Scientific Open Access Publishing

International Journal of Chemistry and Materials Science

Article

Research on the application of Accuracy control technology for 3D printed ceramic dentures

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Abstract: The rapid advancement of additive manufacturing has revolutionized restorative dentistry, yet achieving precise dimensional fidelity in 3D-printed ceramic dentures remains a significant clinical and engineering challenge. This paper first analyzes the key factors affecting the accuracy of ceramic dentures from four critical dimensions: data acquisition in the digital modeling stage, the precise setting of 3D printing process parameters, the inherent rheological characteristics of ceramic slurry materials, and the complex dimensional changes occurring during the debinding and sintering phases. To systematically address these technical issues, a robust modeling accuracy control method based on advanced digital compensation is proposed. This methodology includes comprehensive strategies for overall dimensional shrinkage compensation alongside targeted accuracy compensation in key local anatomical areas. Furthermore, engineering optimization schemes are extensively explored, focusing on the coordinated setting of printing process parameters—such as layer thickness and exposure parameters—as well as the strategic orientation of the printing direction and the meticulous design of support structures. In the critical debinding and sintering stages, sophisticated temperature control strategies, including segmented heating protocols and optimized heat preservation curves, are developed to effectively mitigate structural deformation caused by residual thermal stress. By implementing these comprehensive accuracy control technologies, the dimensional accuracy, mechanical integrity, and ultimate clinical fit of 3D-printed ceramic dentures can be significantly improved, thereby offering a highly reliable and scalable solution for modern digital dentistry applications.

Keywords: 3D printing; ceramic dentures; accuracy control; digital compensation; sintering; process optimization

Received: 10 April 2026
Revised: 23 May 2026
Accepted: 05 June 2026
Published: 11 June 2026

1. Analysis of Technical Issues Regarding the Accuracy of 3D Printed Ceramic Dentures Forming

1.1. The Impact of the Digital Modeling on Accuracy of Denture

Incomplete oral scan data or interference caused by noise during the scanning process can result in surface defects during the reconstruction of 3D models. These defects negatively impact the dimensional accuracy of subsequent stages, including printing and sintering [1]. Specifically, during the reconstruction phase, algorithms may fail to accurately recognize edge lines, which directly affects the marginal fit between the restoration and the prepared tooth [2,3]. Poor marginal fit has been identified as a critical factor in increasing the risk of microleakage and secondary caries, as it compromises the seal between the restoration and the tooth structure. Additionally, compatibility issues between various 3D data processing software can lead to information loss during data conversion. This problem is particularly pronounced in posterior teeth with intricate anatomical features, where subtle occlusal details may be smoothed out or entirely lost during format conversion. Such losses can compromise the functional and aesthetic quality of the final restoration. Furthermore, the interplay between software algorithms and hardware precision plays a significant role in determining the overall accuracy of the 3D printed ceramic dentures. Ensuring seamless integration between scanning devices, modeling software, and printing hardware is essential to minimize errors and optimize outcomes. Advanced techniques, such as adaptive algorithms and enhanced data processing protocols, are being explored to address these challenges. These methods aim to improve edge detection, preserve occlusal details, and ensure compatibility across different software platforms. By refining these processes, the accuracy and reliability of 3D printed ceramic dentures can be significantly enhanced, ultimately improving clinical outcomes and patient satisfaction.

1.2. The Impact of 3D Printing Forming Process on the Accuracy of Ceramic Dentures

When utilizing digital light processing (DLP) and stereolithography (DLP) printing systems, notable variations in accuracy are observed across different devices. Research indicates that the average deviation between similar DLP devices can range significantly, from as high as 207.1 micrometers to as low as 25.1 micrometers. This variation underscores the critical role of printing resolution in determining the precision of ceramic denture fabrication. Higher resolution enables the accurate reproduction of intricate surface details, which is essential for achieving both aesthetic appeal and functional adaptability in dental restorations. Conversely, inadequate resolution can compromise the replication of natural tooth textures and edge morphology, leading to suboptimal outcomes in both appearance and functionality. Additionally, the layer thickness settings during the printing process play a pivotal role in influencing the final quality of the denture. Excessive layer thickness can result in a pronounced step effect and increased surface roughness, which may distort the occlusal surface anatomy. Such distortions can negatively impact the restoration of occlusal function, potentially leading to discomfort or reduced effectiveness in dental applications. Therefore, careful calibration of layer thickness is essential to minimize these issues and ensure the production of high-quality ceramic dentures [4, 5]. The interplay between resolution and layer thickness highlights the importance of optimizing 3D printing parameters to achieve superior results. Figure 1 illustrates the process of forming 3D-printed ceramic dentures, providing a visual representation of the discussed concepts. By addressing these technical considerations, advancements in 3D printing technology can continue to enhance the precision and reliability of ceramic denture manufacturing, ultimately benefiting both dental professionals and patients.

Figure 1. 3D printed ceramic denture forming.

1.3. The Impact of Ceramic Slurry and Material Properties on Accuracy

The material properties of ceramic slurry play a pivotal role in determining the accuracy of 3D printing processes [6,7]. These properties influence not only the stability of the printing operation but also the dimensional precision and consistency of the final printed product. Key parameters such as viscosity, particle size distribution, and solid loading ratio are critical in ensuring optimal performance. For instance, the viscosity of the slurry must be carefully controlled to balance flowability and structural integrity during the printing process. Excessively high viscosity can hinder the smooth extrusion of material, while low viscosity may lead to deformation or collapse of the printed structure. Similarly, the particle size distribution affects the packing density and surface finish of the printed object. A narrow particle size distribution typically results in higher packing density, which enhances the mechanical properties and dimensional accuracy of the final product. The solid loading ratio, on the other hand, directly impacts the shrinkage behavior during drying and sintering, which are crucial stages in ceramic 3D printing. Improper control of this parameter can lead to warping, cracking, or other defects that compromise the quality of the printed object. A comprehensive understanding of these factors is essential for optimizing the ceramic slurry formulation and achieving high-precision 3D printing outcomes. Table 1 provides a detailed analysis of the mechanisms through which these parameters influence printing accuracy.

Table 1. Impact Mechanism of Key Ceramic Slurry Parameters on Printing Accuracy

Material parameters	Ideal range	Impact on printing stability	Impact on dimensional consistency
Particle size distribution	D50: 0.5-1.0μm	Narrow distribution results in good fluidity and uniform layer thickness.	Uniform particles result in consistent shrinkage.
Solid content	50-87wt.%	High solid content results in high core sturcutre strength and low deformation.	Solid content is negatively correlated with sintering shrinkage.
Rheological properties	Viscosity 7-9 Pa s	Medium viscosity ensures smooth extrusion and shape retention.	If the rheological properties are stable, the thickness of each layer will be uniform.
Dispersion stability	Zeta potential > 30mV	Good dispersion results in a uniform slurry with no sedimentation.	Uniform dispersion ensures consistent contraction in all directions.
Organic content	8-15wt.%	Organic phase ensures interlayer bonding and green body strength	When the organic phase is evenly distributed, defatting shrinkage is uniform.

2. Modeling Accuracy Control Technology Based on Digital Compensation

2.1. Overall Size Shrinkage Compensation Strategy

To address the inevitable dimensional shrinkage of ceramic materials during the debinding and sintering processes, overall dimensional shrinkage compensation has emerged as a widely adopted and effective accuracy control method in engineering applications. This approach involves pre-scaling and amplifying the design model during the digital modeling phase to counteract the shrinkage that occurs in subsequent stages [8–10]. The compensation coefficient, a critical parameter in this strategy, is determined based on systematic experimental data. This typically necessitates the creation of a shrinkage rate database tailored to specific material and process combinations. For zirconia ceramic materials, the linear shrinkage rate generally falls within the range of 18% to 22%. However, through optimization of the slurry formulation and fine-tuning of process parameters, it is possible to maintain the shrinkage rate within a relatively stable and predictable range, thereby enhancing the precision of the final product.

In practical applications, it is essential to account for the anisotropy of the compensation coefficient. This anisotropy arises due to the inherent characteristics of layer-by-layer additive manufacturing processes and the influence of external factors such as gravity. Specifically, the shrinkage rate along the Z-axis often differs from that observed in the XY plane. This discrepancy necessitates a more nuanced approach to compensation, where adjustments are made to account for directional variations in shrinkage behavior. By incorporating these considerations into the modeling process, engineers can achieve higher levels of dimensional accuracy in the final ceramic components.

Moreover, the development of advanced computational tools and simulation techniques has further enhanced the effectiveness of shrinkage compensation strategies. These tools enable the precise prediction of shrinkage behavior under varying conditions, allowing for more accurate adjustments to the design model. As a result, the integration of digital compensation methods with experimental data and computational modeling has become a cornerstone of modern accuracy control technology in the field of ceramic material engineering.

2.2. Accuracy Compensation for Key Local Areas (edges, Occlusal Surfaces)

In addition to overall dimensional compensation, ensuring precise partial accuracy for key functional areas of dental restorations is essential for achieving clinical success. Among these areas, the marginal region plays a pivotal role as it serves as the interface between the restoration and the natural tooth structure. This interface directly influences the long-term stability and functionality of the restoration. Traditional compensation methods often rely on a single compensation coefficient, which may not adequately address the complex shrinkage behaviors observed during sintering. Variations in geometry and support conditions can lead to differential shrinkage, particularly in the marginal area compared to the main body of the restoration. To address this, advanced compensation techniques segment the restoration into distinct characteristic regions, such as the marginal line, axial wall, and occlusal surface, and apply tailored compensation strategies to each. For the marginal area, a slightly overcompensated approach can be employed to ensure proper placement pressure post-sintering. However, the degree of overcompensation must be meticulously controlled to prevent complications such as placement difficulties or misalignment. Similarly, occlusal surface compensation requires careful consideration of functional requirements. While compensating for shrinkage, it is critical to preserve the necessary occlusal contact characteristics to maintain proper functionality. Overcompensation in this area can result in the loss of occlusal contact, which may compromise the restoration's effectiveness, while undercompensation can lead to occlusal high points, causing discomfort or functional issues for the patient. By implementing region-specific compensation strategies, it is possible to optimize the fit and functionality of the restoration, ensuring both clinical success and patient satisfaction. These approaches highlight the importance of precision and customization in modern restorative dentistry, where even minor inaccuracies can have significant implications for long-term outcomes. Advanced computational modeling and material science innovations continue to enhance the accuracy and predictability of these compensation techniques, further improving the quality of dental restorations.

3. Accuracy Control Methods for Optimizing Printing Process Parameters

3.1. Coordinated Optimization of Layer Thickness and Exposure Parameters

For zirconia ceramic slurries, determining the optimal layer thickness is a critical factor in achieving high precision and efficiency in the printing process. Typically, this thickness ranges between 25 and 50 micrometers, and the specific value is adjusted based on the particle size and solid content of the ceramic particles within the slurry. The particle size directly influences the packing density and surface smoothness, while the solid content affects the viscosity and curing behavior of the slurry. Exposure time, another key parameter, must be carefully calibrated by considering multiple factors such as light intensity, slurry transmittance, and the light scattering characteristics of the ceramic particles. These factors collectively determine the curing depth and uniformity of each layer. To ensure optimal curing, exposure testing is often employed to identify the critical exposure time that allows a single layer to cure completely without leading to over-curing, which can compromise the structural integrity of the printed part. Furthermore, the geometric features of the part play a significant role in parameter optimization. For regions with overhanging structures, exposure parameters may need to be adjusted to enhance the strength and stability of the supporting structures, preventing deformation or collapse during the printing process. Conversely, areas with intricate or fine features require thinner layer thickness and more precise exposure control to maintain dimensional accuracy and detail resolution. Advanced techniques, such as dynamic variable layer thickness technology, offer significant advantages by enabling the adjustment of layer thickness within a single printing job [11, 12]. This approach allows for the customization of layer thickness based on the specific requirements of different areas of the part, thereby improving overall printing efficiency while ensuring high accuracy in critical regions. By integrating these optimization strategies, the printing process can achieve a balance between speed, precision, and material utilization, ultimately enhancing the quality and performance of zirconia ceramic components.

3.2. Engineering Optimization of Printing Direction and Support Structure Design

The orientation of 3D printing plays a critical role in determining the distribution of the step effect and the anisotropic mechanical properties of the printed parts. For dental crown restorations, commonly used printing orientations include occlusal downwards, axially perpendicular, and marginal downwards. Each orientation has distinct implications for the final quality and mechanical performance of the restoration. For instance, an occlusal-downwards orientation may optimize surface smoothness in critical areas, while an axially perpendicular orientation might enhance structural integrity along specific axes. The design of the support structure is equally crucial, as it must strike a balance between providing adequate support and minimizing the number of contact points. Excessive support points can degrade surface quality and complicate post-processing, while insufficient support may lead to deformation or complete failure during the printing process. This balance becomes even more challenging when working with high-viscosity materials such as ceramic slurries. In such cases, the support structure must account for the material's fluidity to ensure that all support areas are adequately filled and cured during the printing process. Advanced algorithms for support generation have been developed to address these challenges. These algorithms analyze the geometry of the part, the properties of the material, and the chosen printing orientation to automatically generate optimized support structures. Special attention is given to reinforcing areas that are prone to deformation, such as thin walls, overhangs, and edges. By focusing on these critical regions, the algorithms help to ensure the structural stability of the part while minimizing the need for extensive post-processing. This optimization process is essential for achieving high-quality, reliable dental restorations and other precision components produced through 3D printing technologies [13].

4. Accuracy Control Technology in the Debinding and Sintering Stages

4.1. Temperature Control Strategy during the Defatting Stage

For polymer adhesive systems commonly utilized in ceramic dentures, the degreasing process is divided into distinct temperature ranges to optimize material integrity and minimize defects. In the initial range of 100-250°C, the primary objective is the removal of moisture and low-molecular-weight plasticizers. This stage requires precise control of the heating rate, typically maintained at 1-3°C per minute, to prevent rapid temperature changes that could induce stress. As the temperature progresses to the

250-450°C range, the polymer backbone begins to decompose. This phase necessitates an even slower heating rate, generally between 0.5-1.5°C per minute, accompanied by multiple heat-preserving platforms. These platforms are critical for ensuring adequate diffusion and the escape of decomposition byproducts, which helps to mitigate internal stress accumulation. Extending the heat preservation time during this stage has been shown to significantly reduce the risk of cracking, particularly in complex restorations. In the final range of 450-600°C, the oxidative removal of residual carbon becomes the focus. This step requires an oxidizing atmosphere and carefully managed heat preservation to ensure complete removal of carbon residues without compromising the structural integrity of the material. For restorations with intricate internal geometries, such as full crowns with pulp chamber morphology, the design of the gas escape path during the degreasing process is paramount [14]. Poorly designed escape paths can lead to gas retention and pressure buildup, which may result in internal cracks or other structural failures. Advanced strategies, including segmented degreasing approaches, have proven more effective than linear heating methods in controlling stress accumulation. These strategies are particularly beneficial in temperature ranges where polymer decomposition is most intense. By optimizing the degreasing process through precise temperature control, heat preservation, and gas escape path design, the risk of defects such as cracking can be significantly minimized, ensuring the production of high-quality ceramic dentures.

4.2. Dimensional Stability Control Strategy

The control of dimensional stability during the sintering process of zirconia ceramics is a critical aspect of ensuring the desired mechanical and structural properties. Uniform heating is essential to prevent the development of thermal stress, which can arise from excessively rapid temperature increases. For zirconia ceramics, the heating rate is typically maintained at 3-5°C per minute from room temperature to 1000°C. This gradual increase minimizes the risk of phase transformation stress, particularly in temperature ranges where phase transitions occur. Beyond this, the heating rate may need further reduction depending on the specific characteristics of the material and the phase transformation temperature range. Optimal sintering temperatures for dental zirconia ceramics generally fall between 1450°C and 1550°C, with a holding time of 1-2 hours to ensure complete densification and the achievement of desired mechanical properties. These parameters, however, must be tailored to the specific powder composition, the presence of additives, and the targeted application properties.

Equally important is the control of the sintering atmosphere. An oxidizing atmosphere is often preferred as it facilitates the removal of residual organic matter, ensuring the purity of the ceramic material. However, certain ceramic systems may require a neutral or reducing atmosphere to prevent unwanted oxidation reactions that could compromise the material's integrity. The cooling phase, though frequently overlooked, plays a vital role in maintaining dimensional stability [15]. Rapid cooling can lead to deformation and the formation of microcracks due to thermal stress, particularly when the material passes through its brittle temperature range. To mitigate these risks, the cooling rate must be carefully controlled, ensuring a gradual transition through critical temperature zones.

For restorations with complex geometries, container sintering or the use of sintering supports is highly beneficial. These supports are designed to shrink synchronously with the restoration during the sintering process, providing uniform constraint and reducing the likelihood of deformation. This approach is particularly advantageous for intricate designs, as it ensures the preservation of the intended shape and structural integrity of the final product.

5. Conclusion

This paper introduces a comprehensive modeling accuracy control technology centered on digital compensation, which encompasses strategies for addressing both overall dimensional shrinkage and localized critical area accuracy. These methods enable precise prediction and correction of sintering shrinkage, ensuring enhanced dimensional fidelity. The optimization of printing process parameters, particularly through the synergistic adjustment of layer thickness and exposure settings, plays a pivotal role in improving the precision and reliability of the additive manufacturing process. Furthermore, engineering optimizations, such as the strategic selection of printing direction and the design of supports, contribute significantly to minimizing errors and ensuring structural integrity. During the degreasing and sintering stages, advanced temperature control strategies, including segmented heating protocols, optimized heat preservation curves, and real-time monitoring of the sintering process, are employed to mitigate deformation caused by thermal stress. These measures collectively enhance dimensional stability and reduce the risk of defects. The integration of these accuracy control technologies into the manufacturing workflow has profound implications for the production of 3D-printed ceramic prostheses. By achieving superior dimensional accuracy and clinical fit, this approach not only addresses critical challenges in dental restoration manufacturing but also paves the way for the broader adoption of digital and personalized production techniques. The proposed solutions hold substantial clinical application value, offering improved outcomes for patients, and present significant prospects for industrialization. Future research could explore the scalability of these methods to other materials and applications, as well as the integration of real-time feedback systems to further refine accuracy. This work represents a significant step forward in advancing the precision and reliability of additive manufacturing technologies, particularly in the context of high-demand applications such as dental prosthetics.

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