

Review
**A Critical Review on 3D-Printed Dental Ceramics
in Prosthodontic Rehabilitation**

L. Yao*

Department of Prosthodontics, Hangzhou Dental Clinic, Hangzhou, 310000, China
received March 8, 2025; received in revised form March 30, 2025; accepted April 15, 2025

Abstract

Additive manufacturing (AM) technologies have transformed the way ceramic dental restorations are made, allowing for more complex designs and reducing material waste compared to traditional methods. This comprehensive review examines the current state of ceramic AM technologies in prosthodontic applications, focusing on three primary approaches: vat photopolymerization, direct inkjet printing, and 3D gel printing. Each technology presents distinct advantages and challenges in producing high-quality dental restorations. Critical processing parameters, including build orientation, layer thickness, and post-processing protocols, significantly influence the final properties of printed restorations. While recent advances have demonstrated promising results in terms of mechanical properties and aesthetic outcomes, challenges remain in achieving optimal accuracy, density, and long-term stability. The review analyzes material science considerations, particularly the formulation of ceramic suspensions and their impact on printability and final properties. Current limitations in resolution, material loading, and processing consistency are identified as key barriers to widespread clinical adoption. The potential for multi-material printing and functionally graded materials represents promising directions for future development, potentially enabling more biomimetic restorations.

Keywords: Computer-aided manufacturing, stereolithography, zirconium oxide, mechanical properties, digital workflow.

I. Introduction

The field of prosthodontic rehabilitation has witnessed significant evolution in ceramic manufacturing technologies over the past few decades. Dental ceramics have become the material of choice for prosthodontic restorations due to their outstanding aesthetics, mechanical properties, and biocompatibility^{1,2}. Traditional ceramic manufacturing methods, particularly the lost-wax technique and computer-aided design/computer-aided manufacturing (CAD/CAM) subtractive methods, have long been the gold standard in fabricating ceramic restorations³. These traditional methods have consistently delivered reliable clinical results, backed by decades of research and application^{4,5}. However, traditional manufacturing methods present several inherent limitations that impact both the production process and the final restoration quality⁶. The lost-wax technique, while capable of producing highly aesthetic restorations, is heavily dependent on the technician's skill and involves multiple labor-intensive steps that increase the risk of human error. The technique also suffers from material wastage and dimensional changes during the casting process⁷. Similarly, subtractive manufacturing, despite its widespread adoption and digital workflow integration, has significant drawbacks. The milling pro-

cess generates substantial material waste, as up to 90 % of the ceramic block may be discarded during fabrication^{8,9}. Furthermore, the size and geometry of milling tools limit the ability to reproduce fine details and internal geometries, particularly in complex restoration designs¹⁰.

The emergence of additive manufacturing (AM) technologies, commonly known as 3D printing, represents a paradigm shift in dental ceramic fabrication. This revolutionary approach builds objects layer by layer from digital designs, offering unprecedented freedom in geometry and internal structure design^{11,12}. Unlike subtractive methods, AM can create complex shapes without the limitations imposed by cutting tools, enabling the production of restorations with intricate internal features and optimized material distribution¹³. The technology also promises significant reduction in material waste, as only the necessary amount of material is used in the building process. In prosthodontic applications, ceramic AM technologies have evolved from simple prototype production to the fabrication of functional restorations^{14,15}. Current systems employ various approaches, including stereolithography (SLA), digital light processing (DLP), and direct inkjet printing (DIP). Each technology offers distinct advantages and faces unique challenges in producing dental ceramics that meet the demanding requirements of oral rehabilitation^{16,17}. The integration of these technologies

* Corresponding author: 3775057919@qq.com

with digital workflows has opened new possibilities for customization and process optimization, potentially improving both the efficiency of production and the quality of final restorations¹⁸. Despite the promising potential, the adoption of ceramic AM in clinical prosthodontics faces several critical challenges. The technology must demonstrate comparable or superior outcomes to existing methods in terms of accuracy, mechanical properties, and long-term clinical performance¹⁹. The complexity of ceramic processing, particularly the need for post-processing steps such as debinding and sintering, introduces additional variables that can affect the final restoration quality²⁰. Furthermore, the relationship between processing parameters and final properties must be thoroughly understood to ensure consistent and predictable results.

Recent technological advances have begun to address these challenges, with new materials and processing strategies emerging to improve the reliability and efficiency of ceramic AM. The development of optimized ceramic suspensions, innovative post-processing protocols, and enhanced printing technologies has led to significant improvements in the quality of printed restorations^{21–23}. However, questions remain regarding the long-term performance of these restorations in the oral environment and their cost-effectiveness compared to traditional manufacturing methods. An exciting development in ceramic AM is the potential for creating functionally graded materials (FGMs) that better mimic the natural properties of dental tissues²⁴. This approach allows for the controlled variation of composition and properties within a single restoration, potentially improving both mechanical performance and aesthetic outcomes²⁵. The ability to precisely control material distribution and properties at the microscale represents a significant advantage over conventional manufacturing methods and could lead to more biomimetic restorations.

This comprehensive review aims to critically evaluate the current status of ceramic AM technologies in prosthodontic rehabilitation, with a particular focus on their clinical applicability and limitations. We will examine the various AM technologies available for ceramic processing, analyzing their underlying principles and technical considerations. The review will assess the material science aspects, including composition requirements and processing parameters that influence the final restoration properties. Special attention will be given to evaluating the clinical performance of AM ceramic restorations, including accuracy, mechanical properties, and aesthetic outcomes. Finally, we will explore future perspectives and research directions, identifying areas requiring further development and validation.

II. Methods

To ensure a comprehensive and methodologically rigorous review, an extensive literature search was conducted to identify relevant studies focusing on the application of 3D printing technologies in the fabrication of dental ceramics for prosthodontic rehabilitation. The search strategy involved accessing multiple academic databases, including PubMed, Scopus, and Web of Science, to retrieve peer-re-

viewed journal articles, conference proceedings, and systematic reviews. A combination of carefully selected keywords and Boolean operators was utilized to optimize the search process. The primary search terms included “3D printing” or “additive manufacturing” in combination with terms such as “dental ceramics,” “prosthodontic ceramics,” “zirconia,” and “lithium disilicate.” Additionally, to capture a broad range of relevant literature, the search was extended to include specific additive manufacturing technologies, such as “stereolithography,” “digital light processing,” and “direct inkjet printing,” alongside terms such as “dental restorations” and “prosthodontics.”

The search was restricted to publications released between 2010 and 2024 to ensure that the review captured the most recent advancements, clinical applications, and technological developments in the field. Only studies published in English were considered to maintain consistency and clarity in data interpretation. Following the initial search, duplicate records were removed, and the remaining articles underwent a two-stage screening process. The first stage involved a review of the titles and abstracts to assess their relevance to the research objectives. In the second stage, the full texts of potentially relevant articles were evaluated to determine their suitability for inclusion in the review.

The inclusion criteria focused on studies that examined the application of 3D printing technologies in the fabrication of ceramic dental restorations, with an emphasis on articles reporting mechanical properties, dimensional accuracy, aesthetic outcomes, and clinical performance. Studies highlighting advances in ceramic materials, post-processing protocols, and multi-material approaches were also prioritized. Conversely, articles that concentrated solely on polymer-based or metal-based additive manufacturing technologies without direct relevance to ceramic applications were excluded. Non-peer-reviewed literature, case reports, and opinion pieces were likewise excluded, as they did not provide sufficient data for critical evaluation. Furthermore, articles lacking detailed information on processing parameters or final material properties were excluded to maintain the scientific rigor of the review.

The selection of literature was guided by the objective of identifying studies that evaluated the performance of 3D-printed dental ceramics under clinically relevant conditions. Priority was given to investigations that explored the relationship between processing parameters, material formulations, and the resultant mechanical and aesthetic properties of the printed restorations. Studies introducing novel technologies, identifying critical limitations, or offering insights into future research directions were also included to ensure a balanced and comprehensive analysis. By adhering to these criteria, the review aimed to provide an in-depth evaluation of the current status of ceramic additive manufacturing technologies and their clinical applicability in prosthodontic rehabilitation.

III. Additive Manufacturing Technologies for Dental Ceramics

The evolution of additive manufacturing in dental ceramics has led to the development of several distinct technologies, each with unique capabilities and limitations. These

technologies can be broadly classified into three main categories: vat photopolymerization, direct inkjet printing, and 3D gel printing. Each approach offers specific advantages for dental ceramic fabrication while presenting distinct challenges that influence their clinical applicability.

(1) Classification of ceramic AM technologies

Vat photopolymerization technologies, particularly SLA and DLP, have emerged as cornerstone methods in dental ceramic manufacturing due to their superior precision and versatility (Fig. 1). These technologies work by selectively curing ceramic-loaded resins using light. The ceramic particles are evenly distributed in a photosensitive polymer. The process begins with a ceramic suspension containing photoinitiators that trigger polymerization upon exposure to specific wavelengths of light. In SLA systems, a precisely controlled laser beam, typically operating in the UV spectrum, traverses the surface of the ceramic suspension according to predetermined pathways derived from the CAD model. The laser energy initiates localized polymerization, creating solid structures while leaving surrounding areas uncured. This selective curing mechanism allows for the fabrication of intricate dental components with feature sizes down to 50 micrometers^{26, 27}. The build platform adjusts vertically after each layer's completion, allowing fresh ceramic suspension to flow over the previously cured layer. This process continues iteratively until the entire structure is complete. Critical parameters affecting print quality include laser power, scanning speed, and layer thickness, which must be optimized based on the ceramic suspension's properties^{28, 29}. DLP technology, while sharing the same fundamental photopolymerization principle, employs a fundamentally different approach to light delivery. Instead of a scanning laser, DLP systems utilize a digital micromirror device (DMD) that projects entire layer patterns simultaneously onto the ceramic suspension. Each micromirror in the DMD array can be individually controlled, creating a dynamic mask that determines which areas of the suspension receive light exposure. This parallel processing approach typically results in faster build times compared to the sequential scanning method of SLA^{30, 31}. However, the resolution in DLP systems is inherently limited by the pixel size of the projected image, which is determined by the DMD specifications and the projection optics. Both technologies require careful formulation of the ceramic suspension to achieve optimal results. Key considerations include the solid loading content, which affects the final density and shrinkage of the printed parts, and the rheological properties, which influence the recoating process and layer uniformity^{32, 33}. Typical ceramic suspensions contain 40–60 vol% ceramic powder, with particle sizes carefully selected to achieve high packing density while maintaining suitable viscosity for processing. The choice of photoinitiators and dispersants also plays a crucial role in ensuring uniform particle distribution and appropriate curing characteristics^{34, 35}.

Direct inkjet printing represents a fundamentally different approach to ceramic AM, utilizing the precise deposition of ceramic-loaded droplets through specialized

piezoelectric printheads, such as the Dimatix DMP-2850, which operates with nozzle diameters of 10–30 μm . The optimal viscosity range for printable suspensions is typically between 10–40 mPa·s, with particle sizes maintained below 1 μm to prevent nozzle clogging. Recent advances in nanoparticle jetting technology have enabled improved control over droplet placement, allowing for higher resolution and better consistency in multi-material printing. The technology operates by selectively depositing microscopic droplets of ceramic suspension through specialized printheads. This process can be implemented through either continuous jetting or drop-on-demand approaches, with the latter offering superior control over material placement. As demonstrated by Ebert *et al.*³⁷, when printing zirconia dental prostheses, drop-on-demand systems achieved better dimensional accuracy and surface quality compared to continuous jetting methods. The key advantage of this technology lies in its versatility for multi-material printing and the ability to create functionally graded structures. For instance, researchers have successfully fabricated dental restorations combining different ceramic materials with varying mechanical and aesthetic properties in a single printing process. The technology has shown particular promise in creating dental crowns and bridges with naturalistic color gradients and mechanical property variations that mirror natural tooth structure.

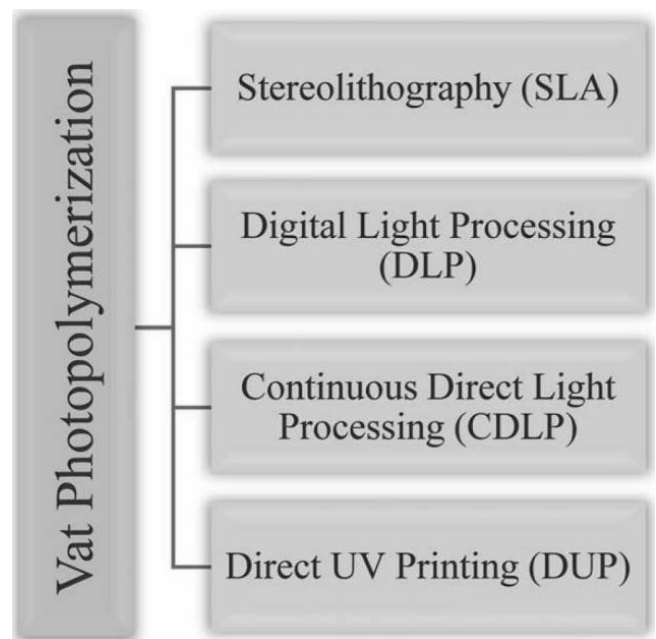


Fig. 1: Overview of vat photopolymerization technologies according to ISO 17296–2³⁶.

Recent developments in nanoparticle jetting have significantly expanded the capabilities of inkjet-based ceramic printing. These advanced systems can achieve higher resolution and better control over material properties, though they typically require more specialized material formulations. As shown in Fig. 2, which illustrates a sintered zirconium oxide fiber squeezed out through a 76- μm sapphire nozzle, the technology can achieve remarkable precision in material deposition³⁸. However, the success of the printing process heavily depends on precise control over suspension rheology and particle size distribution.

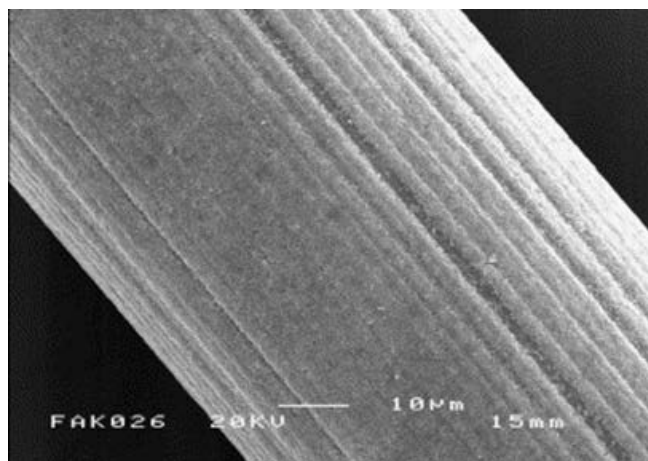


Fig. 2: Sintered zirconium oxide fiber of 65 μm in diameter squeezed out through a 76- μm nozzle diameter ³⁸.

This is particularly critical in preventing nozzle clogging and ensuring consistent droplet formation. According to Grida and Evans' research ³⁸, the optimal particle size for stable jetting should be at least an order of magnitude smaller than the nozzle diameter, typically requiring ceramic particles in the sub-micron range. The rheological properties of the ceramic suspension must be carefully balanced – the viscosity needs to be low enough to allow droplet formation (typically between 1–40 mPa·s) but high enough to prevent satellite droplet formation and ensure proper spreading behavior upon impact. Research has shown that adding specific dispersants and controlling solid loading (typically between 20–40 vol%) can help achieve these properties. The surface tension of the ink also plays a crucial role, as it affects droplet formation and spreading behavior. Studies have demonstrated that surface tension modifiers can be used to optimize printing performance, with optimal values typically ranging between 20–40 mN/m. Temperature control during printing is another critical factor, as it affects both viscosity and surface tension. Many systems now incorporate heated printheads and substrate platforms to maintain optimal

printing conditions. Recent advances in printhead technology have also led to better control over droplet size and placement accuracy. Multi-nozzle printheads with independent control over each nozzle have made it possible to achieve higher throughput while maintaining precision. This has been particularly beneficial in dental applications, where both speed and accuracy are essential.

3D gel printing represents a significant advancement in dental ceramic fabrication, particularly for producing complex prosthodontic components. The printing process utilizes extrusion-based systems, such as RegenHu 3DDiscovery, with a nozzle diameter of 76 μm and controlled extrusion speeds of 5–20 mm/s. The ceramic suspension is typically formulated with 50–55 vol% ceramic particles, stabilized using dispersants such as polyacrylic acid and photoinitiators like 2-hydroxyethyl methacrylate (HEMA) to enable rapid gelation during extrusion. This technology is based on the controlled deposition of highly loaded ceramic suspensions that undergo rapid gelation upon extrusion, providing immediate structural stability to the printed components ³⁹. The fundamental principle relies on a water-based gelation system incorporating specific monomers like 2-hydroxyethyl methacrylate (HEMA) or acrylamide, which facilitate the transformation from a flowable suspension to a rigid gel structure. This mechanism allows for the achievement of high solid loadings – typically up to 50 vol% for zirconia-based systems – which is substantially higher than conventional ceramic printing methods that often struggle to exceed 40 vol% ^{40,41}. The higher solid loading is particularly advantageous for dental applications as it contributes to reduced shrinkage during sintering and enhanced mechanical properties of the final restoration. As demonstrated in Fig. 3 of the reference paper, the 3D gel printing process employs a systematic approach incorporating slurry preparation, precise computer-controlled deposition, and post-processing steps, enabling the production of dental components with consistent quality and reproducibility ³⁹.

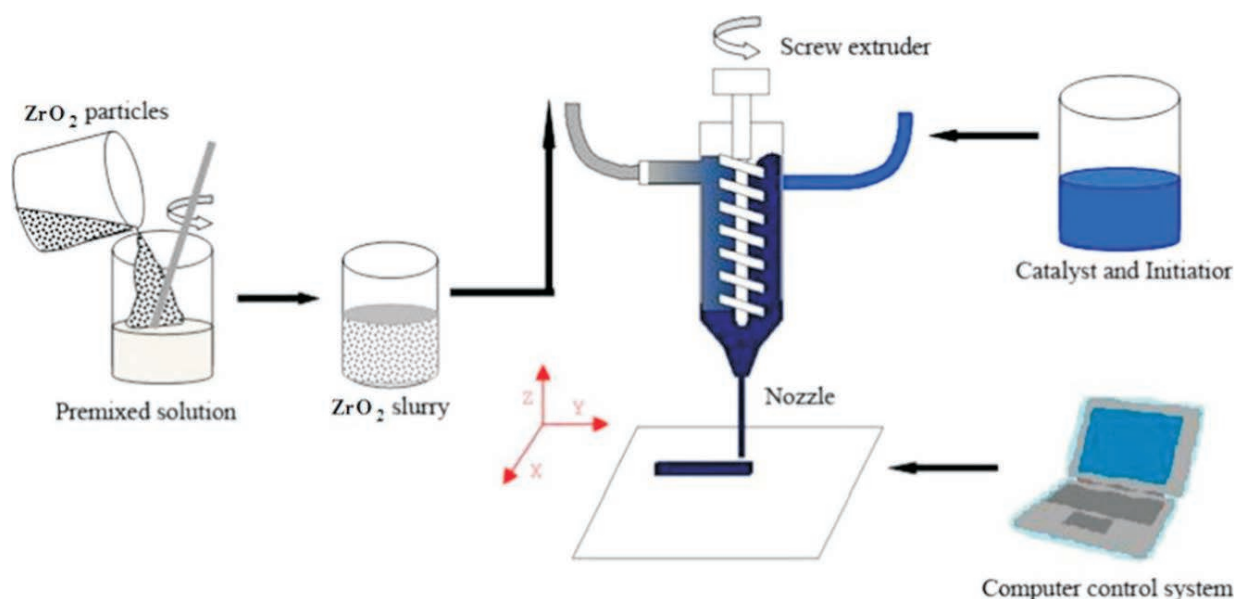


Fig. 3: Schematic diagram of the 3DGP process for printing zirconia parts ³⁹.

The practical implementation of 3D gel printing in dental ceramics has shown promising results, particularly in terms of achieving the mechanical and aesthetic requirements for dental restorations. Studies have demonstrated that 3D gel printing-fabricated zirconia components can achieve relative densities of up to 97.6 % after sintering, with impressive mechanical properties including Vickers hardness values of 14.4 GPa and transverse rupture strength reaching 450 MPa^{42, 43}. These values are comparable to, and in some cases superior to, traditional manufacturing methods. The surface quality of 3D gel printing-produced components is particularly noteworthy, with achieved surface roughness values (R_a) of approximately 8.25 μm after sintering, which is significantly better than other additive manufacturing techniques such as syringe extrusion methods that typically show roughness values around 68 μm ⁴⁴. This superior surface finish is crucial for dental applications, as it directly impacts both the aesthetic outcome and the biological response of surrounding tissues. Additionally, the technology has demonstrated excellent capability in producing complex dental geometries, including crowns, bridges, and custom implant components, with high dimensional accuracy^{45, 46}. The process allows for fine control over the internal architecture of dental restorations, which is particularly important for achieving optimal fit and function. Recent studies have also shown that the mechanical properties of 3D-gel-printing-produced dental ceramics remain stable under physiological conditions, making them suitable for long-term clinical applications^{47–49}. However, ongoing research continues to focus on optimizing the rheological properties of ceramic suspensions and improving the printing parameters to enhance the overall quality and reliability of the printed dental restorations.

(2) Critical comparison of manufacturing principles

The fundamental differences between additive manufacturing technologies have significant implications for their application in dental ceramics, particularly regarding resolution, material properties, and processing requirements. Vat photopolymerization technologies, especially SLA, demonstrate superior capabilities in producing intricate dental restorations due to their high resolution and excellent surface finish characteristics. However, these technologies face a critical challenge in achieving high ceramic loading in the initial suspensions. Dehurtevent *et al.*⁵⁰ found that the viscosity of ceramic suspensions must be carefully controlled within a narrow window ($137.7 \pm 12.68 \text{ mPa}\cdot\text{s}$ to $218.9 \pm 12.78 \text{ mPa}\cdot\text{s}$) to achieve successful printing while maintaining adequate particle loading (Fig. 4). This balance is crucial as higher ceramic content is desirable for improved final properties but can compromise printability. The technology has demonstrated success in producing dental implants with high dimensional accuracy and mechanical properties comparable to conventionally manufactured ceramics, with flexural strengths reaching up to 943 MPa for zirconia components⁵¹.

Direct inkjet printing technologies offer unique advantages in terms of material composition control and resolu-

tion capabilities. This approach, as demonstrated by Ebert *et al.*³⁷, can achieve relative densities of up to 96.9 % in zirconia components with mechanical properties comparable to conventionally produced materials. The technology's ability to precisely control droplet placement makes it particularly suitable for creating functionally graded dental restorations, where properties can be tailored across the component. However, the process demands extremely precise control over multiple parameters. The successful formation of uniform droplets requires careful optimization of suspension properties, including particle size distribution and rheological behavior. Scheithauer *et al.*⁵² introduced the concept of a droplet fusion factor (dff) to quantify the necessary conditions for successful printing, finding that a dff of 44 % or higher is required for producing homogeneous structures. This level of control, while enabling high precision, can result in slower processing speeds and increased system complexity compared to other AM technologies. The technology has shown particular promise in producing dental crowns with complex occlusal surface topography³⁷.

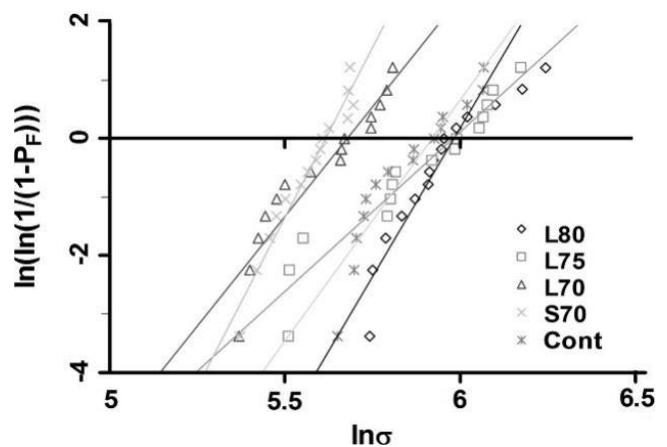


Fig. 4: Weibull plot comparing the strength distribution of alumina ceramics manufactured by the stereolithographic process⁵⁰.

3D gel printing represents an emerging approach that offers distinct advantages in material efficiency and processing simplicity. This technology, as investigated by Shao *et al.*⁵³, can achieve higher density and improved surface finishing compared to traditional extrusion methods. The ability to handle highly loaded ceramic suspensions (> 50 vol%) is particularly advantageous for achieving superior mechanical properties in the final components. The process demonstrated the capability to produce zirconia components with no visible defects or deformation after sintering, achieving relative densities of 97.6 % and significant improvements in surface quality compared to conventional extrusion methods. However, the technology requires careful control of rheological properties, particularly in terms of the gel point of different formulations. Fahimipour *et al.*⁵⁴ highlighted this challenge in their work with TCP/alginate/gelatin scaffolds, where needle blocking during extrusion became problematic if the gel point was above room temperature. Despite these challenges, the technology has shown promising results in producing complex dental structures

with porosity levels of $73.42 \pm 8.4\%$ and Young's modulus values of 98.31 ± 10.21 MPa, making it particularly suitable for applications requiring controlled porosity such as tissue engineering scaffolds.

(3) Process chain analysis and workflow considerations

The implementation of ceramic AM technologies in dental applications requires comprehensive workflow inte-

gration, beginning with accurate digital data acquisition. The primary methods include direct intraoral scanning or digitization of conventional impressions, which must capture sub-millimeter anatomical details with high precision^{55, 56}. As shown in Fig.5, the workflow typically involves multiple stages from initial scanning through design verification and final manufacturing. The digital acquisition process must account for various clinical scenarios,



Fig. 5: Description of the procedure for the production of dental bridges using the technology of selective laser sintering (SLS) from metal powders; a detailed description of the meaning of (a-h) images in the text. (a) preparing teeth for treatment; (b) virtual tooth model together with post models; (c) considering pillars; (d) prosthetic reconstruction project; (e) finished model; (f) designed supports; (g) tooth forming; (h) final result⁶⁴.

from single-unit restorations to full-arch rehabilitations^{57, 58}. Modern intraoral scanners can achieve accuracy levels between 50–70 μm , which approaches the maximum precision capabilities of CNC milling systems⁵⁹. The captured data undergoes extensive processing using specialized dental CAD software that must consider not only the geometric requirements but also material-specific constraints and the particular limitations of the chosen AM technology^{60, 61}. This includes factors such as minimum feature size, support structure requirements, and build orientation optimization to minimize post-processing needs while maintaining critical functional surfaces^{62, 63}.

The printing process itself represents a critical but intermediate step in a complex manufacturing chain that demands careful orchestration of multiple parameters and environmental conditions. Each ceramic AM technology presents unique processing challenges – vat photopolymerization systems require precise control of exposure parameters, layer thickness, and resin viscosity^{65, 66}, while powder-based systems must maintain consistent powder spreading and local sintering conditions^{67, 68}. The post-processing phase is particularly crucial for ceramic materials, with debinding and sintering steps largely determining final part properties^{69, 70}. Debinding protocols must be optimized to remove organic components without introducing defects or dimensional distortion, typically requiring carefully controlled heating rates and atmospheric conditions^{37, 71}. The subsequent sintering process, which can involve temperatures exceeding 1500 °C for dental ceramics, must be precisely controlled to achieve desired density while managing shrinkage and maintaining geometric accuracy⁷². These high-temperature processes can introduce residual stresses and potential distortions that must be anticipated during the design phase⁷³.

Quality control considerations permeate the entire manufacturing chain and vary significantly between AM technologies and material systems. For vat photopolymerization, critical parameters include not only exposure control but also resin homogeneity, temperature stability, and post-curing protocols^{74, 75}. Powder-based systems require careful attention to particle size distribution, powder flowability, and layer uniformity^{76, 77}. The integration of in-process monitoring and feedback control systems becomes increasingly important for ensuring consistent part quality, particularly for high-value dental applications where failure rates must be minimized^{78, 79}. Final quality assessment must consider multiple factors including dimensional accuracy, surface quality, density, and mechanical properties, often requiring specialized measurement techniques and acceptance criteria specific to dental applications⁸⁰. Regular calibration and validation of both the AM system and post-processing equipment are essential to maintain process stability and repeatability⁸¹. The entire workflow must be validated according to relevant dental standards and regulations, with appropriate documentation and traceability systems in place⁸².

IV. Material Science and Technical Considerations

(1) Ceramic materials and compositions

The selection of ceramic materials for additive manufacturing in prosthodontics primarily centers on three main categories: yttria-partially stabilized zirconia (Y-TZP), alumina, and lithium disilicate glass ceramics. Each material presents distinct characteristics that influence their processability and final properties, which, in turn, affect the clinical performance of the printed restorations. For instance, Y-TZP demonstrates transformation toughening, which enhances fracture resistance by delaying crack propagation, contributing to the superior long-term clinical performance of zirconia-based restorations. Similarly, the optimal particle size distribution in ceramic slurries not only improves suspension stability but also minimizes porosity and shrinkage, ensuring precise marginal fit and reduced risk of microleakage, which is critical for clinical longevity. Moreover, the choice of sintering parameters directly influences the densification and grain growth of the printed ceramics, affecting mechanical properties such as flexural strength and hardness, which are essential for withstanding occlusal forces in the oral environment. Y-TZP remains the predominant choice for dental applications due to its exceptional combination of mechanical strength, biocompatibility, and aesthetic potential. The material's transformation toughening mechanism provides superior fracture resistance compared to other dental ceramics. The process of 3D printing in medical applications, including dental ceramics, follows a systematic workflow from imaging to final production, which is crucial for achieving precise results with these materials. The selection of appropriate ceramic materials must consider various factors including the specific printing technology being employed, the required mechanical properties, and the aesthetic demands of the final restoration. For instance, Y-TZP processed by means of SLS has demonstrated superior mechanical properties with flexural strength values exceeding 900 MPa, making it particularly suitable for high-stress bearing applications such as posterior bridges and implant abutments^{83, 84}. Recent advancements in Y-TZP formulations have focused on optimizing particle size distribution and sintering behavior to enhance printability while maintaining the material's inherent mechanical advantages. Studies have shown that controlling the particle size between 20–50 μm and implementing appropriate thermal post-processing protocols can significantly improve the density and mechanical properties of the printed structures^{85, 86}.

Alumina-based ceramics and lithium disilicate materials represent alternative options, each with distinct advantages and limitations in the context of additive manufacturing. Alumina ceramics, while offering excellent biocompatibility and wear resistance, require specific processing considerations to achieve optimal results in AM systems. Wu *et al.*⁸³ demonstrated that the particle size and debinding process significantly influence the final density and mechanical properties of 3D-printed alumina structures. Their research showed that optimizing these parameters could achieve relative densities exceeding 98 % and

improve the mechanical properties of the printed components. The integration of vacuum infiltration techniques has further enhanced the capabilities of alumina-based systems, addressing some of the traditional limitations associated with porosity and mechanical strength⁸⁶. Lithium disilicate materials, though less commonly employed in AM processes, have gained attention due to their superior aesthetic properties and adequate mechanical strength for various dental applications. The processing of these materials with AM systems presents unique challenges, particularly in controlling crystallization during the thermal treatment stages. Recent developments have focused on developing specialized slurry formulations and post-processing protocols to overcome these limitations^{84, 86}. The incorporation of specific additives and careful control of the printing parameters has shown promising results in achieving the desired microstructure and mechanical properties. Additionally, hybrid approaches combining different ceramic materials or incorporating reinforcing phases have emerged as potential solutions to optimize both mechanical and aesthetic properties. These developments have opened new possibilities for creating gradient structures that better mimic the natural tooth structure while maintaining the required mechanical integrity.

The formulation of ceramic suspensions for additive manufacturing in dental applications requires precise control over multiple parameters to achieve optimal processing and final properties. The ceramic loading level represents one of the most critical factors, as it directly influences both the printability and the final mechanical properties of the prosthetic restoration. The ceramic slurry must maintain consistent rheological properties throughout the layer-by-layer fabrication process. Studies have demonstrated that for dental applications, particularly in the fabrication of all-ceramic crowns, the optimal ceramic content typically ranges between 50–80 volume percent. For instance, Dehurtevent *et al.*⁵⁰ demonstrated that alumina slurries with 70–80 % dry matter content yielded the most favorable results for stereolithography-based manufacturing of dental prosthetics. The higher ceramic loading contributes to reduced shrinkage during sintering and enhanced mechanical properties in the final restoration, which is crucial for withstanding intraoral masticatory forces.

The stability of ceramic suspensions represents another fundamental requirement that significantly impacts the success of the additive manufacturing process. This aspect becomes particularly critical in dental applications where high precision and consistency are essential for achieving accurate marginal fits and optimal mechanical properties. The incorporation of dispersants plays a vital role in maintaining uniform particle distribution and preventing agglomeration throughout the printing process. For example, studies have shown that the addition of appropriate dispersants to zirconia-based suspensions can help achieve zeta potential values that promote stable suspensions, typically maintaining absolute values greater than 30 mV⁸⁷. The rheological behavior of these suspensions must be carefully controlled to ensure proper flow during processing while maintaining shape fidelity after deposi-

tion. This is particularly evident in direct ink writing processes, where Wang *et al.* demonstrated that dental porcelain slurries prepared within a pH range of 7.0–7.5 exhibited optimal pseudoplastic behavior necessary for successful extrusion and shape retention⁸⁸. For photopolymerization-based systems, such as stereolithography, the formulation becomes even more complex due to the need to balance the ceramic content with photocurable resin components. The addition of photoinitiators must be carefully optimized to achieve appropriate cure depth while maintaining dimensional accuracy. Studies have shown that the cure depth is inversely proportional to the ceramic loading, requiring careful optimization of photoinitiator concentration and exposure parameters to achieve successful layer-by-layer fabrication^{89, 90}. This balance becomes particularly critical in the fabrication of dental prostheses, where both dimensional accuracy and mechanical properties must meet stringent clinical requirements.

(2) Critical processing parameters

Build orientation plays a crucial role in determining the strength, accuracy, and surface quality of printed dental restorations. It affects how well the layers bond, the need for support structures, and the overall efficiency of the printing process. As demonstrated by Dehurtevent *et al.*⁵⁰, parts built with their major axis perpendicular to the build direction (ZY orientation) exhibited superior flexural strength (409.7 ± 29.6 MPa) compared to other orientations (ZX: 313.8 ± 27.9 MPa; XY: 334.3 ± 62.1 MPa). This variation in mechanical properties stems from the anisotropic nature of the layer-by-layer manufacturing process, where the bonding between successive layers creates inherent directional dependencies. As shown in Fig. 6, scanning electron microscopy revealed that the major axis of alumina grains runs parallel to the layer orientation, directly impacting the mechanical behavior. This microstructural alignment resulted in more transgranular failures in ZY-oriented specimens compared to predominantly intergranular failures in ZX-oriented specimens, explaining the superior mechanical performance of ZY-oriented parts when tested perpendicular to the layer direction. The selection of optimal build orientation must therefore carefully balance mechanical requirements against practical manufacturing considerations.

The implications of build orientation extend beyond just mechanical properties to impact several other critical aspects of the manufacturing process. Processing time and efficiency are significantly affected by orientation choice – while ZX-oriented specimens showed favorable minimum slurry resting periods (7 seconds between layers), they required substantially more layers (480 layers, 186 minutes total manufacturing time) compared to ZY orientation (86 layers, 47 minutes) and XY orientation (34 layers, 35 minutes)⁵⁰. Surface quality and the requirement for support structures also vary with orientation. Parts oriented parallel to the build platform (XY) typically exhibit better surface finish on upward-facing surfaces but may require more extensive support structures, increasing post-processing requirements^{92, 93}. Additionally, build orientation influences the structural reliability of the final

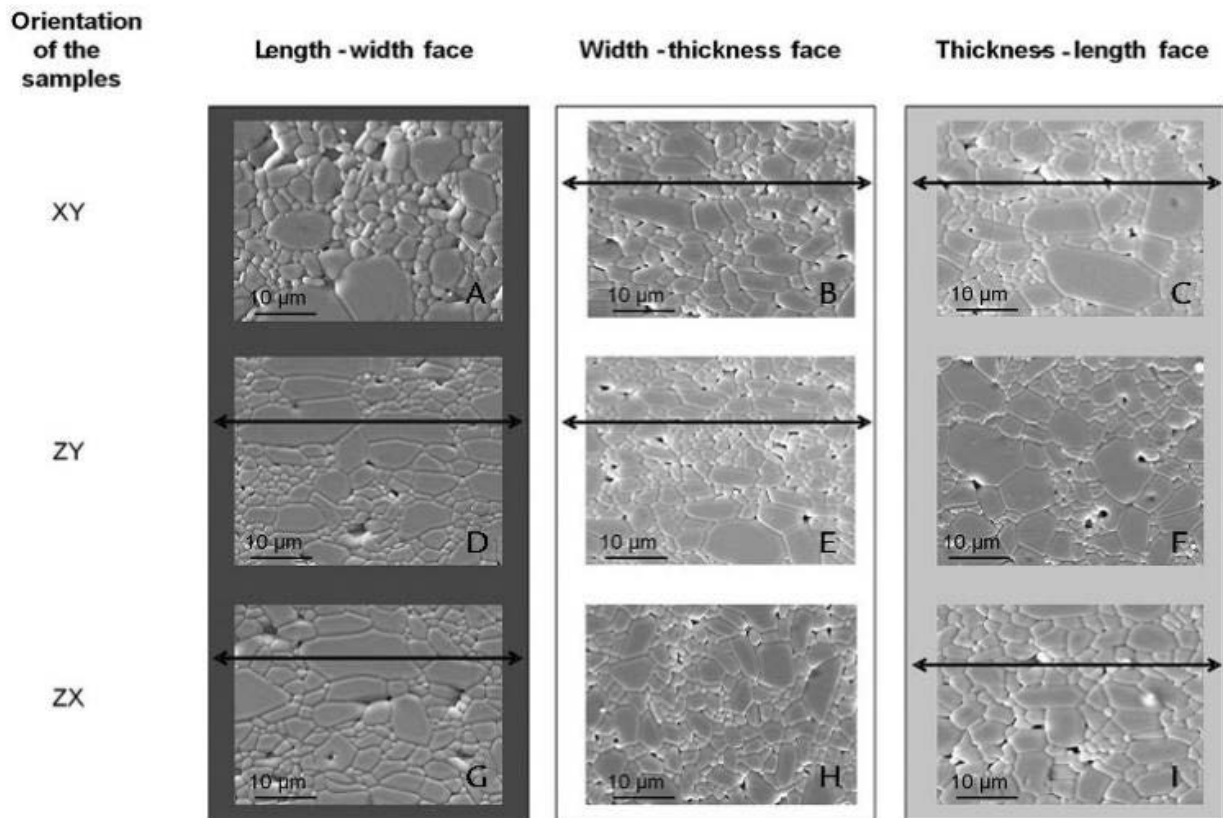


Fig. 6: Micrographs of 3 faces of ZX-, ZY-, and XY-oriented SLA alumina specimens (original magnification $\times 2000$)⁹¹.

restoration – Weibull analysis revealed higher moduli for ZX (13.7) and ZY (16.1) orientations compared to XY (6.2), indicating more consistent and predictable mechanical performance. For dental applications where consistent performance and reliability are paramount, these orientation-dependent variations must be carefully considered during the manufacturing process planning stage. Recent studies have also highlighted how build orientation can affect dimensional accuracy and internal fit of dental restorations, with different orientations showing varying degrees of geometric deviation from the designed specifications⁹³.

Layer thickness represents a critical parameter that directly impacts both the quality of printed parts and the efficiency of the manufacturing process. Thinner layers generally produce better surface quality and more accurate reproductions of fine features, but at the cost of increased building time and potentially higher risk of process failures. The optimal layer thickness depends on multiple factors including the specific AM technology, material properties, and application requirements. In stereolithography-based ceramic manufacturing (LCM), studies have shown significant differences in mechanical properties between different layer thicknesses. For instance, Baumgartner *et al.*⁹⁴ demonstrated that lithium disilicate specimens printed with 25-µm layers exhibited superior mechanical properties compared to those printed with 50-µm layers, achieving an outstanding average bending strength of 430 MPa for polished samples. This enhancement in mechanical properties can be attributed to better interlayer bonding and reduced potential for defect formation between layers. As shown in Fig. 7, the fracture sur-

face analysis of specimens printed with 25-µm layers revealed no visible layer interfaces or significant pores, indicating excellent integration between successive layers.

For dental applications, layer thicknesses typically range from 25 to 100 micrometers, with the selection based on a compromise between accuracy requirements and processing efficiency. The relationship between layer thickness and curing parameters becomes particularly crucial in photopolymerization-based systems, where overcuring can lead to dimensional inaccuracies while undercuring may result in insufficient layer bonding. The interplay between layer thickness and process parameters significantly affects the final properties of printed restorations. For example, when working with lithium disilicate, researchers have found that specimens printed with 25-µm layers demonstrated higher Weibull modulus values (11.5) compared to those printed with larger layer thicknesses, indicating better reliability and consistency in mechanical properties^{50, 95}. This improvement in reliability is particularly crucial for dental applications where consistent performance is essential. However, it is important to note that reducing layer thickness comes with practical considerations. Studies have shown that printing time can increase substantially – for instance, Baumgartner *et al.*⁹⁴ reported that reducing layer thickness from 50 µm to 25 µm nearly doubled the printing time from 2.3 hours to 4.2 hours for similarly sized specimens. Additionally, the optimization of exposure parameters becomes more critical with thinner layers, as both under- and over-exposure can lead to defects that compromise the structural integrity of the final restoration. Recent

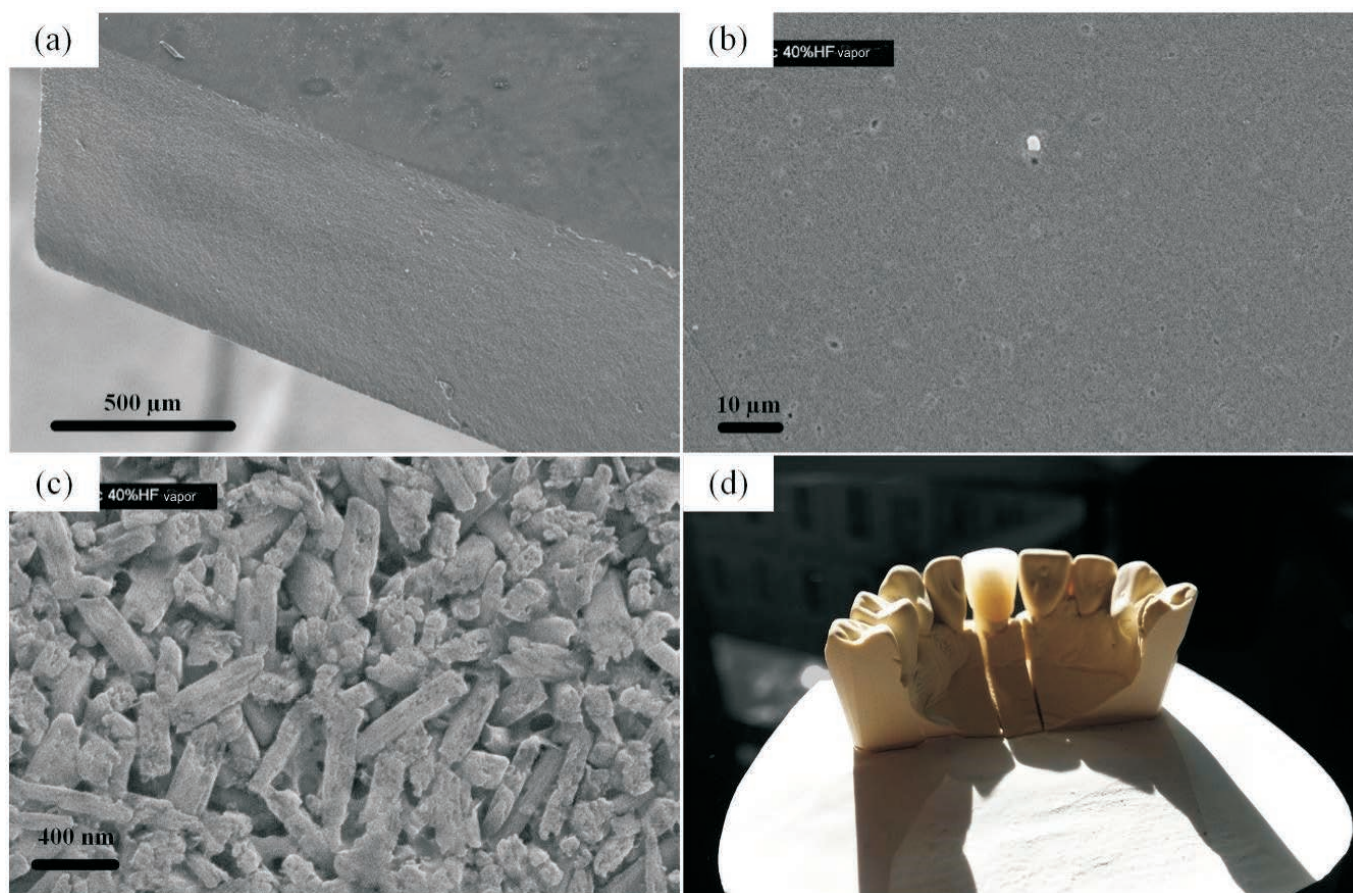


Fig. 7: Analysis of the microstructure and translucency of sintered lithium disilicate parts. (a) the fracture surface of a polished biaxial bending strength test platelet. After etching for 20 s with 40 % HF vapor (b), the lithia crystals of around 500 nm are clearly visible (c). To demonstrate the high translucency of the printed dental restorations, an LCM-produced anterior crown placed on a plaster model can be seen in (d) ⁹⁴.

investigations have also highlighted the importance of controlling the rheological properties of ceramic slurries when working with different layer thicknesses, as viscosity and shear behavior can significantly impact the quality of layer deposition and subsequent curing %.

Post-processing steps, particularly debinding and sintering, play a crucial role in determining the final properties of AM ceramic restorations. The debinding process must effectively remove organic components while preventing defect formation. This requires careful control of heating rates and environmental conditions to prevent cracking and warping. For ink/slurry-based AM technologies like VP and MJ, the green bodies contain significant amounts of organic materials (40–60 vol%) that must be carefully removed ^{97,98}. Han *et al.* ⁹⁷ demonstrated that using reliable plasticizers like polyethylene glycol 200 during the debinding process of DLP-printed ZrO₂ crowns effectively suppressed defect formation, resulting in a substantial increase in flexural strength from 302 MPa to 1 210 MPa. The optimization of debinding protocols depends heavily on the specific material composition and part geometry. For example, Zhang *et al.* ⁹⁸ investigated the stability and rheological behaviors of 3Y-ZrO₂ ceramic suspensions in stereolithography and found that higher solid content (> 50 vol%) resulted in less organic content requiring removal during debinding, leading to reduced

shrinkage and improved dimensional accuracy. However, they also noted that excessively high solid content adversely affected the viscosity and printability of the ceramic suspensions, necessitating careful balance in formulation.

Sintering conditions significantly influence the final density, grain size, and mechanical properties of ceramic restorations. Temperature profiles, holding times, and atmospheric conditions must be carefully controlled to achieve optimal results. Different AM technologies require specific post-processing approaches – VP (SL and DLP) processes typically involve support removal, cleaning, debinding and sintering steps, while PBF may require different thermal treatments depending on whether it is SLS or SLM. Chen *et al.* ⁹⁹ prepared ZrO₂ crowns using DLP technology and achieved mechanical properties comparable to traditionally manufactured restorations with optimized sintering protocols. The development of specialized sintering protocols for AM ceramics often differs from traditional ceramics due to differences in green body characteristics and organic content. For instance, Yang *et al.* ¹⁰⁰ optimized laser parameters and sintering processes for dental fluorapatite glass-ceramics produced via SL printing, achieving strength, hardness and elastic modulus values that surpassed those of traditional dry-pressing samples. The sintering behavior is also influenced by the AM process used – Branco *et al.* ^{101,102}

found that robocasting samples were slightly less dense and more porous than conventional subtractive-manufactured samples, requiring modified sintering protocols to achieve optimal properties. Proper control of sintering parameters is especially critical for complex geometries like dental implants and bridges, where maintaining dimensional accuracy while achieving full densification presents significant challenges^{103, 104}.

V. Clinical Performance Assessment

(1) Accuracy and precision analysis

The success and durability of ceramic restorations depend on how accurately they fit, especially around the margins and internal areas. Recent studies evaluating SLA additively manufactured zirconia restorations have shown varying degrees of accuracy. For instance, Revilla-León *et al.*¹⁰⁵ compared the marginal and internal discrepancies of milled and SLA additively manufactured zirconia crowns using the silicone replica technique. Their findings revealed significantly lower marginal and internal discrepancies in the milled method compared to AM groups. Importantly, while both milled and splinted AM groups demonstrated clinically acceptable marginal and internal discrepancies, the anatomic-contour AM zirconia crowns exhibited clinically inappropriate adaptations. Similarly, Li *et al.*⁹⁵ assessed the internal and marginal adaptation of SLA-manufactured zirconia crowns and found that despite achieving adequate mechanical strength, the restorations showed suboptimal clinical adaptation. The cement space measurements revealed variations across different regions: $63.40 \pm 6.54 \mu\text{m}$ in the occlusal area, $135.08 \pm 10.55 \mu\text{m}$ in the axial area, and $169.58 \pm 18.13 \mu\text{m}$ in the marginal area, which exceeded clinically acceptable thresholds.

The layer-wise construction process inherent to additive manufacturing creates unique challenges for surface quality and dimensional accuracy. The SLA apparatus's building process significantly influences the final product's characteristics. The curing depth serves as a crucial parameter determining both formability and accuracy. Various manufacturing factors, including light scattering caused by ceramic particles, can impact dimensional accuracy even when the particles themselves are transparent to irradiation. These effects can deteriorate light penetration into the suspension and consequently affect dimensional precision¹⁰⁶. Multiple studies have highlighted how ceramic particle size, volume percentage, materials' refractive index, and light exposure energy can influence curing depth and thus layer thickness⁹⁰. The significant difference in refractive index between the photopolymerizable liquid and zirconia particles poses particular challenges, as higher refractive index particles may absorb more UV radiation, resulting in shorter curing depths and reduced photopolymerization reactions¹⁰⁷.

Surface finish represents a critical aspect requiring careful consideration. As illustrated in Fig. 8, various dental prostheses manufactured with AM techniques demonstrate different surface characteristics depending on their specific application and manufacturing parameters. The surface quality is largely determined by the AM technology em-

ployed, processing conditions, and raw material properties, which collectively impact the thickness of each printed layer¹⁰⁸. Wang *et al.*¹⁰⁹ conducted a comprehensive assessment of dimensional accuracy and clinical adaptation of AM-stereolithography-fabricated ceramic crowns. Their study demonstrated dimensional accuracy values of $65 \pm 6 \mu\text{m}$ for zirconia crowns (CL) compared to $41 \pm 11 \mu\text{m}$ for alumina crowns (CF), with differences attributed to variations in ceramic slurries, light sources, and polymerization techniques between systems. Notably, while no significant differences were found between AM zirconia crowns and milled versions, distinct adaptation patterns emerged across different restoration regions.



Fig. 8: 3D-printed dental medical devices made on a CeraFab System S65 Medical: Dental implants (left top), zirconia bridge (3Y-TZP, right top), molar crown precolored (center), molar crown uncolored (right bottom), zirconia implant and abutment (center bottom)¹¹¹.

The precision of AM ceramic restorations varies significantly based on geometric complexity and specific manufacturing parameters. Li *et al.*¹¹⁰ evaluated the effectiveness of SLA-manufactured zirconia crowns with different finishing line designs, including chamfer, rounded shoulder, and knife-edge configurations. Their findings indicated that while AM crowns showed comparable accuracy to milled restorations, both manufacturing methods demonstrated susceptibility to marginal chipping in knife-edged designs. The AM process notably produced crowns with rounded line angle margins free of minor defects, whereas milled crowns exhibited sharp line angle margins with discrete chipping patterns. These variations highlight the importance of considering design parameters in conjunction with manufacturing methods to optimize clinical outcomes. The manufacturing accuracy in the Z-direction typically presents greater challenges compared to X- and Y-directions, affected by various process parameters including powder spreading – compaction/densification, material evaporation, and shrinkage during solidification¹⁰⁸. These factors necessitate careful consideration of build orientation and support structures to achieve optimal results for complex dental geometries.

(2) Evaluation of the mechanical properties

The mechanical performance of 3D-printed ceramic restorations exhibits complex characteristics that differ significantly from conventionally manufactured ceramics. Recent studies have demonstrated that the flexural strength of additively manufactured zirconia typically ranges from 320–943 MPa, which is generally lower than milled zirconia (> 1 000 MPa). For instance, Revilla-León *et al.*¹¹² reported that stereolithography (SLA) additively manufactured specimens showed a mean flexural strength of 320.32 ± 40.55 MPa, significantly lower than milled zirconia. This reduction in strength can be attributed to the layer-by-layer construction process, which introduces potential weak points at layer interfaces. The manufacturing parameters, particularly layer thickness and curing conditions, play crucial roles in determining the final mechanical properties. Nakai *et al.*¹¹³ demonstrated that different commercial AM systems produce varying mechanical properties – ATZ (alumina-toughened zirconia) showed the highest flexural strength, while DLP-printed zirconia with 90-degree printing orientation exhibited lower values. The printing orientation significantly affects the mechanical properties, with 0-degree vertical printing typically showing superior strength compared to other orientations.

The long-term stability of printed ceramic restorations under physiological conditions remains a critical consideration for clinical applications. Studies have shown that aging processes can significantly impact the mechanical integrity of AM zirconia. For example, Revilla-León *et al.*¹¹² investigated the effect of aging simulation on the flexural strength of SLA additively manufactured bar-shaped zirconia applications. Their results indicated that mastication-simulating aging caused a significant decrease in both AM and milled groups in terms of flexural strength and fracture resistance. The presence of residual porosity, which is often higher in AM ceramics compared to milled ones, can accelerate aging processes. This is particularly evident in cases where the solid loading of the ceramic suspension is below optimal levels (< 40 % by volume), leading to increased porosity and potentially compromised long-term performance^{83, 90, 114, 115}.

The mechanical properties of AM zirconia are highly dependent on the manufacturing parameters and resulting microstructure. Recent studies have focused on optimizing these parameters to enhance mechanical performance. For instance, Zhang *et al.*¹¹⁶ developed a high-loading (55 vol%) photosensitive ZrO_2 suspension, which provided new possibilities for fabricating high-performance ZrO_2 objects by means of SLA. The solid loading percentage significantly influences the final density and mechanical properties – higher solid loading generally results in better mechanical properties but must be balanced against processability constraints. The sintering process also plays a crucial role, with parameters such as temperature and gradient affecting the final densification and strength¹¹⁷. Studies have shown that the relative density of well-processed AM zirconia can reach 98.58 %, with Vickers hardness values of approximately 1 398 HV¹¹⁴. However, internal defects detected by SEM analysis remain a common

challenge, necessitating careful control of processing parameters. The correlation between processing conditions and mechanical properties is particularly evident in the thermal processing stages, where factors such as debinding rate and sintering schedule can significantly impact the final mechanical performance.

(3) Optical properties and aesthetics

The aesthetic outcomes of printed ceramic restorations are fundamentally influenced by both intrinsic material properties and manufacturing parameters that affect light interaction. Similar to conventional zirconia ceramics, the optical behavior of printed ceramics is governed by several key factors including chemical composition, microstructural features, and processing conditions. As highlighted by Shahmiri *et al.*¹¹⁸, the translucency and opacity of ceramic materials depend critically on how incident light is reflected, scattered, refracted, transmitted, and absorbed through the material structure. In printed ceramics, these optical interactions are particularly complex due to the layer-wise construction process. The interfaces between printed layers can create additional opportunities for light scattering, potentially affecting the overall translucency of the restoration. This is analogous to how grain boundaries and pores influence light transmission in conventional ceramics, where features of size similar to visible light wavelengths (400–700 nm) can significantly impact optical properties through scattering effects. As shown in Fig. 9, the scattering coefficient of zirconia varies significantly across the visible spectrum, with minimal scattering occurring around 520 nm wavelength¹¹⁹. This wavelength-dependent behavior must be carefully considered when formulating printable ceramic materials to achieve natural-looking restorations.

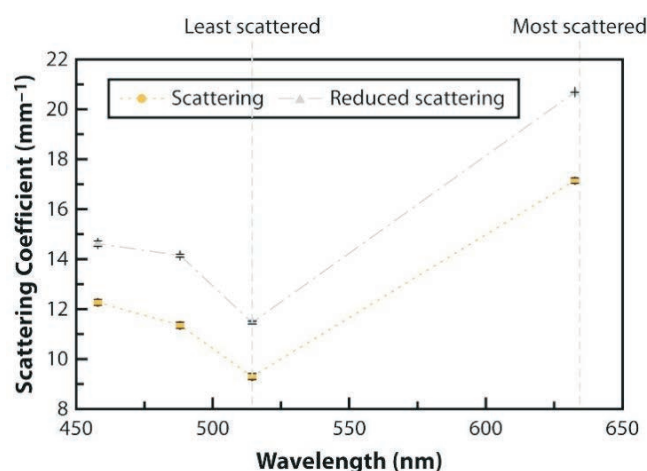


Fig. 9: Spectral values for scattering coefficient of zirconia (450 to 650 nm)¹¹⁹.

The incorporation of processing additives necessary for 3D printing, such as binders and dispersants, introduces additional complexity to the optical properties of printed ceramics. These additives, while essential for achieving proper printing rheology and green body strength, can leave residual effects on the final optical characteristics even after thermal processing. This is particularly crucial for achieving proper shade matching and color stabil-

ity in the final restoration. Similar to how conventional zirconia materials utilize dopants to modify optical properties, as discussed by Zhang *et al.*¹²⁰, printed ceramics may require specific additives or dopants to achieve desired aesthetic outcomes while maintaining printability. The processing parameters during both printing and subsequent sintering also play a critical role. Temperature gradients and atmospheric conditions during sintering can affect grain growth and pore elimination, which in turn influence light transmission characteristics. This is reminiscent of how conventional processing techniques impact optical properties through microstructural development, as demonstrated in studies of hot isostatic pressing and other densification methods^{121, 122}. Furthermore, the layer-wise construction inherent to 3D printing can potentially create anisotropic optical properties, where translucency and color appearance vary depending on viewing angle or light source direction. This presents unique challenges compared to traditionally manufactured ceramics, requiring careful optimization of both material composition and processing parameters to achieve consistent optical properties throughout the printed structure.

VI. Future Perspectives and Research Directions

The advancement of ceramic additive manufacturing in prosthodontics continues to face several significant technological barriers that require innovative solutions. Resolution limitations in current printing technologies affect the ability to reproduce fine anatomical details and achieve optimal marginal fit. The layer-wise construction process inherently creates surface irregularities that necessitate extensive post-processing, increasing production time and potentially compromising dimensional accuracy. Furthermore, the challenge of maintaining consistent material properties throughout the printing process remains a significant concern, particularly in terms of achieving uniform density and preventing the formation of critical defects. The current limitations in achievable ceramic loading during printing restrict the final mechanical properties of printed restorations. This constraint, combined with challenges in controlling the microstructure during sintering, often results in mechanical properties that fall short of traditionally manufactured ceramics. Additionally, the complexity of post-processing steps, particularly in terms of debinding and sintering protocols, introduces variability that can affect the reproducibility of final properties.

The development of new ceramic materials specifically designed for additive manufacturing represents a promising avenue for advancement. Future materials research should focus on optimizing particle size distributions and surface modifications to enable higher ceramic loading while maintaining printability. The incorporation of novel additives that can enhance both processing characteristics and final properties offers significant potential for improvement. These might include new dispersants that enable better particle distribution, alternative photoinitiator systems for improved cure depth control, or innovative binder systems that facilitate cleaner burnout during post-processing. Opportunities also exist in developing hybrid materials that combine the advantages of different ceramic

systems. The exploration of new ceramic compositions that offer improved sinterability while maintaining mechanical and aesthetic properties could lead to simplified post-processing requirements. Additionally, the development of materials with enhanced aging resistance and reduced sensitivity to processing variations could improve the reliability of printed restorations.

The potential for multi-material printing represents one of the most exciting developments in ceramic additive manufacturing. This approach could enable the fabrication of restorations with spatially varied properties, better mimicking the structure of natural teeth. Recent advancements in multi-material additive manufacturing have demonstrated the feasibility of creating functionally graded materials (FGMs) that offer a gradual transition in mechanical, optical, and biological properties across different regions of a restoration. FGMs can enhance the durability of restorations by distributing stress more effectively, reducing the likelihood of fracture. Moreover, multi-material printing allows the combination of materials with complementary properties, such as high-strength zirconia for core support and highly translucent lithium disilicate for the outer layer, resulting in restorations with superior mechanical performance and aesthetic outcomes. Advanced printing systems capable of precisely depositing different ceramic compositions could create restorations with optimized mechanical and aesthetic properties in different regions. The development of compatible material systems and precise interface control between different materials remains crucial for realizing this potential. The concept of functionally graded materials (FGMs) in dental ceramics offers unprecedented opportunities for biomimetic restorations. By gradually varying material composition and properties throughout the restoration, FGMs could better replicate the natural transition between enamel and dentin. This approach could potentially reduce stress concentrations at material interfaces and improve overall restoration performance. The implementation of FGM concepts requires advanced control over material deposition and property development during processing.

The translation of ceramic additive manufacturing technologies into widespread clinical practice requires comprehensive validation studies. Long-term clinical trials comparing printed restorations with traditional manufacturing methods are essential for establishing clinical efficacy. These studies should evaluate not only survival rates but also parameters such as wear resistance, color stability, and biological response. Standardized testing protocols specifically designed for additively manufactured ceramics need development to ensure consistent quality assessment. The establishment of clear processing-structure-property relationships through systematic studies would enable better prediction of clinical performance. This understanding becomes particularly important as new materials and manufacturing approaches are developed. Additionally, validation of digital workflows integrating ceramic printing technologies with existing clinical procedures requires attention to ensure practical implementation.

References

- ¹ D, K.P., Shetty, M., Alva, H., D, A.P.: Provisional restorations in prosthodontic rehabilitations – concepts, materials and techniques, *J. Health Allied Sci. NU*, **2**, 72–77, (2020).
- ² Kavita, K., Iqbal, M.A., Singh, R., Singh, S., Nazeer, J., Singh, R.: Factors affecting patient satisfaction among patients undergone removable prosthodontic rehabilitation, *J. Family Med. Prim. Care.*, **9**, 3544, (2020).
- ³ D, K.P., Prasad, B.R., D, A.P., Mehra, D.: Interocclusal records in prosthodontic rehabilitations - materials and techniques – a literature review, *J. Health Allied Sci. NU*, **2**, 54–60, (2020).
- ⁴ Huang, Y.-F., Chang, C.-T., Lin, C.-H., Shen, Y.-F.: Prosthodontic rehabilitation with all-on-four implant treatment combined CAD/CAM prosthesis in an oral cancer patient: a case report, *BMC Oral Health*, **24**, 1080, (2024).
- ⁵ Saeed, F., Muhammad, N., Khan, A.S., Sharif, F., Rahim, A., Ahmad, P., Irfan, M.: Prosthodontics dental materials: from conventional to unconventional, *Mater. Sci. Eng. C Mater. Biol. Appl.*, **106**, 110167, (2020).
- ⁶ Yeung, C., Leung, K.C.M., Yu, O.Y., Lam, W.Y.H., Wong, A.W.Y., Chu, C.H.: Prosthodontic rehabilitation and follow-up using maxillary complete conventional immediate denture, *Clin. Cosmet. Investig. Dent.*, **12**, 437–445, (2020).
- ⁷ Rassawet, R.R., Mittal, S., Kalra, H.: Magnets – role in prosthodontic Rehabilitation: A review, *Indian J. Dent. Sci.*, **12**, 168, (2020).
- ⁸ Fiorillo, L., D'Amico, C., Gorassini, F., Varrà, M., Parbonetti, E., Varrà, S., Ronsivalle, V., Cervino, G.: Innovating prosthodontic Rehabilitation: A streamlined two-step technique for mobile denture fabrication, *Prosthesis*, **6**, 527–539, (2024).
- ⁹ Mostafa, A., Aljanakh, M., Lopez, J., Alshammari, R., Altamimi, Y., Siddigui, A.: Prosthodontic treatment services in Ha'il: A survey of routine prosthodontics rehabilitation or refer done by dentists, *Hail J. Health Sci.*, **3**, (2021).
- ¹⁰ Kurosaki, Y., Kimura-Ono, A., Mino, T., Arakawa, H., Koyama, E., Nakagawa, S., Nguyen, H.T.T., Osaka, S., Saeki, M., Minakuchi, H., Ono, M., Maekawa, K., Kuboki, T.: Six-year follow-up assessment of prosthesis survival and oral health-related quality of life in individuals with partial edentulism treated with three types of prosthodontic rehabilitation, *J. Prosthodont. Res.*, **65**, 332–339, (2021).
- ¹¹ Zhu, H., Jiang, J., Wang, Y., Wang, S., He, Y., He, F.: Additive manufacturing of dental ceramics in prosthodontics: the status quo and the future, *J. Prosthodont. Res.*, advpub, (2024).
- ¹² Al Hamad, K.Q., Al-Rashdan, B.A., Ayyad, J.Q., Al Omrani, L.M., Sharoh, A.M., Al Nimri, A.M., Al-Kaff, F.T.: Additive manufacturing of dental Ceramics: A systematic review and meta-analysis, *J. Prosthodont.*, **31**, e67–e86, (2022).
- ¹³ Hesse, H., Özcan, M.: A review on current additive manufacturing technologies and materials used for fabrication of metal-ceramic fixed dental prosthesis, *J. Adhes. Sci. Technol.*, **35**, 2529–2546, (2021).
- ¹⁴ Revilla-León, M., Sadeghpour, M., Özcan, M.: A review of the applications of additive manufacturing technologies used to fabricate metals in implant dentistry, *J. Prosthodont.*, **29**, 579–593, (2020).
- ¹⁵ Rakesh Reddy, R., Jaya Prakash, K., Koteswari, S., Ud, A., Srinivasa Prasad, B., Narayan, Y.S.: Additive manufacturing of a human mandible and finite element analysis of dental implant for prosthodontic applications, *Int. Conf. Adv. Mater. Res.*, **45**, 3028–3035, (2021).
- ¹⁶ Barbin, T., Velôso, D.V., Del Rio Silva, L., Borges, G.A., Preotto, A.G.C., Barão, V.A.R., Mesquita, M.F.: 3D metal printing in dentistry: an *in vitro* biomechanical comparative study of two additive manufacturing technologies for full-arch implant-supported prostheses, *J. Mech. Behav. Biomed. Mater.*, **108**, 103821, (2020).
- ¹⁷ Savsani, S., Singh, S., Mali, H.S.: Additive manufacturing for prostheses development: state of the art, *Rapid Prototyp. J.*, **29**, 741–765, (2022).
- ¹⁸ Schweiger, J., Edelhoff, D., GÜth, J.-F.: 3D printing in digital prosthetic Dentistry: an overview of recent developments in additive manufacturing, *J. Clin. Med.*, **10**, 2010, (2021).
- ¹⁹ Goodacre, B.J., Goodacre, C.J.: Additive manufacturing for complete denture Fabrication: A narrative review, *J. Prosthodont.*, **31**, 47–51, (2022).
- ²⁰ Mukhtar, G.A., Shehzadi, S., Shahid, U., Shakeel, G., Mustafa, R.A.: Optimizing bottleneck flow and enhancing throughput in prosthodontic services using additive manufacturing with discrete event simulation and central composite design, *Eng. Proc.*, **75**, 9, (2024).
- ²¹ Su, C.-Y., Wang, J.-C., Chen, D.-S., Chuang, C.-C., Lin, C.-K.: Additive manufacturing of dental prosthesis using pristine and recycled zirconia solvent-based slurry stereolithography, *Ceram. Int.*, **46**, 28701–28709, (2020).
- ²² Zhang, T., Zheng, Y., Pradíes, G., Bai, S.: Factors affecting accuracy in the additive manufacturing of interim dental prostheses: A systematic review, *J. Prosthet. Dent.*, (2024).
- ²³ Kouhi, M., de Souza Araújo, I.J., Asa'ad, F., Zeenat, L., Bojedla, S.S.R., Pati, F., Zolfagharian, A., Watts, D.C., Bottino, M.C., Bodaghi, M.: Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation, *Dent. Mater.*, **40**, 700–715, (2024).
- ²⁴ Dimitrova, M., Vlahova, A., Kalachev, Y., Zlatev, S., Kazakova, R., Capodiferro, S.: Recent advances in 3D printing of polymers for application in prosthodontics, *Polymers*, **15**, 4525, (2023).
- ²⁵ Methani, M.M., Cesar, P.F., de Paula Miranda, R.B., Morimoto, S., Özcan, M., Revilla-León, M.: Additive manufacturing in Dentistry: current technologies, clinical applications, and limitations, *Curr. Oral Health Rep.*, **7**, 327–334, (2020).
- ²⁶ Ling, L., Taremi, N., Malyala, R.: A novel low-shrinkage resin for 3D printing, *J. Dent.*, **118**, 103957, (2022).
- ²⁷ Tzeng, J.-J., Yang, T.-S., Lee, W.-F., Chen, H., Chang, H.-M.: Mechanical properties and biocompatibility of urethane acrylate-based 3D-printed denture base resin, *Polymers*, **13**, 822, (2021).
- ²⁸ Wang, L., Ni, X.: The effect of the inorganic nanomaterials on the UV-absorption, rheological and mechanical properties of the rapid prototyping epoxy-based composites, *Polym. Bull.*, **74**, 2063–2079, (2017).
- ²⁹ Hata, K., Ikeda, H., Nagamatsu, Y., Masaki, C., Hosokawa, R., Shimizu, H.: Development of dental Poly(methyl methacrylate)-based resin for stereolithography additive manufacturing, *Polymers*, **13**, 4435, (2021).
- ³⁰ de Armentia, S.L., Fernández-Villamarín, S., Ballesteros, Y., del Real, J.C., Dunne, N., Paz, E.: 3D printing of a graphene-modified photopolymer using stereolithography for biomedical Applications: A study of the polymerization reaction, *Int. J. Bioprint.*, **8**, 503, (2022).
- ³¹ Hada, T., Kanazawa, M., Miyamoto, N., Liu, H., Iwaki, M., Komagamine, Y., Minakuchi, S.: Effect of different filler contents and printing directions on the mechanical properties for photopolymer resins, *Int. J. Mol. Sci.*, **23**, 2296, (2022).
- ³² Tiskaya, M., Shahid, S., Gillam, D., Hill, R.: The use of bioactive glass (BAG). in dental composites: A critical review, *Dent. Mater.*, **37**, 296–310, (2021).
- ³³ Alsandi, Q., Ikeda, M., Arisaka, Y., Nikaido, T., Tsuchida, Y., Sadr, A., Yui, N., Tagami, J.: Evaluation of Mechanical and Physical Properties of Light and Heat Polymerized UDMA for DLP 3D Printer, *Sensors*, **21**, 3331, (2021).

- 34 Redutko, J., Kalwik, A., Szarek, A.: Influence of curing time on properties of dental photosensitive resin applied in DLP technique of 3D printing, *Arch. Metall. Mater.*, **66**, 419–424, (2021).
- 35 Bayarsaikhan, E., Lim, J.-H., Shin, S.-H., Park, K.-H., Park, Y.-B., Lee, J.-H., Kim, J.-E.: Effects of postcuring temperature on the mechanical properties and biocompatibility of three-dimensional printed dental resin material, *Polymers*, **13**, 1180, (2021).
- 36 Andjela, L., Abdurahmanovich, V.M., Vladimirovna, S.N., Mikhailovna, G.I., Yurievich, D.D., Alekseevna, M.Y.: A review on vat photopolymerization 3D-printing processes for dental application, *Dent. Mater.*, **38**, e284 – e296, (2022).
- 37 Ebert, J., Özkol, E., Zeichner, A., Uibel, K., Weiss, Ö., Koops, U., Telle, R., Fischer, H.: Direct inkjet printing of dental prostheses made of zirconia, *J. Dent. Res.*, **88**, 673–676, (2009).
- 38 Grida, I., Evans, J.R.G.: Extrusion freeforming of ceramics through fine nozzles, *J. Eur. Ceram. Soc.*, **23**, 629–635, (2003).
- 39 Ren, X., Shao, H., Lin, T., Zheng, H.: 3D gel-printing—An additive manufacturing method for producing complex shape parts, *Mater. Des.*, **101**, 80–87, (2016).
- 40 Sachs, E., Cima, M., Cornie, J.: Three-dimensional printing: rapid tooling and prototypes directly from a CAD model, *CIRP Ann.*, **39**, 201–204, (1990).
- 41 Bergmann, C., Lindner, M., Zhang, W., Koczur, K., Kirsten, A., Telle, R., Fischer, H.: 3D printing of bone substitute implants using calcium phosphate and bioactive glasses, *J. Eur. Ceram. Soc.*, **30**, 2563–2567, (2010).
- 42 Wei, K., He, R., Cheng, X., Zhang, R., Pei, Y., Fang, D.: Fabrication and mechanical properties of lightweight ZrO₂ ceramic corrugated core sandwich panels, *Mater. Des.*, **64**, 91–95, (2014).
- 43 Sun, J., Gao, L.: Influence of forming methods on the microstructure of 3Y-TZP specimens, *Ceram. Int.*, **29**, 971–974, (2003).
- 44 de Luis Chueca, L.: 3D Printing with advanced ceramic materials, (2016).
- 45 Stefanic, M., Krnel, K., Pribošic, I., Kosmac, T.: Rapid biomimetic deposition of octacalcium phosphate coatings on zirconia ceramics (Y-TZP). for dental implant applications, *Appl. Surf. Sci.*, **258**, 4649–4656, (2012).
- 46 Rosentritt, M., Kolbeck, C., Handel, G., Schneider-Feyrer, S., Behr, M.: Influence of the fabrication process on the *in vitro* performance of fixed dental prostheses with zirconia substructures, *Clin. Oral Investig.*, **15**, 1007–1012, (2011).
- 47 Li, S., Xie, Z., Xue, W.: Microstructure and mechanical properties of zirconia ceramics consolidated by a novel oscillatory pressure sintering, *Ceram. Int.*, **41**, 10281–10286, (2015).
- 48 Soon, G., Pingguan-Murphy, B., Lai, K.W., Akbar, S.A.: Review of zirconia-based bioceramic: surface modification and cellular response, *Ceram. Int.*, **42**, 12543–12555, (2016).
- 49 Miyazaki, T., Nakamura, T., Matsumura, H., Ban, S., Kobayashi, T.: Current status of zirconia restoration, *J. Prosthodont. Res.*, **57**, 236–261, (2013).
- 50 Dehurtevent, M., Robberecht, L., Hornez, J.-C., Thuault, A., Deveaux, E., Béhin, P.: Stereolithography: A new method for processing dental ceramics by additive computer-aided manufacturing, *Dent. Mater.*, **33**, 477–485, (2017).
- 51 Osman, R.B., van der Veen, A.J., Huiberts, D., Wismeijer, D., Alharbi, N.: 3D-printing zirconia implants; a dream or a reality? an *in-vitro* study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs, *J. Mech. Behav. Biomed. Mater.*, **75**, 521–528, (2017).
- 52 Scheithauer, U., John, R., Weingarten, S., Schwarzer, E., Richter, H.-J., Moritz, T., Michaelis, A.: Investigation of droplet deposition for suspensions usable for thermoplastic 3D printing (T3DP), *J. Mater. Eng. Perform.*, **27**, 44–51, (2018).
- 53 Shao, H., Zhao, D., Lin, T., He, J., Wu, J.: 3D gel-printing of zirconia ceramic parts, *Ceram. Int.*, **43**, 13938–13942, (2017).
- 54 Fahimipour, F., Rasoulboroujeni, M., Dashtimoghdam, E., Khoshroo, K., Tahriri, M., Bastami, F., Lobner, D., Tayebi, L.: 3D printed TCP-based scaffold incorporating VEGF-loaded PLGA microspheres for craniofacial tissue engineering, *Dent. Mater.*, **33**, 1205–1216, (2017).
- 55 Mandelli, F., Gherlone, E., Gastaldi, G., Ferrari, M.: Evaluation of the accuracy of extraoral laboratory scanners with a single-tooth abutment model: A 3D analysis, *J. Prosthodont. Res.*, **61**, 363–370, (2017).
- 56 Marghalani, A., Weber, H.-P., Finkelman, M., Kudara, Y., El Rafie, K., Papaspyridakos, P.: Digital versus conventional implant impressions for partially edentulous arches: an evaluation of accuracy, *J. Prosthet. Dent.*, **119**, 574–579, (2018).
- 57 Emir, F., Ayyıldız, S.: Evaluation of the trueness and precision of eight extraoral laboratory scanners with a complete-arch model: a three-dimensional analysis, *J. Prosthodont. Res.*, **63**, 434–439, (2019).
- 58 Vögtlin, C., Schulz, G., Jäger, K., Müller, B.: Comparing the accuracy of master models based on digital intra-oral scanners with conventional plaster casts, *Phys. Med.*, **1**, 20–26, (2016).
- 59 Anh, J., Park, J.-M., Chun, Y.-S., Kim, M., Kim, M.: A comparison of the precision of three-dimensional images acquired by 2 digital intraoral scanners: effects of tooth irregularity and scanning direction, *Korean J. Orthod.*, **46**, 3–12, (2016).
- 60 Patzelt, S.B.M., Emmanouilidi, A., Stampf, S., Strub, J.R., Att, W.: Accuracy of full-arch scans using intraoral scanners, *Clin. Oral Invest.*, **18**, 1687–1694, (2014).
- 61 Renne, W., Ludlow, M., Fryml, J., Schurch, Z., Mennito, A., Kessler, R., Lauer, A.: Evaluation of the accuracy of 7 digital scanners: an *in vitro* analysis based on 3-dimensional comparisons, *J. Prosthet. Dent.*, **118**, 36–42, (2017).
- 62 Hayama, H., Fueki, K., Wadachi, J., Wakabayashi, N.: Trueness and precision of digital impressions obtained using an intraoral scanner with different head size in the partially edentulous mandible, *J. Prosthodont. Res.*, **62**, 347–352, (2018).
- 63 Bosch, G., Ender, A., Mehl, A.: A 3-dimensional accuracy analysis of chairside CAD/CAM milling processes, *J. Prosthet. Dent.*, **112**, 1425–1431, (2014).
- 64 Dobrzański, L.A., Dobrzański, L.B.: Dentistry 4.0 concept in the design and manufacturing of prosthetic dental restorations, *Processes*, **8**, 525, (2020).
- 65 Patzelt, S.B.M., Bishti, S., Stampf, S., Att, W.: Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data, *J. Am. Dent. Assoc.*, **145**, 1133–1140, (2014).
- 66 Su, T., Sun, J.: Comparison of repeatability between intraoral digital scanner and extraoral digital scanner: an *in-vitro* study, *J. Prosthodont. Res.*, **59**, 236–242, (2015).
- 67 Fielding, G.A., Bandyopadhyay, A., Bose, S.: Effects of silica and zinc oxide doping on mechanical and biological properties of 3D printed tricalcium phosphate tissue engineering scaffolds, *Dent. Mater.*, **28**, 113–122, (2012).
- 68 Fukazawa, S., Odaira, C., Kondo, H.: Investigation of accuracy and reproducibility of abutment position by intraoral scanners, *J. Prosthodont. Res.*, **61**, 450–459, (2017).
- 69 Park, J.-M.: Comparative analysis on reproducibility among 5 intraoral scanners: sectional analysis according to restoration type and preparation outline form, *J. Adv. Prosthodont.*, **8**, 354–362, (2016).
- 70 Kim, K.R., Seo, K., Kim, S.: Conventional open-tray impression versus intraoral digital scan for implant-level complete-arch impression, *J. Prosthet. Dent.*, **122**, 543–549, (2019).

- 71 Łomżyński, Ł.G., Mierzińska-Nastalska, E.: Cyfrowe wyciski wykonywane z zastosowaniem optycznych skanerów wewnątrzustnych. systematyczny przegląd piśmiennictwa. Część I: właściwości i zalety stosowania techniki wycisków cyfrowych w stomatologii oraz analiza cech pożądanego optymalnego systemu skanującego, *Protet. Stomatol.*, **69**, 217–223, (2019).
- 72 Atieh, M.A., Ritter, A.V., Ko, C.-C., Duqum, I.: Accuracy evaluation of intraoral optical impressions: A clinical study using a reference appliance, *J. Prosthet. Dent.*, **118**, 400–405, (2017).
- 73 Sakornwimon, N., Leevailoj, C.: Clinical marginal fit of zirconia crowns and patients' preferences for impression techniques using intraoral digital scanner versus polyvinyl siloxane material, *J. Prosthet. Dent.*, **118**, 386–391, (2017).
- 74 Mehl, A., Ender, A., Mörmann, W., Attin, T.: Accuracy testing of a new intraoral 3D camera, *Int. J. Comput. Dent.*, **12**, 11–28, (2009).
- 75 Seelbach, P., Brueckel, C., Wöstmann, B.: Accuracy of digital and conventional impression techniques and workflow, *Clin. Oral Invest.*, **17**, 1759–1764, (2013).
- 76 Kachalia, P.R., Geissberger, M.J.: Dentistry a la carte: in-office CAD/CAM technology, *J. Calif. Dent. Assoc.*, **38**, 323–330, (2010).
- 77 Lenguas, A., Ortega, R., Samara, G., López, M.: Tomografía computarizada de haz cónico. aplicaciones clínicas en odontología; comparación con otras técnicas, *Cient. Dent.*, **7**, 147–159, (2010).
- 78 Marinescu Gava, M., Suomalainen, A., Vehmas, T., Ventä, I.: Did malpractice claims for failed dental implants decrease after introduction of CBCT in Finland?, *Clin. Oral Invest.*, **23**, 399–404, (2019).
- 79 Fakhraan, S., Alhilali, L., Sreedher, G., Dohatcu, A.C., Lee, S., Ferguson, B., Branstetter B.F. IV: Comparison of simulated cone beam computed tomography to conventional helical computed tomography for imaging of rhinosinusitis, *The Laryngoscope*, **124**, 2002–2006, (2014).
- 80 Tsuchida, R., Araki, K., Okano, T.: Evaluation of a limited cone-beam volumetric imaging system: comparison with film radiography in detecting incipient proximal caries, *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, **104**, 412–416, (2007).
- 81 Mischkowski, R.A., Pulsfort, R., Ritter, L., Neugebauer, J., Brochhagen, H.G., Keeve, E., Zöller, J.E.: Geometric accuracy of a newly developed cone-beam device for maxillofacial imaging, *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, **104**, 551–559, (2007).
- 82 Haiter-Neto, F., Wenzel, A., Gotfredsen, E.: Diagnostic accuracy of cone beam computed tomography scans compared with intraoral image modalities for detection of caries lesions, *Dentomaxillofac. Radiol.*, **37**, 18–22, (2008).
- 83 Wu, H., Cheng, Y., Liu, W., He, R., Zhou, M., Wu, S., Song, X., Chen, Y.: Effect of the particle size and the debinding process on the density of alumina ceramics fabricated by 3D printing based on stereolithography, *Ceram. Int.*, **42**, 17290–17294, (2016).
- 84 Goodall, W., Greer, A., Martin, N.: Unilateral removable partial dentures, *Br. Dent. J.*, **222**, 79–84, (2017).
- 85 Scheithauer, U., Schwarzer, E., Richter, H.-J., Moritz, T.: Thermoplastic 3D printing – an additive manufacturing method for producing dense ceramics, *Int. J. Appl. Ceram. Technol.*, **12**, 26–31, (2015).
- 86 Maleksaeedi, S., Eng, H., Wiria, F.E., Ha, T.M.H., He, Z.: Property enhancement of 3D-printed alumina ceramics using vacuum infiltration, *J. Mater. Process. Technol.*, **214**, 1301–1306, (2014).
- 87 Vallar, S., Houivet, D., El Fallah, J., Kervadec, D., Haussonne, J.-M.: Oxide slurries stability and powders dispersion: optimization with zeta potential and rheological measurements, *J. Eur. Ceram. Soc.*, **19**, 1017–1021, (1999).
- 88 Wang, J., Shaw, L.L.: Rheological and extrusion behavior of dental porcelain slurries for rapid prototyping applications, *Mater. Sci. Eng. A*, **397**, 314–321, (2005).
- 89 Halloran, J.W.: Ceramic stereolithography: additive manufacturing for ceramics by photopolymerization, *Annu. Rev. Mater. Res.*, **46**, 19–40, (2016).
- 90 Griffith, M.L., Halloran, J.W.: Freeform fabrication of ceramics via stereolithography, *J. Am. Ceram. Soc.*, **79**, 2601–2608, (1996).
- 91 Dehurtevent, M., Robberecht, L., Thuault, A., Deveaux, E., Leriche, A., Petit, F., Denis, C., Hornez, J.-C., Béhin, P.: Effect of build orientation on the manufacturing process and the properties of stereolithographic dental ceramics for crown frameworks, *J. Prosthet. Dent.*, **125**, 453–461, (2021).
- 92 Puebla, K., Arcaute, K., Quintana, R., Wicker, R.B.: Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography, *Rapid Prototyp. J.*, **18**, 374–388, (2012).
- 93 Unkovskiy, A., Bui, P.H.-B., Schille, C., Geis-Gerstorf, J., Huettig, F., Spintzyk, S.: Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin, *Dent. Mater.*, **34**, e324–e333, (2018).
- 94 Baumgartner, S., Gmeiner, R., Schönherr, J.A., Stampfl, J.: Stereolithography-based additive manufacturing of lithium disilicate glass ceramic for dental applications, *Mater. Sci. Eng. C Mater. Biol. Appl.*, **116**, 111180, (2020).
- 95 Li, R., Wang, Y., Hu, M., Wang, Y., Xu, Y., Liu, Y., Sun, Y.: Strength and adaptation of stereolithography-fabricated zirconia dental crowns: an *in vitro* study, *Int. J. Prosthodont.*, **32**, 439–443, (2019).
- 96 Goswami, A., K, A., Balashanmugam, N., Umarji, A.M., Madras, G.: Optimization of rheological properties of photopolymerizable alumina suspensions for ceramic microstereolithography, *Ceram. Int.*, **40**, 3655–3665, (2014).
- 97 Han, Z., Liu, S., Qiu, K., Liu, J., Zou, R., Wang, Y., Zhao, J., Liu, F., Wang, Y., Li, L.: The enhanced ZrO₂ produced by DLP via a reliable plasticizer and its dental application, *J. Mech. Behav. Biomed. Mater.*, **141**, 105751, (2023).
- 98 Zhang, C., Jiang, Z., Zhao, L., Guo, W., Gao, X.: Stability, rheological behaviors, and curing properties of 3Y-ZrO₂ and 3Y-ZrO₂/GO ceramic suspensions in stereolithography applied for dental implants, *Ceram. Int.*, **47**, 13344–13350, (2021).
- 99 Chen, F., Zhu, H., Wu, J.-M., Chen, S., Cheng, L.-J., Shi, Y.-S., Mo, Y.-C., Li, C.-H., Xiao, J.: Preparation and biological evaluation of ZrO₂ all-ceramic teeth by DLP technology, *Ceram. Int.*, **46**, 11268–11274, (2020).
- 100 Yang, B., Wang, S., Wang, G., Yang, X.: Mechanical properties and wear behaviors analysis of fluorapatite glass-ceramics based on stereolithography 3D printing, *J. Mech. Behav. Biomed. Mater.*, **124**, 104859, (2021).
- 101 Branco, A.C., Silva, R., Santos, T., Jorge, H., Rodrigues, A.R., Fernandes, R., Bandarra, S., Barahona, I., Matos, A.P.A., Lorenz, K., Polido, M., Colaço, R., Serro, A.P., Figueiredo-Pina, C.G.: Suitability of 3D printed pieces of nanocrystalline zirconia for dental applications, *Dent. Mater.*, **36**, 442–455, (2020).
- 102 Branco, A.C., Silva, R., Jorge, H., Santos, T., Lorenz, K., Polido, M., Colaço, R., Serro, A.P., Figueiredo-Pina, C.G.: Tribological performance of the pair human teeth vs 3D printed zirconia: an *in vitro* chewing simulation study, *Mech. Behav. Biomed. Mater.*, **110**, 103900, (2020).
- 103 Aldesoki, M., Keilig, L., Dörsam, I., Evers-Dietze, B., Elshazly, T.M., Bourauel, C.: Trueness and precision of milled and 3D

- printed root-analogue implants: A comparative *in vitro* study, *J. Dent.*, **130**, 104425, (2023).
- ¹⁰⁴ Zhu, L., Xu, Y., Liu, S., Chen, H., Tao, J., Tong, X., Li, Y., Huang, S., Lin, J., Wen, C., Ma, J.: Microstructure, mechanical properties, friction and wear performance, and cytotoxicity of additively manufactured zirconia-toughened alumina for dental applications, *Compos. B Eng.*, **250**, 110459, (2023).
 - ¹⁰⁵ Revilla-León, M., Methani, M.M., Morton, D., Zandinejad, A.: Internal and marginal discrepancies associated with stereolithography (SLA). additively manufactured zirconia crowns, *J. Prosthet. Dent.*, **124**, 730–737, (2020).
 - ¹⁰⁶ Gentry, S.P., Halloran, J.W.: Depth and width of cured lines in photopolymerizable ceramic suspensions, *J. Eur. Ceram. Soc.*, **33**, 1981–1988, (2013).
 - ¹⁰⁷ Badev, A., Abouliatim, Y., Chartier, T., Lecamp, L., Lebaudy, P., Chaput, C., Delage, C.: Photopolymerization kinetics of a polyether acrylate in the presence of ceramic fillers used in stereolithography, *J. Photochem. Photobiol. A Chem.*, **222**, 117–122, (2011).
 - ¹⁰⁸ Galante, R., Figueiredo-Pina, C.G., Serro, A.P.: Additive manufacturing of ceramics for dental applications: A review, *Dent. Mater.*, **35**, 825–846, (2019).
 - ¹⁰⁹ Wang, W., Sun, J.: Dimensional accuracy and clinical adaptation of ceramic crowns fabricated with the stereolithography technique, *J. Prosthet. Dent.*, **125**, 657–663, (2021).
 - ¹¹⁰ Li, R., Chen, H., Wang, Y., Sun, Y.: Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs, *J. Mech. Behav. Biomed. Mater.*, **115**, 104255, (2021).
 - ¹¹¹ Khanlar, L.N., Salazar Rios, A., Tahmaseb, A., Zandinejad, A.: Additive manufacturing of zirconia ceramic and its application in clinical Dentistry: A review, *Dent. J.*, **9**, 104, (2021).
 - ¹¹² Revilla-León, M., Al-Haj Husain, N., Ceballos, L., Özcan, M.: Flexural strength and weibull characteristics of stereolithography additive manufactured versus milled zirconia, *J. Prosthet. Dent.*, **125**, 685–690, (2021).
 - ¹¹³ Nakai, H., Inokoshi, M., Nozaki, K., Komatsu, K., Kamijo, S., Liu, H., Shimizubata, M., Minakuchi, S., Van Meerbeek, B., Vleugels, J., Zhang, F.: Additively manufactured zirconia for dental applications, *Materials*, **14**, 3694, (2021).
 - ¹¹⁴ Lian, Q., Sui, W., Wu, X., Yang, F., Yang, S.: Additive manufacturing of ZrO₂ ceramic dental bridges by stereolithography, *Rapid Prototyp. J.*, **24**, 114–119, (2018).
 - ¹¹⁵ Liu, K., Zhang, K., Bourell, D.L., Chen, F., Sun, H., Shi, Y., Wang, J., He, M., Chen, J.: Gelcasting of zirconia-based all-ceramic teeth combined with stereolithography, *Ceram. Int.*, **44**, 21556–21563, (2018).
 - ¹¹⁶ Zhang, K., He, R., Xie, C., Wang, G., Ding, G., Wang, M., Song, W., Fang, D.: Photosensitive ZrO₂ suspensions for stereolithography, *Ceram. Int.*, **45**, 12189–12195, (2019).
 - ¹¹⁷ Wang, J.-C., Dommati, H.: Fabrication of zirconia ceramic parts by using solvent-based slurry stereolithography and sintering, *J. Adv. Manuf. Technol.*, **98**, 1537–1546, (2018).
 - ¹¹⁸ Shahmiri, R., Standard, O.C., Hart, J.N., Sorrell, C.C.: Optical properties of zirconia ceramics for esthetic dental restorations: A systematic review, *J. Prosthet. Dent.*, **119**, 36–46, (2018).
 - ¹¹⁹ Fernández-Oliveras, A., Rubiño, M., Pérez, M.: Scattering and absorption properties of biomaterials for dental restorative applications, *J. Eur. Opt. Soc. Rapid Publ.*, **8**, 13056, (2013).
 - ¹²⁰ Zhang, Y.: Making yttria-stabilized tetragonal zirconia translucent, *Dent. Mater.*, **30**, 1195–1203, (2014).
 - ¹²¹ Venkatachari, K.R., Raj, R.: Enhancement of strength through sinter forging, *J. Am. Ceram. Soc.*, **70**, 514–520, (1987).
 - ¹²² Panda, P.C., Wang, J., Raj, R.: Sinter-forging characteristics of fine-grained zirconia, *J. Am. Ceram. Soc.*, **71**, C-507–C-509, (1988).

