

Article

Feasibility of DLP-Printed Alumina Mold Inserts for Curved Optical Component Replication

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Abstract

This study evaluates the rapid tooling feasibility and structural significance of utilizing digital light processing (DLP)-printed alumina as a near-net-shape ceramic mold-insert preform route for replication of curved polymer optics. While conventional production tooling for precision optics demands immediate optical-grade tolerances, the fundamental mechanisms governing polymer replication close to additively manufactured ceramic interfaces remain insufficiently understood. To isolate these multi-factor processing signatures, alumina specimens incorporating concave and convex parabolic surfaces were synthesized via lithography-based ceramic manufacturing. Our design acts as a geometric control lens, ensuring that thermal shrinkage trends, slicing kinematics, and interfacial replication behaviors are clearly exposed and quantified under uniform boundary conditions. Following debinding and sintering, exploratory hot-pressing cycles were executed to evaluate gross profile transfer and surface inheritance on poly(methyl methacrylate) (PMMA) replicas. Quantitative laser scanning confocal microscopy confirmed successful gross curvature generation and revealed geometry-dependent post-sintering shrinkage trends. The convex inserts exhibited an average peak-to-valley (PV) error of $123.48 \pm 3.30 \mu\text{m}$ and an RMS error of $29.76 \pm 1.23 \mu\text{m}$, whereas the concave alumina inserts showed an average PV error of $137.98 \pm 5.80 \mu\text{m}$ and an RMS error of $34.68 \pm 1.20 \mu\text{m}$. The PMMA replicas also showed substantial form deviation, with an average PV error of $163.72 \pm 15.64 \mu\text{m}$ and RMS error of $27.37 \pm 2.03 \mu\text{m}$. Our work presents a route for producing near-net-shape ceramic mold-insert preforms that transforms complex processing variations into a predictable, mathematically addressable roadmap. A geometry-specific CAD pre-compensation can then be performed while the remaining precision gap can be selectively closed via targeted post-polishing depending on the desired optical application tier.

Keywords: digital light processing; ceramic 3D printing; ceramic mold inserts; rapid tooling; geometry-dependent roughness

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1. Introduction

Advanced optical systems increasingly rely on compact polymer components with aspheric, diffractive, microstructured, and freeform surfaces for imaging, sensing, artificial intelligence hardware, precision metrology, and digital-twin technologies, where computational models increasingly rely on high-quality visual data [1]. Polymers have become the material of choice for next-generation optical systems because they offer low-cost mass production, impact resistance, lightweight construction, and rapid prototyping capability compared with glass [2]. Most high-volume polymer optics are produced by polymer injection molding (PIM), in which the shape and surface condition of the mold insert are transferred directly to the final component [3,4]. As a result, the final optical performance is strongly governed by mold-insert form accuracy, surface finish, thermal stability, and replication fidelity. Small errors in insert geometry or surface texture can become form errors, aberrations, residual stresses, or birefringences in the molded polymer [5–7]. In practical optical replication, mold inserts are used as master surfaces for polymer lenses, light-guiding elements, micro-optical arrays, diffractive or Fresnel features, and transparent functional components produced by injection molding, injection-compression molding, embossing, or hot-press replication. In these applications, the mold insert not only defines the macroscopic shape of the polymer component but also directly governs the final optical surface quality. Therefore, two requirements are particularly critical: form accuracy and surface finish. Form error changes the designed sag profile and effective radius of curvature, leading to optical aberration or dimensional mismatch, whereas surface texture may be replicated as haze, scattering, gloss reduction, or roughness on the molded polymer surface. Previous reviews on optical mold-insert fabrication have emphasized that optical inserts require outstanding form accuracy and surface quality and that the suitable manufacturing route must be selected according to the required optical geometry and replication function [8]. These requirements provide the application basis for the present study, where geometry-dependent shrinkage affects the final curvature of the ceramic insert and layer-wise surface formation produces radial-position- and slope-dependent roughness.

Conventional optical mold inserts are produced by precision machining, electrical discharge machining, grinding, lapping, and polishing. These processes can achieve high surface quality, but are time-, material-, and cost-intensive [9]. Additive manufacturing (AM) is attractive for rapid prototyping and functional component production [10–12], particularly for mold-insert fabrication, because it can shorten design iteration, reduce material waste, create complex external and internal geometries, and enable conformal cooling channels that improve thermal control during molding. However, polymer-based AM inserts lack the thermal conductivity and mechanical durability required for precision molding, while metal AM inserts require substantial post-processing before optical use because their as-built surfaces and thermal properties do not meet optical-grade requirements [5,6,13–17]. These limitations motivate the search for alternative insert materials and fabrication routes.

Ceramic materials, particularly alumina, offer a promising alternative because they offer high hardness, excellent wear resistance, thermal stability, and low thermal expansion under repeated mechanical and thermal loading [7,18,19]. Lithography-based ceramic manufacturing, including digital light processing (DLP), can fabricate dense ceramic parts with fine features and complex shapes with high geometric precision that are difficult to obtain by conventional ceramic processing. Recent studies on DLP-printed alumina, zirconia, and ceramic cores show that layer thickness, build orientation, exposure conditions, debinding, and sintering temperature influence density, shrinkage, microstructure, mechanical properties, and surface roughness [20–33]. Beyond these material-processing studies, ceramic additive manufacturing has also begun to appear in precision

tooling and optical-interface applications. From a tooling perspective, Fraunhofer IKTS has reported ceramic mold inserts for small-series injection molding, including Al_2O_3 , zirconia-toughened alumina, SiSiC , and ceramic composites, produced by routes including ceramic additive manufacturing and integrated into modular mold bases [34]. These ceramic inserts were investigated for thermoplastic and thermoset molding conditions, demonstrating the practical interest in ceramic mold components for precision replication environments. However, this example mainly establishes the feasibility of ceramic mold components for injection molding and does not address optical-grade curved mold surfaces or polymer optical replication. From an optical-interface perspective, additively manufactured ceramics have also been investigated as functional optical or quasi-optical components. Kaděra et al. fabricated a wide-angle alumina Luneburg lens using lithography-based ceramic manufacturing for millimeter-wave localization, demonstrating the use of printed ceramic lens geometries in wave-control applications [35]. Lam et al. reported 3D-printed alumina as a millimeter-wave optical element and incorporated printed sub-wavelength anti-reflection structures directly onto the alumina surface, showing that ceramic AM can form functional optical-interface features [36]. More recently, 3D-printed alumina has also been investigated for terahertz lens applications [37]. These studies demonstrate that ceramic AM is progressing beyond structural ceramic parts toward functional optical and quasi-optical components in which geometry, surface structure, and material properties directly influence performance. However, these prior studies mainly concern ceramic tooling feasibility, dielectric or wave-control behavior, or directly printed optical components. They do not systematically evaluate DLP-printed ceramic surfaces as mold inserts for replicating curved polymer optical components.

The requirements for optical mold inserts are more restrictive than those for most structural ceramic parts, and two fundamental challenges arising from the ceramic AM process remain unresolved. First, dimensional accuracy is strongly affected by anisotropic shrinkage during debinding and sintering. Second, the layer-wise fabrication mechanism introduces staircase-type discretization of the surface geometry [20–22,29,38]. However, much less is known about how curved ceramic surfaces evolve during debinding and sintering, or how local curvature interacts with the staircase texture generated by layer-wise fabrication. This represents a critical gap because optical surfaces are defined by curvature: the same layer thickness can produce different surface textures depending on local slope, and the same global XYZ scaling may compensate for average shrinkage without correcting local geometry-dependent distortion in convex and concave features.

In this study, cylindrical specimens incorporating simplified concave and convex conic surfaces were fabricated by a lithography-based ceramic manufacturing process. The study quantified convex and concave form accuracy, evaluated geometry-dependent roughness caused by stair step surface formation, and examined geometry-dependent sintering distortion after global shrinkage compensation. PMMA components were also produced from the ceramic mold insert and compared in their as-molded state to assess moldability and surface transfer. The results show that DLP-printed alumina can reproduce curved mold-insert geometries and enable PMMA replication, but the as-sintered ceramic surfaces exhibit geometry-dependent roughness and opposite distortion trends in convex and concave profiles. These findings clarify the challenges that must be addressed before DLP-printed ceramics can be used for optical mold inserts and provide guidance for improving insert design, geometric compensation, surface finishing, and replication performance.

2. Materials and Methods

2.1. The Design of Conic (Aspheric) Surface Specimens

Cylindrical specimens incorporating conic surfaces were designed to provide a controlled framework for analyzing geometry-dependent surface formation. The axisymmetric geometry ensures that the surface profile varies solely with radial distance from the central axis, enabling consistent evaluation of surface characteristics along the radial direction.

The aspheric surfaces were defined using the conventional sag equation for rotationally symmetric conic surfaces [39], which describes the axial displacement $z(h)$ of the surface relative to the vertex as a function of radial coordinate h :

$$z(h) = \frac{h^2}{R_s \left[1 + \sqrt{1 - (1+k) \left(\frac{h}{R_s} \right)^2} \right]} + \sum_{n=2}^m A_{2n} h^{2n}, \quad (1)$$

where h is the radial distance from the optical axis, R_s is the vertex radius of curvature, k is the conic constant, and A_{2n} are the higher-order even aspheric coefficients describing polynomial deviations from the base conic surface. In this work, the higher-order coefficients were set to zero ($\sum_{n=2}^m A_{2n} h^{2n}$), such that the surface geometry was governed only by the base conic term. This simplification allows the manufacturability of a pure conic profile to be investigated without introducing additional geometric complexity from higher-order polynomial corrections.

A conic constant of $k = -1$ was selected, corresponding to a parabolic surface. Under this condition, the sag equation simplifies to

$$z(h) = \frac{h^2}{2R_s} \quad (2)$$

Based on Equations (1) and (2), the nominal geometry of the designed mold insert was established in SolidWorks 2025 with a diameter of 8 mm and a height of 4 mm. As shown in Figure 1, there are two distinct surface configurations: (i) a convex parabolic surface and (ii) a concave parabolic surface. In each case, the surface profile extended across the full aperture of the specimen to maintain consistent boundary conditions for comparison. The vertex radius of curvature was fixed at 10 mm, providing a controlled curvature range relative to the specimen size and enabling measurable variation in surface slope across the radial direction.

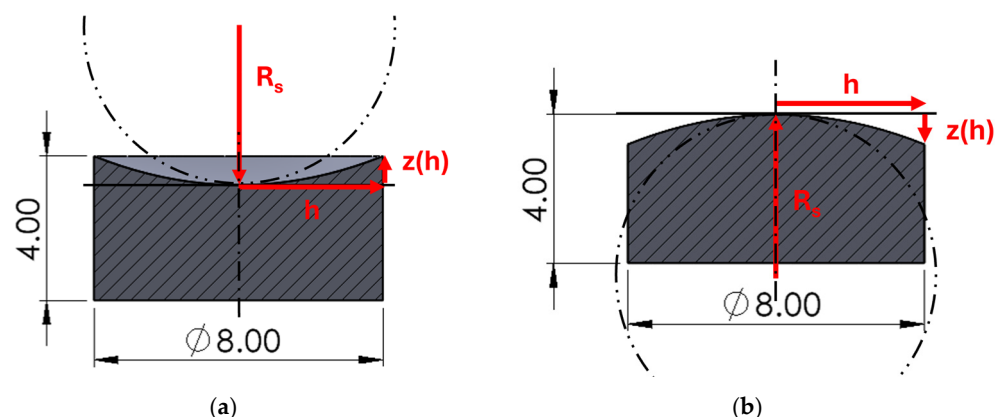


Figure 1. Cross-sectional design schematics of the parabolic mold inserts (dimensions in mm). (a) Sectioned view of the concave design profile. (b) Sectioned view of the convex design profile. For both designs, the axial displacement $z(h)$ along the mold height follows the parabolic function defined in Equation (1).

To compensate for shrinkage during thermal processing, scaling factors of 1.245 in the in-plane directions (XY) and 1.275 in the build direction (Z) were applied to fabrica-

tion. This approach minimizes global dimensional deviation while preserving process-induced effects associated with layer-wise fabrication and sintering. The geometries were implemented using equation-driven modeling to ensure consistency between the analytical surface definition and the fabricated specimens. Convex and concave specimens are denoted as “Cvx” and “Cnc”, respectively. Measurement directions along the central cross-sectional profile are indicated as horizontal (H) and vertical (V). Two independent specimens were analyzed for each geometry, denoted as Sample 1 and Sample 2. Accordingly, identifiers such as Cvx-H1 and Cnc-V2 refer to convex-horizontal Sample 1 and concave-vertical Sample 2, respectively.

2.2. Preparation of 3D-Printed Green Specimens

Alumina specimens were fabricated using a lithography-based ceramic manufacturing (LCM) system (CeraFab CF7500, Lithoz GmbH, Vienna, Austria) with digital light projection using a 460 nm light source. A commercial alumina slurry (LithaLox HP500, Lithoz GmbH, Vienna, Austria) containing high-purity alumina powder (Al_2O_3 , 99.99%) dispersed in an acrylate-based photopolymer binder system was used, with a solid loading of 49 vol.%, a density of 2.49 g/cm³. Printing was carried out with a layer thickness of 25 μm and an exposure energy of approximately 130 mJ/cm². After printing, the green bodies were cleaned using LithaSol 20 solvent (Lithoz GmbH, Vienna, Austria) with an airbrush system, and UV post-cured for 5 min prior to thermal processing.

Thermal debinding of the green specimens was conducted in a programmable furnace (FMJ-07/11, Facerom Intelligent Equipment Co., Hefei, China) using a multi-step heating profile (Figure 2a). The temperature increased from 25 °C to 75 °C at 0.2 °C/min and held for 18 h, followed by heating to 115 °C at 0.2 °C/min with a dwell of 66 h. It was subsequently raised to 205 °C at 0.4 °C/min and held for 22 h, then further increased to 430 °C at 0.4 °C/min and to 900 °C at 0.7 °C/min. The furnace was cooled to 600 °C and then to room temperature at rates of 0.6 and 1.2 °C/min, respectively. The resulting brown bodies were sintered in a high-temperature furnace (FJL-09/16, Facerom Intelligent Equipment Co., China), as illustrated in Figure 2b. The temperature increased from 25 °C to 200 °C at 2.9 °C/min, followed by heating to 600 °C at 0.7 °C/min and to 1150 °C at 1.5 °C/min. The temperature was then raised to 1600 °C at 0.8 °C/min and held for 2 h. After sintering, the furnace was cooled to 1200 °C at 0.8 °C/min and subsequently to 50 °C at 1.6 °C/min.

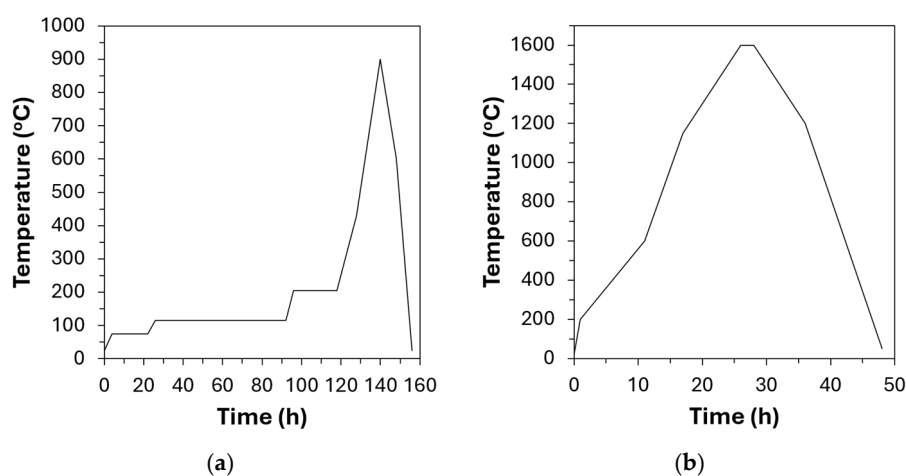


Figure 2. The heating profile of the 3D printed specimens. (a) The heating profile as recommended by the manufacturer for the debinding process of the 3D printed green bodies. (b) The heating profile as recommended by the manufacturer for the sintering process of the 3D printed specimens.

All printing and thermal processing conditions followed manufacturer-recommended profiles to ensure consistent layer formation, uniform debinding, and densification while minimizing defects. To track dimensional evolution during thermal processing, the external diameter and total height of the specimens were measured after printing, after debinding, and after sintering. The nominal final target dimensions were 8.00 mm in diameter and 4.00 mm in height. After applying the shrinkage compensation factors of 1.245 in the in-plane direction and 1.275 in the build direction, the corresponding scaled green-body design dimensions were 9.96 mm in diameter and 5.10 mm in height. The measured green-body dimensions after printing were 9.94 ± 0.017 mm in diameter and 5.14 ± 0.021 mm in height. After debinding, the dimensions decreased to 9.59 ± 0.030 mm in diameter and 4.89 ± 0.026 mm in height. After sintering, the final dimensions were 8.01 ± 0.010 mm in diameter and 3.98 ± 0.030 mm in height, which were close to the nominal target dimensions. The sintered LithaLox HP500 alumina processed under the recommended thermal route has a relative density of 99.4%. This corresponds to a nominal residual porosity of approximately 0.6%, indicating a highly densified alumina body after sintering. Together with the applied geometric scaling factors, these conditions provide a controlled baseline, enabling observed dimensional deviation and surface features to be attributed primarily to geometry-dependent effects and inherent sintering behavior.

2.3. Surface Characterization and Geometric Analysis

Geometric accuracy and surface characteristics of the fabricated specimens were evaluated using a laser scanning confocal microscope (LEXT OLS5100, Olympus, Tokyo, Japan) equipped with an Olympus MPLFLN 10× objective. For each measured surface, a three-dimensional height map was acquired over a scan area of 8.2 mm × 8.2 mm. The acquired height map had a resolution of 5490 × 5490 pixels. The same measurement settings were used for the alumina specimens and the PMMA replicas to ensure direct comparability. The methodology was designed to separate local surface texture from global form accuracy to enable analysis of geometry-dependent surface formation.

For each specimen, a central cross-sectional profile was extracted. Horizontal and vertical profiles were referenced to the vertex region and corrected for global tilt and vertical offset before comparison with the nominal parabolic profile. Global form accuracy was evaluated by comparing the corrected measured profile with the nominal design profile using peak-to-valley (PV) and root-mean-square (RMS) form error metrics. A least-squares parabolic fit was also applied to each profile to estimate the effective radius of curvature (R_{eff}) relative to the nominal 10 mm design to quantify curvature distortion in all specimens.

Local surface texture was evaluated after removing the fitted global parabolic form from the measured profile. The residual profiles were used to identify layer-induced features and calculate the arithmetical mean roughness (R_a) over selected radial evaluation windows, with scale-limiting smoothing steps to reduce waviness. The same workflow was applied to all specimens to ensure comparability.

Effective layer spacing was estimated from periodic features observed in the residual profile. Local curvature was assigned based on the fitted parabolic profile, and the roughness value was correlated against radial position (h) and local radius of curvature $\rho(h)$ to assess geometry-dependent staircase formation, noting that absolute roughness may also reflect processing effects such as slurry properties, exposure, cleaning, debinding and sintering.

2.4. PMMA Hot-Press Replication

Preliminary polymer replication was carried out to assess the ability of the sintered alumina insert to transfer its surface profile. A 2 mm thick PMMA blank was selected due to its optical transparency and suitability for thermal molding of optical components.

A three-piece steel mold assembly, comprising an upper punch, a cylindrical mold cavity and a bottom support, was used for hot-pressing (Figure 3). The cavity provided lateral confinement and coaxial alignment for the PMMA blank and the ceramic insert during heating and pressing. The bottom mold supported the ceramic insert, and the upper punch applied the forming load to the PMMA blank. In this configuration, the steel tooling defined the mechanical constraint and alignment of the replication stack, whereas the like surface profile was defined by the alumina insert.

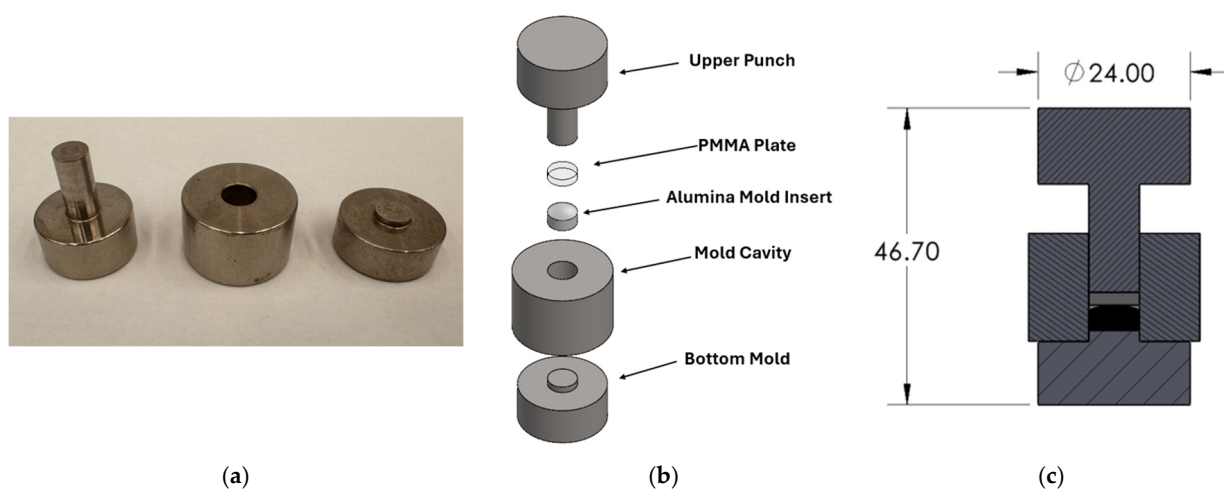


Figure 3. Steel mold components for PMMA hot-press replication. (a) Image of the steel mold components. (b) Schematic illustration of the mold assembly for hot press processing. (c) Sectioned view of the assembled mold with PMMA plate and alumina insert in mm units.

The convex alumina specimen served as the positive ceramic mold insert, producing a concave PMMA replica. Prior to molding, the ceramic insert and PMMA blank were cleaned to remove surface contamination. Replication was carried out at 160 °C in two stages: an initial contact stage without applied pressure for 15 min to allow thermal equilibration and softening of the PMMA, followed by pressing at 2 MPa for 15 min to promote polymer flow and profile transfer. The assembly was then cooled from 160 °C to 40 °C under constant pressure at an average cooling rate of 1.6 °C/min before mold release. The pressure was maintained during cooling to preserve contact between the softened PMMA and the alumina insert while the polymer passed through the temperature range where thermal contraction and viscoelastic recovery can influence residual stress, elastic recovery, and profile fidelity. Mold release was performed only after the assembly reached 40 °C to reduce thermally induced deformation during demolding. This stepwise loading approach minimized mechanical stress on the ceramic insert while allowing replication above the PMMA softening range.

After the mold released, the replicated PMMA concave surface was visually inspected and subsequently characterized. Profile fidelity and surface texture were compared with the ceramic insert to assess gross moldability and the extent of feature transfer, including layer-induced surface features.

PMMA concave specimens are denoted as “PCnc”, with measurement directions along the central cross-sectional profile indicated as horizontal (H) and vertical (V). Two replicates were analyzed for each geometry, denoted as Sample 1 and Sample 2. Accord-

ingly, identifiers such as PCnc-H1 and PCnc-V2 refer to PMMA concave-horizontal Sample 1 and PMMA concave-vertical Sample 2, respectively.

3. Results

3.1. Observation of As-Sintered Alumina Specimens

Both specimen geometries retained the intended cylindrical form after debinding and sintering, and no obvious macroscopic collapse or cracking was observed. This result confirms that the lithography-based ceramic manufacturing process could produce self-supporting alumina inserts with non-planar optical surfaces under the selected printing and thermal-processing conditions (Figure 4).

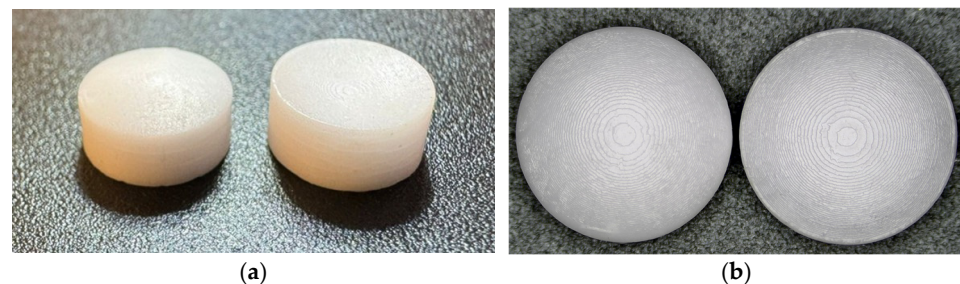


Figure 4. Optical images of the as-sintered DLP-printed alumina mold-insert specimens. The concave and convex specimens are shown in the left and right inset images, respectively. (a) Oblique view of the cylindrical alumina specimens after debinding and sintering. (b) Top-view image of the curved surfaces.

The optical images also show concentric ring-like features are present on the curved surfaces, particularly in top-view images. These terrace-like rings are attributed to the layer-wise discretization of the DLP process, in which a nominally continuous conic surface is approximated by successive planar layers. The presence of these visible steps suggests that staircase-related surface features were not fully removed by thermal treatments and are therefore expected to contribute to the measured surface roughness and to the surface quality transferred during polymer replication.

3.2. Surface Profile and Form Accuracy of the As-Sintered Alumina Specimens

The surface geometry of the printed specimens was characterized using laser scanning confocal microscopy. For each convex and concave geometry, central cross-sectional profiles were extracted in both horizontal and vertical directions from two independent samples. The measured surface profiles generally followed the nominal parabolic form, showing that the global curved shape was retained after printing, debinding and sintering. However, fitting the profiles to the design geometry also revealed measurable form errors and systematic curvature shifts, indicating that shape retention was incomplete even though the specimens remained macroscopically sound.

For the convex specimens, the form deviation $\Delta z(h)$ remained comparatively consistent across the four measured profiles. The peak-to-valley (PV) values ranged from 119.20 to 126.76 μm and root-mean-square (RMS) error ranged from 28.73 to 31.54 μm . The average PV and RMS values were $123.48 \pm 3.30 \mu\text{m}$ and $29.76 \pm 1.23 \mu\text{m}$, respectively, as summarized in Table 1. The fitted effective radius of curvature (R_{eff}) was $9.22 \pm 0.02 \text{ mm}$, corresponding to a negative deviation of $-7.78 \pm 0.20\%$ from the nominal 10 mm radius. The smaller fitted radius of the convex surfaces indicates a slight over-curvature after processing.

Table 1. Summary of form accuracy metrics for the printed convex specimen.

Samples	Cvx-H1	Cvx-V1	Cvx-H2	Cvx-V2	Mean $\pm$ SD
PV (μm)	125.21	126.76	122.76	119.20	123.48 $\pm$ 3.30
RMS (μm)	29.36	31.54	29.43	28.73	29.76 $\pm$ 1.23
R _{eff} (mm)	9.24	9.19	9.23	9.22	9.22 $\pm$ 0.02
% error	−7.57%	−8.05%	−7.72%	−7.76%	−7.78% $\pm$ 0.2%

The concave specimens showed a larger and opposite curvature deviation (Table 2). The PV values ranged from 129.94 to 142.42 μm , while their RMS errors ranged from 32.49 to 37.26 μm , with average values of 137.98 $\pm$ 5.80 μm and 34.68 $\pm$ 1.20 μm , respectively. The R_{eff} was 11.22 $\pm$ 0.07 mm, equivalent to a positive deviation of 12.22 $\pm$ 0.70% from the nominal radius. The larger fitted radius suggests systematic flattening of the concave surfaces.

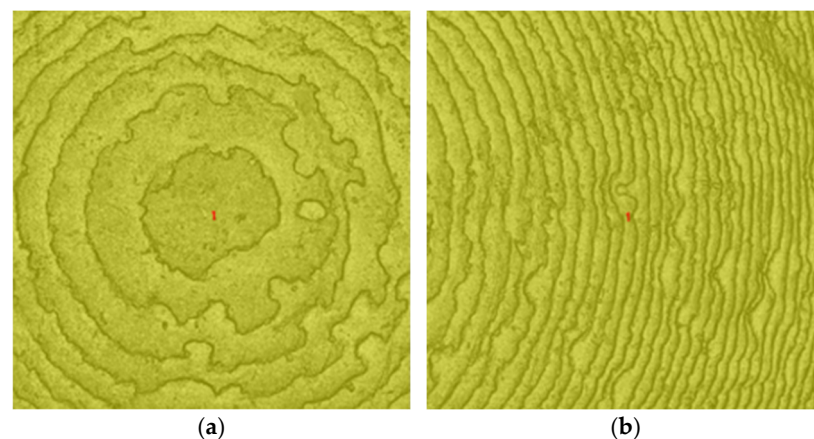
Table 2. Summary of form accuracy metrics for the printed concave specimen.

Samples	Cnc-H1	Cnc-V1	Cnc-H2	Cnc-V2	Mean $\pm$ SD
PV (μm)	142.42	142.04	129.94	137.54	137.98 $\pm$ 5.80
RMS (μm)	34.30	34.68	37.26	32.49	34.68 $\pm$ 1.20
R _{eff} (mm)	11.28	11.14	11.28	11.21	11.22 $\pm$ 0.07
% error	12.75%	11.37%	12.64%	12.09%	12.22% $\pm$ 0.7%

Taken together, the convex and concave results show that the dominant error was not random scatter between measurement directions, but a geometry-dependent curvature bias. Convex surfaces shifted toward over-curvature, whereas concave surfaces shifted toward flattening. The horizontal and vertical profiles within each geometry were nevertheless similar, suggesting good in-plane directional uniformity in the printing process. The larger PV and RMS errors measured for the concave specimens indicate that concave mold inserts are more sensitive to form loss under the present fabrication conditions.

3.3. Residual Profile and Surface Roughness Distribution of As-Sintered Alumina Specimens

Residual surface profiles were analyzed to isolate local surface features associated with the layer-wise fabrication process. The magnified surface profiles in Figure 5 show staircase-like transitions on both convex and concave specimens. The distance between adjacent transitions was measured as the effective layer thickness, t , which represents the residual layer signature expressed on the final sintered surface.



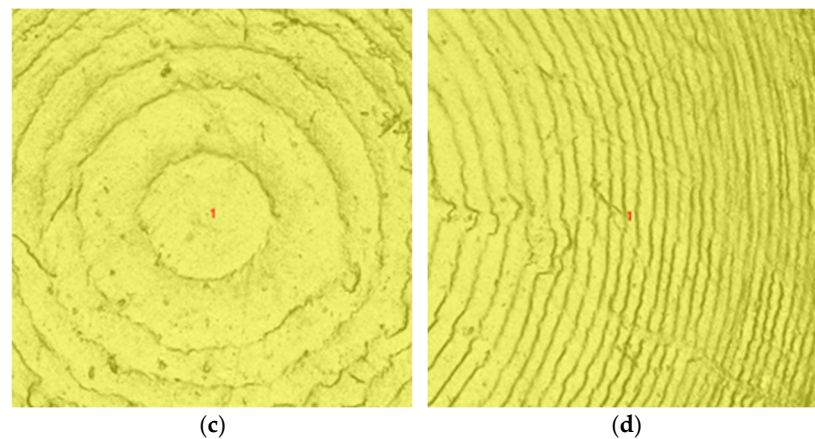


Figure 5. Magnified views of the local specimen surfaces over an area of 2.4 mm × 2.4 mm: (a) central region of the convex specimen; (b) peripheral region of the convex specimen; (c) central region of the concave specimen; and (d) peripheral region of the concave specimen. The red label “1” indicates the region of interest selected for printed-layer thickness measurement.

The measured values of t are summarized in Table 3. Across both geometries, the spacing between successive features was highly consistent, ranging from 19.59 to 19.62 μm on average. This narrow range indicates that the observed staircase features are linked to a repeatable layer-related mechanism rather than isolated surface defects. Minor differences between center and side regions are likely associated with local slope, shrinkage and measurement resolution.

Table 3. Summary of measured effective layer thickness (in μm) on the sintered specimens.

Samples	Sample 1— Central Region	Sample 1— Side Region	Sample 2— Central Region	Sample 2— Side Region	Mean $\pm$ SD
Convex	19.78	19.85	19.34	19.52	19.62 ± 0.24
Concave	19.61	19.35	19.73	19.66	19.59 ± 0.17

Following the identification of the effective layer thickness, the local surface texture was evaluated at discrete radial positions along the profile. The arithmetical mean roughness, R_a , was determined for both convex and concave specimens, and the corresponding local radius of curvature, $\rho(h)$, was calculated analytically for each measurement position. The results are summarized in Table 4. In this table, Cvx-1 and Cvx-2 denote the first and second convex alumina specimens, while Cnc-1 and Cnc-2 denote the first and second concave alumina specimens. Here, h represents the radial distance from the optical axis and is presented in mm.

Table 4. Local radius of curvature and surface roughness for convex and concave specimens.

Samples	Cvx-1		Cvx-2		Cnc-1		Cnc-2	
h (mm)	$\rho(h)$ (mm)	Ra (μm)	$\rho(h)$ (mm)	Ra (μm)	$\rho(h)$ (mm)	Ra (μm)	$\rho(h)$ (mm)	Ra (μm)
1	9.39 ± 0.03	1.98 ± 0.25	9.38 ± 0.02	2.37 ± 0.64	11.34 ± 0.08	1.41 ± 0.30	11.37 ± 0.03	1.64 ± 0.15
2	9.88 ± 0.02	2.60 ± 0.30	9.89 ± 0.01	2.93 ± 0.27	11.75 ± 0.08	2.07 ± 0.35	11.78 ± 0.03	2.04 ± 0.35
3	10.72 ± 0.02	3.08 ± 0.39	10.73 ± 0.00	3.27 ± 0.37	12.43 ± 0.07	3.37 ± 0.75	12.46 ± 0.02	3.06 ± 0.97

For both geometries, R_a increased from the vertex region toward the outer region of the profile. In the convex specimens, R_a increased from approximately 1.98–2.37 μm at $h = 1$ mm to approximately 3.08–3.27 μm at $h = 3$ mm. In the concave specimens, R_a increased from approximately 1.41–1.64 μm at $h = 1$ mm to approximately 3.06–3.37 μm at $h = 3$ mm. This trend indicates that roughness is not uniform over the curved surface but is affected

by surface geometry. Because the local surface slope increases toward the outer region of the parabolic profile, the layer-wise approximation of the continuous surface produces more pronounced staircase features at larger radial positions. Therefore, the roughness increase is interpreted as a geometry-dependent effect associated mainly with radial position, local slope, and residual staircase features. The local radius of curvature is reported as a geometric descriptor, but it is not treated as the direct cause of the roughness increase. The similar trend observed in both convex and concave specimens indicates preliminary consistency in the surface-generation behavior.

3.4. Characterization of As-Molded PMMA Replicas

PMMA replication was carried out using the convex alumina specimen as the positive ceramic mold insert. After mold release, the polymer component exhibited a concave surface on the contact side (Figure 6), confirming the expected geometric inversion from the convex ceramic insert to the PMMA replica.

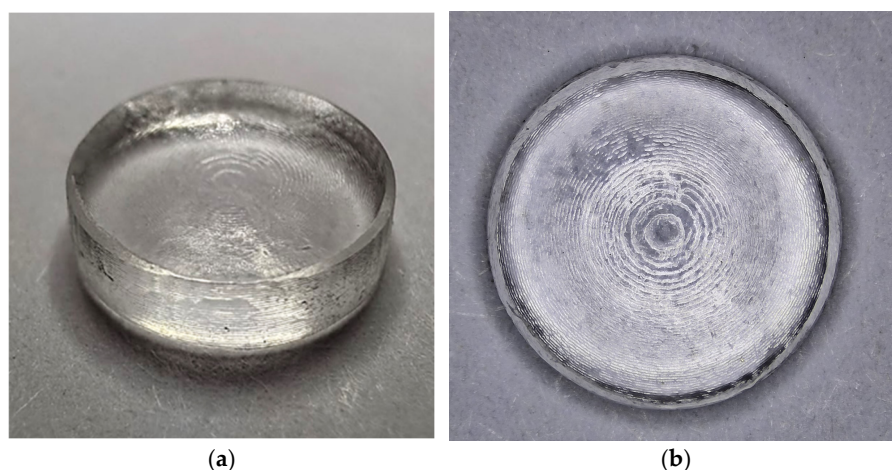


Figure 6. Optical images of the as-molded concave PMMA specimen. (a) Oblique view of the PMMA specimen. (b) Top view of the PMMA specimen.

The as-molded PMMA surfaces were also characterized using laser scanning confocal microscopy. The measured profiles followed the intended concave parabolic shape, confirming that the hot-press process was able to transfer the global curvature of the alumina insert into the polymer. Table 5 summarizes the form accuracy metrics of the as-molded PMMA replicas. The PV values ranged from 142.30 to 179.69 μm , with an average of $163.72 \pm 15.64 \mu\text{m}$, indicating noticeable form deviation across the replicated surface. In contrast, the RMS error remained within a narrower range of 24.70 to 29.01 μm , with an average value of $27.37 \pm 2.03 \mu\text{m}$. The relatively narrow RMS range suggests preliminary profile-transfer consistency, whereas the wider PV range suggests that local extreme deviations are more sensitive to local surface features or molding conditions.

The R_{eff} of the PMMA concave replicas was $9.17 \pm 0.07 \text{ mm}$, corresponding to an average deviation of $8.32 \pm 0.72\%$ from the nominal 10 mm radius. The low standard deviation of the fitted radius indicates preliminary profile consistency among the measured profiles in this exploratory replication test. Since the PMMA concave profile was replicated from the convex ceramic insert, the measured radius also reflects the curvature already present in the ceramic mold surface. Therefore, the replication demonstrates successful gross profile transfer from the insert while also showing that curvature error in the ceramic insert is inherited by the polymer replica.

Table 5. Summary of form accuracy metrics for as-molded PMMA replicas.

Samples	PCnc-H1	PCnc-V1	PCnc-H2	PCnc-V2	Mean $\pm$ SD
PV (μm)	164.77	168.10	142.30	179.69	163.72 $\pm$ 15.64
RMS (μm)	29.01	24.70	26.87	28.89	27.37 $\pm$ 2.03
R _{eff} (mm)	9.12	9.11	9.18	9.27	9.17 $\pm$ 0.07
% error	−8.75%	−8.95%	−8.22%	−7.34%	−8.32% $\pm$ 0.72%

The roughness of the as-molded PMMA concave replicas showed a clear dependence on radial position (Table 6). In this table, PCnc-1 and PCnc-2 denote the first and second concave as-molded PMMA Replicas. Near the central region of the profile, Ra remained relatively low. At the radial distance of 1 mm, the average Ra was approximately 2.93 μm , indicating smoother replication near the vertex where the local surface slope is smaller. As the radial distance increased, the roughness increased substantially. The average Ra increased to approximately 6.72 μm at the radial distance of 2 mm and 8.04 μm at the radial distance of 3 mm. This trend indicates that the outer regions of the molded concave profile were more strongly affected by surface texture transfer and local replication effects.

The local radius of curvature of the PMMA replicas also increased with radial distance, from approximately 9.3 mm near the radial distance of 1 mm to approximately 10.7 mm near the radial distance of 3 mm. This follows the expected geometric behavior of the parabolic profile. The simultaneous increase in Ra with radial position is consistent with the geometry-dependent staircase surface features observed on the ceramic insert. These results indicate that the hot-press replication process reproduced not only the global mold curvature but also surface-quality limitations associated with the printed ceramic insert, particularly in regions with higher local slope.

Table 6. Local radius of curvature and surface roughness for as-molded PMMA replicas.

Samples	PCnc-1		PCnc-2	
	h (mm)	$\rho(h)$ (mm)	$\rho(h)$ (mm)	Ra (μm)
1		9.28 $\pm$ 0.01	2.98 $\pm$ 0.62	9.39 $\pm$ 0.05
2		9.78 $\pm$ 0.01	6.48 $\pm$ 1.73	9.88 $\pm$ 0.05
3		10.64 $\pm$ 0.01	8.57 $\pm$ 4.27	10.73 $\pm$ 0.04

4. Discussion

4.1. Geometry-Dependent Sintering Distortion and Effective Radius Deviation

The results show that both convex and concave alumina specimens retained their overall parabolic surface geometry after DLP printing, debinding, and sintering. However, the fitted effective radius of curvature revealed systematic geometry-dependent distortion. The convex specimens exhibited a reduced effective radius of 9.22 $\pm$ 0.02 mm, corresponding to an over-curved surface relative to the nominal 10 mm design. In contrast, the concave specimens showed an increased effective radius of 11.22 $\pm$ 0.07 mm, indicating flattening of the concave profile. These opposite deviations suggest that the final shape was not controlled simply by uniform isotropic shrinkage, even though global scale factors were applied during specimen design.

The selection of an axisymmetric, highly symmetrical cylindrical substrate for both the convex and concave specimens serves as a critical geometric control framework in this study. As a cylinder possesses uniform theoretical boundary conditions, any spatial deviations or non-uniform thermal shrinkage during debinding and sintering are not masked by geometric complexity, allowing multi-factor processing signatures to be cleanly isolated and quantified. The observed opposite radius deviations, where the convex profile undergoes over-curvature and the concave profile undergoes systematic flattening, point

to a complex coupling between local surface topology and macroscopic densification kinetics.

A proposed mechanism for this behavior is illustrated in Figure 7. Geometry-dependent peripheral shrinkage imposes localized inward physical constraints on the active surface zones. While the rigorous microstructural mapping of localized density gradients or internal porosity lies outside the scope of this preliminary phase, the highly controlled symmetry of our specimens provides a reliable empirical baseline that captures these multi-factor processing inputs. The true technological significance of capturing these precise geometric signatures is that they transform unpredictable ceramic processing variations into quantifiable, systematic trends. By establishing this predictable geometric baseline, these multi-factor material and thermal deviations can be directly absorbed and neutralized via targeted, geometry-specific CAD pre-compensation in the 3D-printing process, bypassing the need for extensive traditional machining modification.

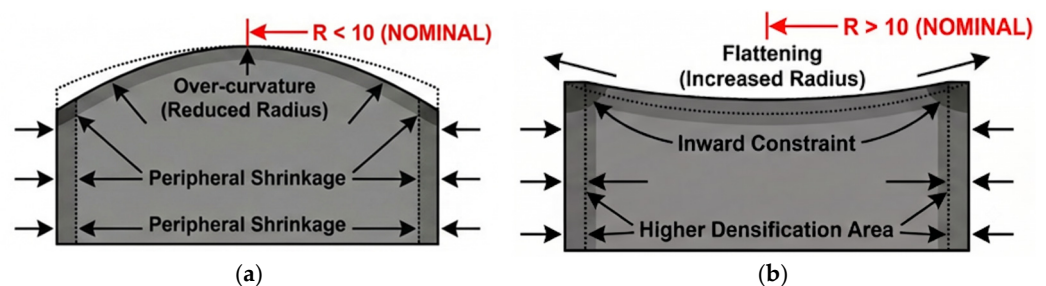


Figure 7. Proposed schematic illustration of geometry-dependent peripheral shrinkage and its effect on curvature deviation. (a) Convex specimen. (b) Concave specimen.

The concave specimens also exhibited larger PV and RMS form errors than the convex specimens, indicating that concave geometries were more sensitive to form loss under the present process conditions. This may arise because concave surfaces contain an inward-facing geometry that is strongly affected by local shrinkage, support from the surrounding material, and possible non-uniform densification across the aperture. Although the horizontal and vertical profiles were relatively consistent within each specimen type, confirming good in-plane directional uniformity, the difference between convex and concave results demonstrates that geometry-specific compensation is required for curved ceramic mold inserts.

These findings highlight an important limitation of using a single global scaling factor for DLP-printed ceramic optical inserts. Global compensation can account for average shrinkage, but it cannot fully correct local geometry-dependent deformation. For high-precision mold inserts, the compensation strategy should therefore include geometry-dependent correction of sag depth and radius, possibly through iterative CAD pre-compensation based on measured post-sintering profiles. Improved thermal uniformity during sintering may also reduce this distortion. Alternative approaches such as optimized packing, modified support conditions, slower heating profiles, or volumetric heating methods such as microwave sintering may help reduce differential densification, although these routes require further experimental validation.

4.2. Geometry-Dependent Roughness and Staircase Formation

The residual profile analysis indicates that surface roughness was strongly dependent on radial position. For both convex and concave alumina specimens, R_a was lowest near the vertex and increased toward the outer regions of the profile. This trend is consistent with staircase formation on curved surfaces produced by layer-wise DLP fabrication. Near the center of a parabolic surface, the local slope is relatively small, so the printed

layers approximate the target geometry more closely. Toward the edge of the aperture, the local slope increases, causing each layer to intersect the intended continuous surface more visibly. As a result, terrace-like features become more pronounced and the measured roughness increases.

The measured effective layer thickness was approximately 19.6 μm for both convex and concave specimens. This value confirms that a repeatable layer-related surface signature remained visible after sintering. Because the effective layer spacing was smaller than the nominal green-layer height, it is also consistent with shrinkage in the build direction during thermal processing. The persistence of this periodic feature indicates that sintering reduced the dimensions of the layer structure but did not eliminate the staircase morphology.

However, the measured micrometer-scale R_a values should not be attributed to staircase geometry alone. Other process-related factors may also contribute to the final roughness, including ceramic particle size and packing, slurry rheology, exposure conditions, cleaning efficiency, binder removal, and grain growth during sintering. The present results directly demonstrate a radial roughness trend and a residual layer signature, but they do not isolate the relative contribution of each processing factor. Therefore, staircase formation should be interpreted as the dominant geometric explanation for the positional trend, while the absolute roughness magnitude likely reflects the combined effect of layer discretization and ceramic processing.

4.3. Review Between Form Accuracy and Surface Roughness

The results reveal two different but related limitations of DLP-printed alumina mold inserts. The first is global form error, represented by PV error, RMS error, and effective radius deviation. This error determines whether the printed and sintered insert reproduces the intended optical geometry. The second is local surface texture, represented by R_a and residual layer features. This determines whether the surface is suitable for direct replication or requires post-processing.

These two limitations occur at different length scales and therefore require different correction strategies. Form error is mainly associated with sintering distortion and geometry-dependent shrinkage, so it may be improved through CAD pre-compensation, optimized part geometry, modified sintering schedules, and better thermal uniformity. Surface roughness is mainly associated with layer-wise discretization and local surface formation, so it may require finer layer thickness, improved exposure control, optimized slurry formulation, or mechanical finishing such as grinding, lapping, and polishing.

To place these values in the context of optical manufacturing, it is important to note that the allowable thresholds for R_a , PV, and RMS error depend on the optical design, wavelength range, numerical aperture, replication process, and applications. For instance, high-precision imaging applications (such as smartphone optics or camera lenses) operating in the visible light spectrum demand ultra-precision tooling standards ($R_a < 10\text{ nm}$), while an aspheric optical mold-insert example showed PV form deviation below 1 μm [8]. These values provide a practical benchmark for the precision gap between optical mold-insert requirements and the present as-sintered DLP-printed alumina inserts.

Compared with these benchmarks, the present as-sintered alumina inserts show much larger form deviations. The convex alumina inserts exhibited an average PV error of $123.48 \pm 3.30\text{ }\mu\text{m}$ and RMS error of $29.76 \pm 1.23\text{ }\mu\text{m}$, whereas the concave alumina inserts exhibited an average PV error of $137.98 \pm 5.80\text{ }\mu\text{m}$ and RMS error of $34.68 \pm 1.20\text{ }\mu\text{m}$. The PMMA replicas showed an average PV error of $163.72 \pm 15.64\text{ }\mu\text{m}$ and RMS error of $27.37 \pm 2.03\text{ }\mu\text{m}$. A mold insert can therefore retain its general parabolic shape. For optical-grade use, geometry-specific CAD compensation, form correction, and subsequent finishing such as precision grinding, lapping, and polishing will be required.

4.4. Replication Behavior of PMMA Components

The PMMA molding results further clarify the practical implications of the ceramic insert quality. The convex alumina inserts successfully produced a concave PMMA replica, confirming that the hot-press process transferred the global mold geometry into the polymer. The PMMA replicas showed repeatable profile formation, with an effective radius of 9.17 ± 0.07 mm and RMS error of 27.37 ± 2.03 μ m. The low variation between measured profiles indicates that the replication process was reasonably stable.

However, the PMMA replicas also inherited the curvature deviation of the ceramic insert. Since the polymer surface was molded directly from the convex alumina surface, any radius error in the ceramic mold was transferred into the PMMA component. This confirms that the form accuracy of the final polymer replica is limited by the form accuracy of the ceramic insert. Therefore, improving the ceramic insert geometry is essential if DLP-printed alumina molds are to be used for precision polymer optical components.

The surface roughness results reveal another critical limitation for curved optical components. The PMMA surface roughness increased with radial distance, from approximately 2.93 μ m near the radial distance of 1 mm to approximately 8.04 μ m near the radial distance of 3 mm. This trend follows the radial-position- and local-slope-dependent roughness observed on the alumina specimens, indicating that layer-related surface features on the ceramic mold were transferred to the polymer surface. However, the PMMA roughness should not be interpreted as a simple one-to-one inheritance from the ceramic mold. The consistently higher Ra values measured on the PMMA replicas indicate that the ceramic surface features may have been amplified during molding, cooling, and demolding. Several polymer-related effects may contribute to this amplification, including thermal shrinkage during cooling, viscoelastic or elastic recovery after pressure release, local adhesion or friction at the ceramic–PMMA interface, and tensile or shear deformation during mold separation [40]. These findings demonstrate that DLP-printed alumina inserts can replicate gross polymer geometry, but the as-sintered surface quality is insufficient for high-precision optical replication without further finishing. In practical terms, the ceramic insert must first be corrected for both form and roughness before it can produce optical-quality PMMA components.

4.5. Implications for DLP-Printed Alumina Mold Inserts

Overall, the results support the feasibility of DLP-printed alumina as a near-net-shape manufacturing route for ceramic mold inserts. Alumina offers high hardness, thermal stability, and wear resistance, while DLP printing enables the fabrication of curved mold geometries that would be difficult or time-consuming to produce directly by conventional ceramic machining. The successful formation of both convex and concave specimens, together with the successful molding of PMMA replicas, demonstrates the potential of this approach.

From a material-selection viewpoint, alumina is attractive for optical mold-insert preforms because it combines high hardness, wear resistance, thermal stability, chemical inertness, and relatively low thermal expansion. These characteristics are beneficial for preserving mold geometry and surface condition during repeated thermal and mechanical contact with polymer materials. Compared with polymer AM inserts, alumina offers much higher thermal and mechanical stability; compared with metal AM inserts, DLP-printed ceramics can provide finer slurry-based feature formation and avoid melt-pool-related roughness, although both material classes still require post-processing for optical-grade surfaces. In the specific context of PMMA hot-press replication, alumina is therefore most suitable as a durable near-net-shape ceramic preform that can withstand moderate molding temperature and compressive loading before final finishing. However, the use of alumina also requires careful design because alumina is brittle and has limited fracture

toughness compared with metals. Ceramic mold inserts should therefore be used under predominantly compressive loading, with sufficient mechanical support from the surrounding mold assembly, avoidance of sharp corners, reduced stress concentration at the insert edge, controlled demolding force, and a suitable release strategy. For higher-pressure molding or long-cycle production, alternative ceramic choices such as zirconia, zirconia-toughened alumina, silicon nitride, or coated ceramic inserts may be considered when higher fracture toughness, thermal-shock resistance, or demolding robustness is required. Thus, DLP-printed alumina should be regarded as a promising candidate for near-net-shape optical mold-insert preforms, while the final material choice should balance formability, polishability, thermal stability, fracture resistance, and molding load.

In addition, the current as-sintered surfaces do not yet meet the requirements of precision optical mold inserts. The main limitations are systematic curvature distortion, residual staircase features, and micrometer-scale roughness. These limitations imply that post-processing remains necessary. Suitable finishing routes may include precision grinding, lapping, polishing, ultrasonic-assisted machining, laser-assisted machining, or diamond-based ceramic finishing. The measured roughness values suggest that several micrometers of surface material may need to be removed to eliminate staircase-dominated texture, while the PV form errors above 100 μm indicate that form correction may require either larger stock allowance or prior CAD compensation.

The difference between convex and concave distortion also has practical consequences for finishing strategy. A convex surface that becomes over-curved may be corrected by selective material removal, depending on the target profile and fixturing method. A concave surface that becomes flattened may be more difficult to correct by polishing alone, because restoring sag depth requires selective removal near the outer aperture while maintaining a smooth continuous curvature. This reinforces the need for geometry-specific design compensation before sintering.

Future work should therefore focus on three areas: improving sintering uniformity to reduce geometry-dependent distortion, optimizing printing parameters to reduce staircase formation, and developing post-processing strategies tailored to convex and concave ceramic surfaces. With these improvements, DLP-printed alumina could become a useful route for producing durable ceramic mold insert preforms for polymer optical replication.

5. Conclusions

This study evaluated DLP-printed alumina as a near-net-shape ceramic mold-insert preform for curved PMMA replication. Convex and concave alumina specimens retained the intended gross parabolic geometry after printing, debinding, and sintering, and the convex alumina insert was able to generate a concave PMMA replica by hot pressing. These results indicate that DLP-printed alumina has potential as a rapid route for producing ceramic preforms with curved mold-insert geometries. The alumina specimens showed PV form errors above 100 μm , RMS errors of approximately 29.76–34.68 μm , and micrometer-scale roughness. The PMMA replicas also showed substantial form error and higher roughness than the corresponding ceramic insert. This approach transforms complex processing variations, such as asymmetric curvature distortions between convex and concave profiles and localized staircase roughness on steep peripheral slopes, into a highly predictable, mathematically addressable roadmap. Our findings suggest that global isotropic shrinkage compensation alone is fundamentally insufficient for curved ceramic optics, but isolating these geometry-dependent behaviors provides the necessary engineering foundation for advanced CAD pre-compensation loops during the printing phase. For optical-grade applications, further surface finishing, such as precision grinding, lapping, and polishing, is required. Overall, this work demonstrates the exploratory feasibility of DLP-printed alumina for producing near-net-shape ceramic mold-insert pre-

forms. Future work could combine geometry compensation, optical finishing, and material selection strategies to meet application-specific optical tolerances.

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