF FIGURES ····································
LIST OF TABLESvii
ABSTRACT
I. INTRODUCTION1
1. Zirconia 1
1.1. Structure and properties of zirconia1
1.2. Partially stabilized zirconia4
2. The dental zirconia
3. Computer-aided design/computer-aided manufacturing7
3.1. Computer-aided design/computer-aided manufacturing7
3.2. Additive manufacturing for ceramic
4. Research objectives



II. MATERIALS AND METHODS10
1. Materials 10
1.1. Raw materials10
1.2. Characterization of zirconia powder
2. Zirconia slurry manufacturing 13
2.1. Preparation of zirconia slurry13
2.2. Rheological property15
2.3. Fourier transform infrared spectroscopy16
3. DLP 3D printing 17
3.1. Digital light processing
3.2. Fabrication of specimen
4. Thermal analysis 19
4.1. Thermogravimetry analysis
4.2. Debinding and sintering processes20
5. Physical properties analysis21
5.1. Density
5.2. Linear shrinkage
5.3. Microstructure



6. Mechanical properties analy	/sis24	4
6.1. Hardness		4
6.2. Biaxial flexural strength		5
7. Statistical analysis		7

III. RESULTS
1. Characterization of zirconia powder 28
2. Zirconia slurry manufacturing
2.1. Rheological property
2.2. Fourier transform infrared spectroscopy
3. Thermogravimetry analysis
4. Physical properties analysis
4.1. Density
4.2. Linear shrinkage
4.3. Microstructure
5. Mechanical properties analysis
5.1. Hardness
5.2. Biaxial flexural strength40



IV. DISCUSSION	
V. CONCLUSION	 47
REFERENCES	
ABSTRACT (in Korean)	



LIST OF FIGURES

Figure 1. Crystal structure and phase transformation with temperature of zirconia: (A)
monoclinic; (B) tetragonal; (C) cubic; and (D) phase transformation with
temperature of zirconia
Figure 2. Phase equilibrium diagram of the zirconia yttria system with variation
temperature5
Figure 3. The manufacturing principles of the digital light processing 3D printer 17
Figure 4. CAD design of specimens: (a) $5 \times 5 \times 5$ mm; (b) Ø 14×1.4 mm18
Figure 5. Thermal post-processing cycle
Figure 6. Universal testing machine used in biaxial flexural strength
Figure 7. The characteristics of the 3 mol% yittria stabilized zirconia powders. (a) FE-SEM
micrographs of zirconia powder; (b) zirconia particle size distribution; (c) XRD
patterns corresponding to zirconia powder before sintering; (d) XRD patterns
corresponding to zirconia powder after sintering
Figure 8. The viscosity of the zirconia slurry with different dispersants: (a) entire range of
shear rates to confirm the shear thinning behavior; (b) enlargement of the range
1 - 200 s ⁻¹ to confirm the viscosity at 30 s ⁻¹ . $\cdots 31$
Figure 9. The viscosity of the zirconia slurry with different solid loadings: (a) entire range
of shear rates to confirm the shear thinning behavior; (b) enlargement of the range
1 - 200 s ⁻¹ to confirm the viscosity at 30 s ⁻¹ . $\cdots 31$
Figure 10. FT-IR spectra of zirconia slurry for comparison before and after polymerization:
(a) the control group; (b) 45 vol%; (c) 50 vol%



- Figure 11. The TG-DSC curves of the cured zirconia slurry and thermal post-processing cycle. (a) The TG curve of the control group; (b) The TG curve of the 50 vol%.

- Figure 15. Weibull plot of the flexural strength by biaxial flexural strength test: (a) 45 vol%; (b) 50 vol%......41



LIST OF TABLES

Table 1. The information of the raw materials used in this study
Table 2. The composition of the zirconia slurry in this study 14
Table 3. Density and relative density of sintered parts with different solid loadings34
Table 4. Hardness of the two groups of zirconia 3D parts 39
Table 5. Results of biaxial flexural strength test and Weibull analysis



ABSTRACT

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Ji-Hun Youm

Department of Applied Life Science The Graduate School, Yonsei University

(Directed by Professor Jae-Sung Kwon, M.D., Ph.D.)

Zirconia is attracting attention in many studies due to its high mechanical properties, excellent ion conductivity, and outstanding biocompatibility. Recently, it has gained significant research and interest in the dental field, especially in combination with 3D printing. Among those studies, it is being widely used in combination with Digital Light Processing (DLP) technology, which offers advantages such as shortened manufacturing time and lower costs. To print ceramic 3D parts using DLP technology, various prerequisites are necessary. Among them, sufficient solid loading in the slurry is required for the densification and excellent mechanical performance of ceramics. However, most current research focuses on the dispersion of ceramic particles within the slurry.



Furthermore, there is a lack of research on the physical and mechanical properties depending on the solid loading in zirconia slurries. Therefore, the purpose of this study is to investigate the effects of different solid loadings in zirconia slurries on their mechanical and physical properties.

In this study, slurries with different zirconia loading were prepared and compared. Zirconia slurries with solid loadings of 45 vol%, 50 vol%, and 55 vol% were prepared. The name of each group is expressed by converting wt% into vol% calculated based on the density value presented by the manufacturer. In addition, all group consists of 3 mol% yttria-partially stabilized zirconia, monomer, photoinhibitor, and dispersant. Firstly, rheological analysis, polymerization analysis, thermal analysis, and density were conducted to evaluate the characteristics of the zirconia slurries with different solid loadings. The physical properties were evaluated through linear shrinkage and microstructure analysis. Additionally, the mechanical properties were assessed through hardness and biaxial flexural strength. In all evaluations, commercial zirconia slurries were set as the control group for comparison.

In rheological analysis, the control group and 45 vol% and 50 vol% exhibited viscosities below 3 Pa·s at 30 s⁻¹. Therefore, 55 vol% was excluded from in this study. Polymerization analysis confirmed successful polymerization for all three groups. Thermal analysis confirmed the solid loading of the control group (approximately 45 - 47 vol%) and optimized post-processing cycle for prepared slurry, and a highly densified density was obtained through this cycle. The linear shrinkage rates decreased with increasing solid loading. The microstructure analysis revealed dense grain distribution and fine grains with increasing solid loading. In terms of hardness, there was no significant difference between the control group and 45 vol% (p > 0.05), but both groups were significantly different from 50 vol% (p < 0.05). In the biaxial bending strength, there was no significant difference between 45 vol% and 50 vol% (p > 0.05). However, both groups were significantly different compare to the control group (p < 0.05). When compared numerically, the control group showed the highest value, followed by 50 vol%. Weibull analysis indicated higher



reliability for slurry with higher zirconia loading, excluding the control group.

This study successfully prepared zirconia slurries with a viscosity below 3 Pa·s at 30 s⁻¹. In terms of physical properties, an increase in solid loading led to increased hardness depth, lower linear shrinkage rates, and had dense grain distribution and fine grains. In mechanical properties, higher hardness and the reliability for strength were observed with increasing solid loading. Consequently, a foundation for preparing zirconia slurries for DLP has been established. Furthermore, by providing physical and mechanical properties based on solid loading, the application scope of zirconia in the field of 3D printing has been expanded. However, further research is needed to improve dispersion stability and minimize defects occurred in both surface and interior.

Key words: zirconia, zirconia slurry, solid loading, 3D printing, digital light processing, physical properties, mechanical properties



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I. INTRODUCTION

1. Zirconia

1.1 Structure and properties of zirconia

Zirconium is extracted as a silicate mineral called zircon and is a transition metal with significant thermal, mechanical, and thermal properties (Cristache et al., 2011; Hisbergues et al., 2009). Zirconium, with atomic number 40, is a strong metal with similar chemical and physical properties like titanium (Cionca et al., 2017; Cristache et al., 2011). Zirconium dioxide (ZrO₂) is a crystalline oxide of zirconium, also called zirconia (Kongkiatkamon et



al., 2023). Zirconia has excellent strength, toughness, and fatigue resistance, and has many other properties such as excellent biocompatibility, high refractive index, and low thermal conductivity (Kongkiatkamon et al., 2023; Sorrentino et al., 2019). Zirconia is polymorphic crystal that exhibits three crystal structures: monoclinic, tetragonal, cubic (Zhang and Lawn, 2018). At room temperature, it has a monoclinic crystal structure, and at temperatures above 1170 °C, it has a tetragonal crystal structure. When the temperature is increased, it is transformed into a cubic crystal structure at 2370 °C (Fig. 1) (Kelly and Denry, 2008). Upon cooling, it converts from the tetragonal to the monoclinic phase and exhibits a significant volume increase (4.5 %) (Denry and Kelly, 2008). This becomes a factor that causes fatal adverse effects on zirconia.





Figure 1. Crystal structure and phase transformation with temperature of zirconia: (A) monoclinic; (B) tetragonal; (C) cubic; and (D) phase transformation with temperature of zirconia (Kongkiatkamon et al., 2023).



1.2 Partially stabilized zirconia

Adverse effects due to conversion to the monoclinic phase during cooling can be controlled using metal oxides. Substituting with metal oxide prevents crack formation due to phase transformation by maintaining the tetragonal crystal structure even at room temperature (Della Bona et al., 2015). Metal oxides doped into zirconia include yttria, ceria, calcia, and magnesia. Among them, ZrO_2 stabilized with Y_2O_3 has better mechanical properties than other stabilizers (Zhang and Lawn, 2018). Additionally, by doping zirconia with yttria, some of the Zr^{4+} ions are replaced with Y^{3+} cations (Denry and Kelly, 2008). As a result, oxygen vacancies are created, and because of the oxygen vacancies thus created, yttria stabilized zirconia has ionic conductivity (Eichler, 2001). Zirconia has different properties depending on its yttria content. Monoclinic zirconia changes to the tetragonal phase and then to the cubic phase as the dopant concentration increases. An yttria content of 3 mol% provides better mechanical properties but has low translucency. Increasing the yttria content increases translucency but lowers the mechanical properties (Alqutaibi et al., 2022). Zirconia composed of above 8 mol% yttria content exhibits a stable cubic phase at room temperature (Kongkiatkamon et al., 2023).





Figure 2. Phase equilibrium diagram of the zirconia yttria system with variation temperature (Gautam et al., 2016).



2. The dental zirconia

The use of bioceramic restorations is increasing due to the demand for excellent mechanical properties, aesthetic appearance, biocompatibility, and process ability. Ceramics used in the dental field are silica, leucite, lithium disilicate, alumina, and zirconia based materials (Della Bona et al., 2015). Among them, the introduction of zirconia as a dental material has aroused considerable interest in the dental field. Zirconia (3Y-PSZ) used in the dental field mainly contains a small amount of yttria stabilizer, and its mechanical properties are the highest among currently used dental ceramics. In addition, it has optimal properties for dental use, including excellent chemical properties, dimensional stability, high resistance to corrosion, and high biocompatibility. Zirconia structures used in dentistry include root canal posts, crowns, bridges, implant abutments, and orthodontic brackets (Gautam et al., 2016). Zirconia-based posts have excellent biocompatibility and radiopacity, and have good light transmission in the tooth root and restoration (Algutaibi et al., 2022). It also has high flexural strength and excellent corrosion resistance. For crowns and bridges, various types of zirconia frameworks were used. By using zirconia, natural translucency can imitate natural teeth, and it has excellent mechanical properties, making it possible to apply it to crowns and bridges (Gautam et al., 2016). Zirconia-based implant abutments showed very similar bone-implant contact to titanium implants, suggesting that zirconia implants can achieve stability in bone (Guess et al., 2012). In a recent study, osseointegration of zirconia implants was histologically proven. In addition, its excellent toughness and low elastic modulus made it possible to apply it as an implant (Cionca et al., 2017). Zirconia-based orthodontic brackets can be applied due to their enhanced strength, deformation, and wear resistance, reduced plaque adhesion, and improved aesthetics (Algutaibi et al., 2022).



3. Computer-aided design/computer-aided manufacturing

3.1 Computer-aided design/computer-aided manufacturing

Recently, digital technology has been combined with analog-based dental technology (Wazeer et al., 2023). Among them, CAD (Computer-Aided Design)/CAM (Computer-Aided Manufacturing) are the technologies that are developing most rapidly in modern dentistry and where much research is in progress (Skorulska et al., 2021). CAD/CAM technology is a digital technology that uses computers to collect data from the oral cavity, design dental prosthetics, and manufacture them into various products (Beuer et al., 2008). Advantages of CAD/CAM technology include reduction of procedure time using digital techniques, increased efficiency through automation of manufacturing steps, and patient satisfaction (Skorulska et al., 2021). CAD/CAM technology is classified into subtractive manufacturing (SM) and additive manufacturing (AM) depending on the manufacturing method (Moon et al., 2022). Subtractive machining is a process in which a block is milled to reveal the designed volumetric shape using a milling machine that performs with 3-, 4- or 5-axis milling systems in wet or dry conditions (Sulaiman, 2020). AM technology, also called 3D printing, is a process that can form complex structures by adding feedstock of the appropriate shape for each layer based on a designed 3D CAD model (Mamatha et al., 2023; Moon et al., 2022). AM is classified into vat polymerization, Material Extrusion, Material Jetting, Binder Jetting, Powder Bed Fusion, Direct Energy Deposition, and Sheet Lamination depending on the application process, curing principle, and material condition (Mamatha et al., 2023). Compared to SM technology, AM technology has the advantage of having no limitations in manufacturing complex structures, making a reduction in waste material, and being able to produce multiple parts at the same time (Branco et al., 2023; Galante et al., 2019).



3.2 Additive manufacturing for ceramic

The most extensively studied AM technology with regard to ceramic materials is vat polymerization (VP) (Wang et al., 2023). Vat polymerization (VP) is an additive manufacturing process in which a liquid photopolymer within a vat is cured by lightactivated polymerization (Wang et al., 2023). VP technologies mainly involve stereo lithography apparatus (SLA) and digital light processing (DLP). Both technologies are the most widely used ceramic additive manufacturing technologies due to their high forming efficiency, ability to print various ceramic materials, and high printing accuracy (Galante et al., 2019). SLA is a light polymerization technology that selectively cures specific areas of the resin on each layer using a laser beam that serves as a point light source (Chen et al., 2019b). DLP is based on a polymerization technology similar to SLA, but it differs the light source used. In DLP, the material is cured on a surface-by-side basis by exposing it to UV or visible light using a high-resolution projector (Mamatha et al., 2023). Compared to SLA, DLP technology has the advantage of reduced manufacturing time due to fast light shifting and image projection in the process and low cost (Chen et al., 2019b).

Prerequisites are required to print ceramic parts with DLP technology. First, it should generally consist of ceramic powder, monomer, photoinitiator, and dispersant (Galante et al., 2019; Hussain et al., 2023). To exhibit uniform spreading during printing, the slurry of ceramic must have low viscosity (less than 3 Pa \cdot s at a shear rate of 30 s⁻¹) and shear thinning behavior (Chen et al., 2019b). Additionally, the ceramic slurry must have high stability to reduce particle precipitation during printing (Liu et al., 2024a). Finally, the solids content must be high to reduce dimensional shrinkage and defects during debinding and sintering processes (Su et al., 2023).



4. Research objectives

The ceramics in 3D printing require a sufficient amount of ceramic powder for densification and remarkable mechanical properties. However, in most research of 3D printing related ceramics, despite a lot of research on the dispersion of ceramic particles in the monomer (Liu et al., 2024a; Liu et al., 2024b), optimization of processes (Sun et al., 2020), and evaluation of slurry manufactured using specific powder (Inserra et al., 2023; Komissarenko et al., 2021), there is a limited number of research on the intrinsic relationship among the solid loading of zirconia slurry, relative density, strength, and microstructure depending on the solid loading in zirconia slurry. Therefore, the purpose of this study is to investigate the effect of different solid loadings on physical and mechanical properties in zirconia slurry.

The null hypothesis was that there would be no difference in the physical and mechanical properties of 3D printed specimens from the zirconia slurry with different solid loadings.



II. MATERIALS AND METHODS

1. Materials

1.1 Raw materials

3 mol% yttria-partially stabilized zirconia powder (3Y-PSZ,) was used as ceramic powder. The monomers were used as 1,6-hexanediol diacrylate (HDDA, Sigma Aldrich, St. Louise, MO, USA), and isobornyl acrylate (IBOA, Sigma Aldrich, St. Louise, MO, USA). The dispersant used in this study was the Alkylolammonium salt of a copolymer with acidic groups (BYK-180, BYK-Chemie, Geretsried, Germany) for reducing the viscosity of the ceramic slurry. 2, 4, 6-trimethylbenzoyl-diphenylphosphine oxide (TPO, Sigma Aldrich, St. Louise, MO, USA) was used in the ceramic slurry as the photoinitiator induced the beginning of photopolymerization.



Role	Material	Density (g/cm ³)	Manufacturer
Ceramic Powder	3 mol% yttria-partially stabilized zirconia powder (3Y-PSZ)	6.05	Guangdong Orient Zirconic (Shantou, China)
Dhotogongitiya	1,6-hexanediol diacrylate (HDDA)	1.02	Sigma Aldrich
Photosensitive Resin	Isobornyl acrylate (IBOA)	0.99	(St. Louise, MO, USA)
Dispersant	Alkylolammonium salt of a copolymer with acidic groups (BYK-180)	1.08	BYK-Chemie (Geretsried, Germany)
Photoinitiator	2, 4, 6-trimethylbenzoyl- diphenylphosphine oxide (TPO)	1.22	Sigma Aldrich (St. Louise, MO, USA)

Table 1. The information of the raw materials used in this study



1.2 Characterization of zirconia powder

To determine the particle size distribution, the particle size analyzer (ELS-Z1000, Otsuka Electronics, Tokyo, Japan) was used. Suspension was prepared by dispersing zirconia powder in distilled water.

X-ray diffraction (XRD) analysis was conducted the raw powder and sintered specimens using an X-ray diffraction (Ultima IV, Rigaku Corporation, Tokyo, Japan) with CuK α radiation in the 2 θ range 10 - 80°. To analyze the fraction of phases, the intensities of the monoclinic (-111) and (111) peaks and the tetragonal (101) peak were integrated. Phases were identified by JCPD file No. 00-037-1484 for monoclinic and No. 01-083-0113 for tetragonal zirconia.

The morphology of zirconia powder was investigated using field emission scanning electron microscopy (FE-SEM) (JSM-7800F, JEOL Ltd, Tokyo, Japan). The zirconia powder was dispersed in ethyl alcohol. The suspension was performed to an ultrasonication for 1 min. Once the powder was wall-dispersed on the silicon wafer, the suspension was dried by using a dry oven. The zirconia powder was sputter-coated with a layer of Pt for 1 minute.



2. Zirconia slurry manufacturing

2.1 Preparation of zirconia slurry

The raw materials of 3Y-PSZ powder, HDDA, IBOA, dispersant, and photoinitiator are weighed as the proportion indicated in Table 2. To prepare the photosensitive resin medium, a solution of HDDA/IBOA with a 70/30 wt ratio was prepared using a speed mixer (DAC 150.1 FVZ Speed mixer, Hauschild Speed Mixer, Hamm, Germany) for 3 min at 3500 rpm. Then, a certain amount of dispersant was added to the HDDA/IBOA solution and mixed with a speed mixer. Afterward, zirconia powder was gradually added, and finally, the photoinitiator was added in a dark atmosphere and mixed for 5 min at 3500 rpm. Photoinitiator was used at 1 wt% based on the polymer content. A commercial zirconia slurry (INNI-CERA, AON, Seoul, Korea) served as the control group. The commercial product, launched in 2019, is a clinically utilized product for producing artificial teeth such as anterior teeth. In addition, it consists of 3 mol% yttria-partially stabilized zirconia, monomer, photoinhibitor, and dispersant.



Group	3Y-PSZ	HDDA	IBOA	BYK-180	ТРО
(vol%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
45	82.8	10.5	4.5	2.00	0.20
50	85.7	8.50	3.64	2.00	0.14
55	87.8	7.02	3.02	2.00	0.12

Table 2. The composition of the zirconia slurry in this study

The name of each group is expressed by converting wt% into vol% calculated based on the density value of 3Y-PSZ presented by the manufacturer. 3Y-PSZ, 3 mol% yttria-partially stabilized zirconia; HDDA, 1,6-heaxanediol diacrylate; IBOA, Isobornyl acrylate; BYK-180, Alkylolammonium salt of a copolymer with acidic groups; TPO, 2, 4, 6-trimethylbenzoyl-diphenylphosphine oxide.



2.2 Rheological property

To investigate the optimal dispersant content, the solid loading was the same, but the viscosity was measured at a dispersant content of 1 - 5 wt%. Additionally, it was evaluated to measure the viscosity of zirconia slurry with different solid loading. The rheological properties of the zirconia slurry were performed using a rotational rheometer (MCR 702e, Anton Paar, Graz, Austria) equipped with parallel plates. The gap of parallel plates was set to 0.4 mm. The rheological properties were measured as a function of the shear rate in the range of 0.1 - 1000 s⁻¹ under room temperature.



2.3 Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared spectroscopy (FT-IR) was employed to confirm the degree of polymerization by comparing the peaks of the zirconia slurry and cured specimen. The FTIR analysis was performed using an FTIR-ATR Spectrometer (VERTEX 70, Bruker Optics, Billerica, MA, USA). The scanning range was from 800 cm⁻¹ to 4000 cm⁻¹, and the resolution was 4 cm⁻¹. Each specimen was scanned 32 times to obtain a sufficient average for the FT-IR spectrum.



3. DLP 3D printing

3.1 Digital light processing

The zirconia specimens were fabricated using a digital light processing (DLP) 3D printer (INNI-II, AON, Seoul, Korea) that can cure the photosensitive resin using light with 405 nm wavelength. The layer thickness was 50 μ m. The prepared zirconia slurry was added into the printer vat, the layer was exposed to the light which cured it to achieve one layer, and then the build platform moved one--layer thickness upwards so that fresh slurry flowed above the cured layer and the process was continued until the final designed shape was obtained.



Figure 3. The manufacturing principles of the digital light processing 3D printer.



3.2 Fabrication of specimen

Two types of specimens were designed using the AutoCAD software. A first specimen was designed for density, linear shrinkage, and hardness (dimensions of after sintering: $5 \times 5 \times 5$ mm). A second specimen was designed for Biaxial flexural strength (dimensions of after sintering: internal diameter = 14 mm, thickness = 1.4 mm). After printing, the printed specimens were washed in the isopropyl alcohol to remove the uncured polymer and naturally dried. Then, specimens were performed post-processing. Afterward, the surface of the specimen was smoothed using silicon carbide (SiC) paper, polished with diamond paste, and then washed in distilled water.



Figure 4. CAD design of specimens: (a) $5 \times 5 \times 5$ mm; (b) Ø 14 × 1.4 mm.



4. Thermal analysis

4.1 Thermogravimetry analysis

Thermogravimetry analysis was performed to confirm the weight loss of the green body and the solid loading of the control group. Thermogravimetry analysis of the ceramic green body was carried out with a DSC/TGA instrument (SDT Q600, TA Instruments, Leatherhead, UK). The green body was pulverized. The pulverized green body was heated from room temperature to 800 °C in air. This was performed at a constant heating rate of 2 °C/min.



4.2 Debinding and sintering processes

The green body was heat-treated for post-processing. The 3Y-PSZ green body was debinded and sintered in a box-type furnace (CERAFUR-S, AON, Seoul, Korea). Based on the TG-DSC results, multi-stage heat treatment was used as summarized in Fig. 5 to remove HDDA, IBOA, and dispersant at low temperatures. In particular, a very slow heating rate of 0.1 °C/min and holding for 3h was adopted in the temperature range of 270 - 380 °C to remove the polymers completely and then increased temperature to 1550 °C at a rate of 17.2 °C/min and holding for 2 h.



Figure 5. Thermal post-processing cycle.



5. Physical properties analysis

5.1 Density

The density of the sintered specimens was measured using the Archimedes' principle in accordance with ISO 18754. The post-processing is carried out according to the presented debinding and sintering processes. Ten specimens were used for density. The prepared specimens were dried in a drying oven at a temperature of 110 ± 5 °C for at least 2 hours. The dried specimens were naturally cooled at 24 °C. The mass of the dry test specimen (m₁) was measured. The specimens were immersed in distilled water and boiled for more than 3 hours. After the immersing, the specimens were stored until the temperature of the distilled water was cooled at 24 °C. The mass of the immersed specimen (m₂) was measured. Then, the mass of the soaked specimen (m₃) was measured after completely removing moisture from the surface using a dry towel. The density was calculated using the following formula:

$$\rho = \frac{m_1}{m_3 - m_2} \times \rho_{liq}$$

where,

 ρ is density in g/cm³;

 m_1 is the mass of the dry specimen in g;

 m_2 is the mass of the immersed specimen in g;

 m_3 is the mass of the soaked specimen in g;

 ρ_{liq} is the density of the immersion liquid (distilled water) at 24 °C.



5.2 Linear shrinkage

The linear shrinkage was conducted using ten specimens measuring $5 \times 5 \times 5$ mm. A vernier caliper is used to measure the X, Y, and Z directions of the specimen. Measured specimens are post-processed according to the heat treatment conditions. Specimens after sintering should be stored in a dry oven. And then, measure and record each length with a vernier caliper in three directions of X, Y, and Z of the sintered specimen. Before and after sintering, it is calculated using the shrinkage formula based on the length change in each of the X, Y, and Z directions of the specimen.

$$\Delta X = \frac{X_1 - X_2}{X_1} \times 100$$

where,

 X_1 is the length before sintering;

 X_2 is the length after sintering.



5.3 Microstructure

The microstructure was performed to compare the degree of densification and homogeneity according to the zirconia content. In addition, it was intended to evaluate the grain size number. The microstructure was imaged using the FE-SEM (JSM-7800F, JEOL Ltd, Tokyo, Japan). The surface of the specimen was polished and thermally etched at 1450 °C for 20 minutes. The heating and cooling rate was 20 °C/min. The etched specimens were sputter-coated with a layer of Pt for 1 minute. The grain size number was calculated by the following formula:

$$n = \frac{\ln N}{\ln 2} + 1$$

where,

n is the grain size number;

N is the number of grains per square inch at $100 \times$ magnification.



6. Mechanical properties analysis

6.1 Hardness

The hardness was performed using a hardness tester (MMT-X7B, Matsuzawa, Akita-Shi, Japan) under the applied load of 1000 gf (9.81 N), with a dwell time of 10 s. Three specimens were used in each group under each load and dwell time, and ten indentations were randomly made in each specimen. The hardness was calculated from the applied load, previously selected to avoid cracks, and the two diagonals length of the indent (Quinn et al., 2002). The Vickers hardness was calculated by the following formula:

$$H_v = 1.854 \frac{p}{d^2}$$

where,

 H_v is hardness;

P is the indentation load in gf;

d is the average length of the diagonals in mm.



6.2 Biaxial flexural strength

The biaxial flexural strength test was performed on fifteen specimens per group using the Piston-on-Three ball technique according to ISO 6872. The diameter of the cylindrical piston was 1.2 mm and the specimen was placed in three balls located in triangular positions 12 mm apart from each other. It was performed at a crosshead speed of 1 mm/min until failure of the specimen occurred through the universal test machine. The load until the specimen fails is set as N and calculated in MPa using the formula.

$$\sigma = \frac{-0.2387P(X - Y)}{b^2}$$
$$X = (1 + \nu) \ln\left(\frac{r_2}{r_3}\right)^2 + \frac{1 - \nu}{2}\left(\frac{r_2}{r_3}\right)^2$$
$$Y = (1 + \nu) \left[1 + \ln\left(\frac{r_1}{r_3}\right)^2\right] + (1 - \nu)\left(\frac{r_1}{r_3}\right)^2$$

where,



- *P* is the fracture load in N;
- *b* is the specimen disk thickness;
- ν is the Poisson's ratio of the ceramic (= 0.25);
- r_1 is the radius of support circle (= 6.00);
- r_2 is the radius of loaded area (= 0.60);
- r₃ is the radius of specimen.



The reliability of the material was calculated by measuring the Weibull modulus (m) using the following formula.

$$P(\sigma) = 1 - exp\left[-\left(\frac{\sigma}{\sigma_{\theta}}\right)^{m}\right]$$

where,

 $P(\sigma)$ is the probability of failure;

 σ is the fracture strength at a given $P(\sigma)$;

 σ_{θ} is the characteristic strength;

m is the Weibull modulus.



Figure 6. Universal testing machine used in biaxial flexural strength.



7. Statistical analysis

All descriptive statistics were expressed using means \pm standard deviations. The Shapiro-Wilk test was used to confirm the normal distribution of the data. Then, it was analyzed through one-way ANOVA, and the Tukey HSD test was performed for multiple comparisons among the groups. Statistical analysis was performed using SPSS software (SPSS Statistics 23, IBM Corp., Armonk, NY, USA), and the significance level was set to P < 0.05.



III. RESULTS

1. Characterization of zirconia powder

Fig. 7(a) shows the SEM Image of zirconia powder. It was confirmed that the powder consisted of particles with a size in the range of 90 - 500 nm. Fig. 7(b) shows the particle size distribution of 3 mol% yttria-partially stabilized zirconia powder. It is characterized by a monomodal narrow distribution in the range of 70 - 1300 nm, with a d_{50} of approximately 500 nm. Fig. 7(c) and (d) show the powder and sintered specimens observed using XRD analysis. The powder contained tetragonal and monoclinic phases and the monoclinic phased content was 65.49 %. However, only the tetragonal phase was detected in the sintered specimen.





Figure 7. The characteristics of the 3 mol% yittria stabilized zirconia powders. (a) FE-SEM micrographs of zirconia powder; (b) zirconia particle size distribution; (c) XRD patterns corresponding to zirconia powder before sintering; (d) XRD patterns corresponding to zirconia powder after sintering. m-ZrO₂, monoclinic zirconia; t-ZrO₂, tetragonal zirconia.



2. Zirconia slurry manufacturing

2.1 Rheological property

The viscosity corresponding to each dispersant content (1 - 5 wt%) is shown in Fig. 8. 1 wt% did not show the shear thinning behavior, but other groups showed the shear thinning behavior while the viscosity decreased as the shear rate increased. The highest viscosity value was shown in the dispersant content (1 wt%). As the dispersant content increased from 1 wt% to 2 wt%, the viscosity of the slurry decreased in all shear rate ranges. However, it was confirmed that the viscosity increased when the dispersant content was additionally increased. Therefore, 2 wt% is the optimized dispersant content to obtain ceramic slurry with low viscosity which is suitable for DLP. The viscosity corresponding to each zirconia content (45, 50, 55 vol%) and the control group are shown in Fig. 9. The control group of viscosities were 1.2, 2.4, and 7.3 Pa·s at the shear rate of 30 s⁻¹. The 45 vol%, 50 vol%, and 55 vol% of viscosities were shown in all solid loadings except 55 vol% while the viscosity decreased.





Figure 8. The viscosity of the zirconia slurry with different dispersants: (a) entire range of shear rates to confirm the shear thinning behavior; (b) enlargement of the range 1 - 200 s⁻¹ to confirm the viscosity at 30 s⁻¹.



Figure 9. The viscosity of the zirconia slurry with different solid loadings: (a) entire range of shear rates to confirm the shear thinning behavior; (b) enlargement of the range 1 - 200 s⁻¹ to confirm the viscosity at 30 s⁻¹.



2.2 Fourier transform infrared spectroscopy

The FT-IR spectra of the zirconia slurry before and after polymerization are shown in Fig. 10. Three groups confirmed that the stretching vibration peak of C = C at 1635 cm⁻¹ was clearly weakened and even disappeared.



Figure 10. FT-IR spectra of zirconia slurry for comparison before and after polymerization: (a) the control group; (b) 45 vol%; (c) 50 vol%.



3. Thermogravimetry analysis

The TG-DSC curve of the printed specimen is illustrated in Fig. 11. According to the TG curve, the weight loss of 3.25 % occurred from room temperature to 240 °C. Afterward, the highest weight loss (11.51 %) was observed at temperatures ranging from 240 °C to 420 °C (Fig. 11(b)). There was no change in weight after 420 °C. The total weight reduction rate during the debinding process was 14.76 %. The solid loading of the control group was confirmed to be 81.8 wt%, which is approximately 45 - 47 vol% (Fig. 11(a)). In the case of 50 vol%, it was confirmed to exhibit the same value as the zirconia content in the composition presented in Table 2.



Figure 11. The TG-DSC curves of the cured zirconia slurry and thermal post-processing cycle. (a) The TG curve of the control group; (b) The TG curve of the 50 vol%.



4. Physical properties analysis

4.1 Density

The density and relative density were calculated and listed in Table 3. In the case of the control group, the density was 5.99 ± 0.03 g/cm³. At 45 vol%, the density was 6.00 ± 0.03 g/cm³. At 50 vol%, the density was 5.97 ± 0.03 g/cm³. In the case of the control group, there was no significant difference between 45 vol% and 50 vol%, respectively. There was a significant difference between 45 vol% and 50 vol%.

Group	Density (g/cm ³)
Control group	5.99 ± 0.03^{ab}
45 vol%	$6.00\pm0.03^{\rm a}$
50 vol%	$5.97\pm0.03^{\text{b}}$

Table 3. Density and relative density of sintered parts with different solid loadings

Same lowercase letter indicates no significant difference (p > 0.05).



4.2 Linear shrinkage

The linear shrinkage ratios according to solid loadings are shown in Fig. 12. After sintering, the control group showed shrinkage ratios of 21.9 ± 0.34 %, 21.4 ± 0.43 %, 23.5 ± 0.62 % in the X, Y, and Z directions, respectively. 45 vol% showed shrinkage ratios of 21.9 ± 0.23 %, 22.2 ± 0.42 %, and 23.1 ± 0.26 % in the X, Y, and Z directions, respectively. 50 vol% showed shrinkage ratios of 18.9 ± 0.32 %, 19.4 ± 0.73 %, and 20.1 ± 0.55 % in the X, Y, and Z directions, respectively. When comparing the three groups, there was no significant difference between the control group and 45 vol% in the X, Y, and Z directions. However, 50 vol% indicated a significant difference in both groups. When the solid loading was 50 vol%, the minimum shrinkage was observed in the X, Y, and Z directions.





Figure 12. The linear shrinkage of parts with different solid loadings in the X, Y, and Z directions. Same lowercase letter indicates no significant difference (p > 0.05).



4.3 Microstructure

Fig. 13 is an image of the photopolymerized layer and the dispersion of zirconia powder in the photocured matrix before sintering, and the layer after sintering. In the control group, grooves were formed at the interface between photopolymerized layers before sintering. However, no noticeable interface was observed between the photopolymerized layers at 45 vol% and 50 vol%. In the dispersion of zirconia particles in the photosensitive matrix, it was confirmed that the zirconia particles were homogeneously distributed within the matrix without serious aggregation in all three groups. In the case of photopolymerized layers after sintering, no noticeable interfaces between layers were observed in all three groups. Fig. 14 is an image of the densification and microstructure of the sintered zirconia 3D parts. At the selected sintering temperature, all three groups reached a high degree of densification. Also, as can be seen in Fig. 14, as the solid loading increased, it was confirmed that the grains were an almost fully dense and completely homogeneous microstructure, with a fine average grain size. In the case of grain size number, it was 1.62 in the control group, 1.84 in 45 vol%, and 2.50 in 50 vol%.





Figure 13. FE-SEM images of the surface grooves of the green bodies and sintered specimens printed with different solid loadings at lower and higher magnification: (a - d) the control group; (e - h) 45 vol%; (i - l) 50 vol%. The red circles show defects.



Figure 14. FE-SEM images of the microstructure of the green bodies and sintered specimens printed with different solid loadings at lower and higher magnification: (a - c) the control group; (d - f) 45 vol%; (g - i) 50 vol%.



5. Mechanical properties analysis

5.1 Hardness

The change in hardness according to solid loadings is shown in Table 4. The Vickers hardness value of the control group was 1278 ± 22.83 HV. The Vickers hardness value of the 45 vol% was 1270 ± 7.986 HV, and the 50 vol% was 1317 ± 9.195 HV. The control and 45 vol% groups did not indicate a significant difference, but both groups showed a significant difference from 50 vol%.

Table 4. Hardness of the two groups of zirconia 3D parts

Group	D ₁	D ₂	Hardness (HV)
Control group	38.54 ± 0.343	37.66 ± 0.451	$1278\pm22.83^{\text{b}}$
45 vol%	38.54 ± 0.335	37.86 ± 0.344	$1270\pm7.986^{\text{b}}$
50 vol%	37.64 ± 0.319	37.40 ± 0.232	$1317\pm9.195^{\rm a}$

Same lowercase letter indicates no significant difference (p > 0.05).



5.2 Biaxial flexural strength

The biaxial flexural strength, Weibull modulus, and Characteristic strength with different solid loadings are shown in Table. 5. The biaxial flexural strength value of the control group was 989.1 \pm 128.5 MPa, the 45 vol% was 142.8 \pm 24.3 MPa, and the 50 vol% was 153.3 \pm 20.6 MPa. There was no significant difference between 45 vol% and 50 vol%. As a result of Weibull analysis, the control group obtained a characteristic strength $\sigma_{\theta} = 1067$ MPa and a Weibull modulus m = 9.15 \pm 0.46. 45 vol% obtained a characteristic strength $\sigma_{\theta} = 149.7$ MPa and a Weibull modulus m = 7.22 \pm 0.62. In the case of 50 vol%, a characteristic strength $\sigma_{\theta} = 153.7$ MPa and a Weibull modulus m = 8.48 \pm 1.64 were obtained.



Group	Biaxial flexural strength (MPa)	Weibull modulus (m)	Characteristic strength (σ _θ , MPa)
Control group	989.1 ± 128.5^{a}	9.15 ± 0.46	1067
45 vol%	142.8 ± 24.3^{b}	7.22 ± 0.62	149.7
50 vol%	$153.3\pm20.6^{\text{b}}$	8.48 ± 1.64	153.7

 Table 5. Results of biaxial flexural strength test and Weibull analysis

Same lowercase letter indicates no significant difference (p > 0.05).



Figure 15. Weibull plot of the flexural strength by biaxial flexural strength test: (a) 45 vol%; (b) 50 vol%.



IV. DISCUSSION

Zirconia is attracting attention in many studies due to its high mechanical properties, excellent ion conductivity, and outstanding biocompatibility. Recently, it has been receiving a lot of research and attention in the dental field by combining it with DLP technology, one of the 3D printing technologies. To print ceramic 3D parts using DLP technology, various prerequisites are necessary. Among them, sufficient solid loading is required for the densification and excellent mechanical performance of ceramics. However, most current research focuses on the dispersion of ceramic particles within the photosensitive resin. Furthermore, there is a lack of research on the physical and mechanical properties depending on the solid loading in zirconia slurries. Therefore, the purpose of this study is to investigate the effects of different solid loadings in zirconia slurries on their mechanical and physical properties. In this study, the physical and mechanical properties of 3D parts manufactured with different solid loadings were compared. The physical properties according to different solid loadings were compared through the evaluation of the linear shrinkage and microstructure. The mechanical properties according to different solid loadings were compared through hardness and biaxial flexural strength.

In linear shrinkage, there was no significant difference between the control group and 45 vol% in the X, Y and Z directions (p > 0.05), but both groups were significantly different from the 50 vol% (p < 0.05). Therefore, the first null hypothesis was partially rejected. In hardness, there was no significant difference between the control group and 45 vol% (p > 0.05), but both groups were significantly different compared to the 50 vol%. In the biaxial flexural strength, there was no significant difference between 45 vol% and 50 vol% (p > 0.05), but both groups were significantly different from the control group (p < 0.05). Therefore, the second null hypothesis was also partially rejected.

In order to prepare slurries with different solid loadings that can be printed for DLP, rheological behavior, polymerization analysis, thermogravimetry analysis, and density



were evaluated.

The rheological properties in ceramic slurry are a very important factor affecting printability and properties of final ceramic 3D parts (Liu et al., 2024b). Viscosity was evaluated with different dispersant contents (1 - 5 wt%). In the case of 1 wt%, the high viscosity was shown, and the lowest viscosity was shown at 2 wt%. It was also confirmed that the viscosity increased as the dispersant content increased. This can be explained by the dispersant mechanism. When the content of the dispersant is low, particles tend to be aggregated by Van der Waal's force, thereby showing an increase in viscosity. Afterward, when the contents of the dispersant sufficient to cover the surface of the zirconia powder is added, the slurry becomes homogeneous and stable. When the content of the dispersant is high, excess dispersant molecules in the slurry cause aggregation, which again reduces the stability of the slurry and increases viscosity (Liu et al., 2024a). Therefore, 2 wt% is the optimized dispersant content to obtain ceramic slurry with low viscosity which is suitable for DLP. The viscosity was evaluated with different solid loadings at a dispersant content of 2 wt%. 45 vol% and 50 vol% were 1.2 and 2.4 at the shear rate of 30 s^{-1} , respectively. As mentioned in many previous studies, the slurry viscosity should not exceed 3 Pa s at the shear rate of 30 s⁻¹ for proper flow during layer creation (Griffith and Halloran, 1996). It should also exhibit the shear thinning behavior (Komissarenko et al., 2021). However, in the case of 55 vol%, it exceeded 3 Pa·s at the shear rate of 30 s⁻¹ and did not show the shear thinning behavior. Therefore, it was excluded from the study.

The difference before and after polymerization was compared through FT-IR. As shown in Fig. 10, it was confirmed that the stretching vibration peak of C = C at 1635 cm⁻¹ was clearly weakened and even disappeared in all groups (Jiaqi et al., 2022). Through this, it was confirmed that polymerization was successful.

The post-processing is also important for successful DLP 3D printing of ceramics. This is because defect formation can be prevented through optimization of the debinding and sintering processes. The debinding process was optimized through TG-DSC evaluation for



prepared zirconia slurry. It showed a weight loss of 3.25 % from room temperature to 240 °C. This is believed to be a weight loss due to the removal of physically adsorbed water (Chen et al., 2019a; Liu et al., 2020). Afterward, the highest weight loss (11.51 %) was observed at temperatures ranging from 240 °C to 420 °C. This is believed to have resulted in a large weight loss due to all polymer additives were burned in the temperature range (Li et al., 2020). There was no change in weight after 420 °C. This indicates that polymer combustion can be completed above this temperature. Based on the data, the postprocessing was designed. Since there was no significant weight loss below 200 °C, heating to the corresponding temperature was performed at 1 °C/min. Thereafter, the heating rate was reduced to 0.1 °C/min. Dwell time was performed for 3 h at 270, 330 °C and 380 °C. This is to prevent cracks and air bubbles in the specimen by providing sufficient time to remove a large amount of polymer (Sun et al., 2020). After that, the polymer was removed once again at 430 °C and 490 °C, and sintering was performed at 1550 °C. Accordingly, through the optimized post-processing cycle, the density of the control group was 5.99 \pm 0.03 g/cm³, 6.00 \pm 0.03 g/cm³ at 45 vol%, and 5.97 \pm 0.03 g/cm³ at 50 vol%.

In linear shrinkage, there was no significant difference between the control group and 45 vol% on the X, Y and Z directions (p > 0.05), but both groups were significantly different from the 50 vol% (p < 0.05). When the solid loading was 50 vol%, the minimum shrinkage was observed in the X, Y, and Z directions. The monomer content decreases due to the high solid loading. It is, therefore, believed that shrinkage decreased during the polymerization process as more solid loading were incorporated, resulting in a low shrinkage rate.

The microstructure confirmed the cured layer before sintering, the degree of dispersion of zirconia powder in the cured matrix, and the cured layer after sintering using the image obtained through the FE-SEM. In addition, the densification and microstructure of the sintered zirconia object were confirmed. In the case of the control group, it was confirmed that grooves were formed at the interface between the cured layers before sintering, but in the other group, it was confirmed that the cured layers were strongly bonded to each other (Fig. 13a, e, i). However, after sintering, it was confirmed that the layered structure was



less noticeable in all groups (Fig. 13c, g, k). It may be due to the heat-treatment process, during which the ceramic particles stacked freely firstly and followed by a possible particle rearrangement near the interface (Li et al., 2020). In consequence, the boundaries became blurred. In the densification and microstructure of the sintered zirconia object, it was confirmed that the grain boundary and the number of fine grains increased as the solid loading increased (Fig. 14c, f, i). These fine grain microstructures were resulted from the suppressed grain growth during the sintering process as the solid loading increases (Jo et al., 2006). Therefore, as the solid loading increases, a dense grain distribution and fine grains can be obtained.

For the hardness, the Vickers hardness value of the control group was 989.1 ± 128.5 MPa, 45 vol% was 142.8 ± 24.3 MPa, and 50 vol% was 153.3 ± 20.6 MPa. There was no significant difference between the control group and 45 vol%, but both groups showed a significant difference from the 50 vol%. This is believed to be an effect caused by grain. The mechanical properties of crystalline materials are closely related to grain size. As the solid loading increases, the grain growth is significantly inhibited during the sintering process, resulting in a fine-grained microstructure. The resulting fine grains have a higher possibility of being surrounded by more adjacent grain boundaries. These grain boundaries act as obstacles to the movement of dislocations that cause plastic deformation ("Liu et al., 2013). As a result, dislocations interfere with the material's ability to plastically deformed by encountering grain boundaries (Jo et al., 2006). Therefore, as the particle size decreases, the density of the grain boundary increases. Accordingly, it is believed that the mechanical properties increased due to the interference with dislocation movement.

When statistically compared concerning biaxial flexural strength, there was no significant difference between 45 vol% and 50 vol%, but both groups indicated a significant difference from the control group. When flexural strength values were compared numerically, the control group showed the highest value, followed by 50 vol%. The prepared zirconia slurry showed lower flexural strength than the control group. This is believed to be the effect of low dispersion stability and defects occurred in both surface and



interior. The flexural strength is significantly affected by the number of defects in the specimen. As can be seen in Fig. 13 (h) and (l), defects were found in both groups. In addition, more defects were observed on the 50 vol% surface than those of the 45 vol%. Many of these defects may serve as stress concentration, and the specimen may be damaged in early stages when a load is applied. Weibull analysis showed higher reliability at 50 vol% (m = 8.48) than the 45 vol% (m = 7.22). Through this, there was no significant difference in the flexural strength values according to the zirconia content excluding the control group in this experiment. However, the reliability of flexural strength was higher with more solid loadings except for the control group. According to ISO 6872, the required flexural strength for Class 2 ceramics for fixed prostheses is at least 100 MPa. In this study, the flexural strength for 45 vol% and 50 vol% were 142.8 MPa and 153.3 MPa, respectively, which met the ISO 6872 requirements for Class 2. Therefore, both 45 vol% and 50 vol% can be clinically applied as Class 2 materials.

Based on the results of this study, it was found that as the solid content increases, it is possible to achieve lower sintering shrinkage, denser particle distribution, and finer particles in terms of physical properties. These results affected the mechanical properties, such as hardness and strength, and showed high reliability in hardness and strength as the solid content increased. Therefore, high solid content is suitable for achieving high hardness and strength reliability. In conclusion, increasing the solid content of the ceramic slurry can enhance important physical and mechanical properties for clinical success. Thus, the composition with high solid content indicates the potential for clinical. However, the strength of the prepared zirconia slurry was found to be lower than expected. This is thought to be due to low dispersion stability and defects occurred in both surface and interior. Therefore, research on dispersion stability improvement and minimizing defects occurred in both surface and interior is needed in future studies.



V. CONCLUSION

In this study, the physical and mechanical properties of zirconia slurries according to different solid loadings were investigated. Based on the presented results, the following conclusions can be made.

(1) The zirconia parts were produced using DLP 3D printing. The control group and the prepared 45 vol%, and 50 vol% zirconia slurry showed a viscosity of 3 Pa·s at 30 s⁻¹ and showed the shear thinning behavior. The post-processing cycle was optimized using the TG-DSC result for the prepared slurry. After sintering, high density was shown. Through this, the preparation and printing possibility of a zirconia slurry that may be printed for DLP were confirmed.

(2) Physical properties were compared through linear shrinkage and microstructure evaluation. The linear shrinkage rate showed a lower shrinkage rate as the solid loading increased. In the microstructure, as the solid loading increases, a dense grain distribution and fine grains can be obtained.

(3) Mechanical properties were compared through hardness and biaxial bending strength. Hardness increased as the solid loading increased. When compared numerically in biaxial bending strength, the control group showed the highest value, followed by 50 vol%. In Weibull analysis, it was confirmed that the reliability of high-content zirconia, excluding the control group, was higher.

In conclusion, this study laid the foundation for manufacturing zirconia ceramic slurry for DLP. In addition, the scope of zirconia application in the 3D printing field has been expanded by providing physical and mechanical properties according to solid loading. However, further research is needed to improve dispersion stability and minimize defects occurred in both surface and interior.



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ABSTRACT (IN KOREAN)

슬러리 내 지르코니아 함량 변화에 따라

적층 가공으로 제작된 치과용 세라믹의 물리적 및 기계적 특성

<지도교수 권 재 성>

연세대학교 대학원 응용생명과학과

염지 헌

지르코니아는 높은 기계적 특성, 우수한 이온 전도도 및 우수한 생체 적합 성의 특성을 보유하고 있어 많은 연구에서 주목받고 있다. 최근에는 치과분야 에서 3D 프린팅과 결합되어 많은 연구와 관심을 받고 있다. 그 중에서도 제 조 시간의 단축 및 저렴한 비용의 장점을 가지고 있는 Digital light processing (이하 DLP) 기술과 결합되어 많은 연구에 사용되고 있다. DLP 기술로 세라믹 부품을 출력하기 위해서는 다양한 전제조건이 필요하다. 그 중 에서 세라믹의 치밀화와 훌륭한 기계적 성능을 위해서는 슬러리 내에 충분한 고체 함량을 필요로 한다. 그러나 현재 대부분의 연구는 슬러리 내의 세라믹 입자의 분산에 대한 연구가 많다. 더욱이, 지르코니아 슬러리의 고체 함량에 따른 물리적 및 기계적 특성에 대한 연구는 부족하다. 따라서 본 연구의 목적

51



은 지르코니아 슬러리에서 서로 다른 고체 함량이 기계적, 물리적 특성에 미 치는 영향에 대해 확인하는 것이다.

본 연구에서는 서로 다른 지르코니아 함량을 갖는 슬러리를 제작하여 비교 하고자 하였다. 지르코니아 함량이 45 vol%, 50 vol%, 55 vol%인 지르코니아 슬러리를 제작하였다. 각 그룹의 이름은 제조사에서 제시한 밀도 값을 기준으 로 wt%를 vol%로 환산하여 나타냈다. 또한 모든 그룹은 3 mol% 이트리아 부분 안정화 지르코니아, 모노머, 광개시제, 분산제로 구성되어 있다. 먼저, 제 작된 서로 다른 고체 함량을 갖는 지르코니아 슬러리의 특성을 평가하기 위해 유변학적 분석, 중합 분석, 열 분석 및 밀도 실험을 진행하였다. 물리적 특성 은 소결된 시편의 소결수축률 및 미세구조를 통해 평가하였다. 또한 기계적 성질은 경도와 굴곡 강도를 통해 평가하였다. 모든 평가에서 상업용 지르코니 아 슬러리를 대조군으로 설정하여 비교하였다.

유변학적 분석에서 대조군, 45 및 50 vol%만 30 s⁻¹에서 3 Pa·s 이하의 점 도를 나타냈다. 따라서 55 vol%는 모든 실험에서 제외되었다. 광중합 분석을 통해 세 그룹 모두 중합이 잘 이루어지는 것을 확인하였다. 열 분석을 통해 대조군의 고체 함량(대략 45 - 47 vol%)을 확인 및 지르코니아 슬러리에 대 한 후처리 과정을 최적화하였으며, 해당 과정을 통해 고치밀화된 밀도를 얻었 다. 소결수축률에서는 고체 함량이 증가함에 따라 낮은 수축률을 나타냈다. 미세구조에서는 고체 함량이 증가함에 따라 조밀한 grain 분포와 미세한 입자 를 갖는 것을 확인할 수 있었다. 경도에서는 대조군과 45 vol%는 유의한 차 이가 없었으나(*p* > 0.05), 50 vol%와는 유의한 차이를 나타냈다(*p* < 0.05). 이 축 굽힘강도에서 45 vol%와 50 vol%는 유의한 차이가 없었다(*p* > 0.05). 그 러나 두 그룹과 대조군 사이에는 유의한 차이가 있었다(*p* < 0.05). 수치적으 로 비교하였을 때, 대조군이 가장 큰 값을 나타냈고, 50 vol%가 그 뒤를 이었

52



다. Weibull 분석에서 대조군을 제외한 지르코니아 함량이 높은 슬러리의 신 뢰성이 더 높은 것을 확인할 수 있었다.

본 연구는 30 s⁻¹에서 3 Pa·s 미만의 점도를 갖는 지르코니아 슬러리를 제 작하는데 성공하였다. 물리적 특성에서 고체 함량이 증가할수록 낮은 소결수 축률를 나타냈으며, 조밀한 입자(grain) 분포와 미세한 입자(grain)를 갖는 것을 확인할 수 있었다. 기계적 특성에서는 고체 함량이 증가할수록 높은 경 도와 강도에 대한 신뢰성을 확인할 수 있었다. 이에 따라, DLP용 지르코니아 슬러리 제조를 위한 기초를 마련하였으며, 고체 함량에 따른 물리적 및 기계 적 특성을 제공함으로써 3D 프린팅 분야에서의 지르코니아 적용 범위를 확대 하였다. 그러나 분산 안정성을 향상시키고, 표면 및 내부에 존재하는 결함을 최소화하기 위해서는 추가 연구가 필요하다.

핵심되는 말: 지르코니아, 지르코니아 슬러리, 고체 함량, 3D 프린팅, 디지털 광 처리, 물리적 특성, 기계적 특성