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Monolithic Glass Forming Using Laser Heated Sculpting

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Abstract

Additive manufacturing of optics is highly desirable across various applications due to its ability to create complex features, accommodate a wide range of materials, and incorporate digital fabrication, though it remains limited in form precision. This paper presents a novel method of digital glass forming that utilizes localized heating and glass redistribution to create intricate geometries. In this process, glass substrates are positioned relative to a fixed CO_2 laser beam using precision 4-axis CNC stages. A stationary graphite forming tool applies stress to the laser-heated region displacing the glass via controlled plowing. This approach is studied for shaping simple optical forms. There are lower compositional changes in the glass than when it is processed at the temperatures associated with melting. A simple model is studied to understand the effects of temperature, forming speed, and number of passes relative to the final geometry.

1. Introduction

High-precision optics are critical across various applications, with lenses ranging from rotationally symmetric aspheric designs to freeform Alvarez lenses.[1] These optical components require strict tolerances, often necessitating form accuracy within 50 nm and surface roughness below 1 nm.[2] Current commercial manufacturing techniques, such as single-point diamond turning and magneto-rheological finishing, can achieve form accuracies of $\lambda/8$ and surface roughness on the sub-nanometer scale.[2] However, producing lenses with intricate geometries, such as aspheric lenses, typically involves multi-stage grinding and polishing processes, which are both time-intensive and costly.

Glass additive manufacturing has gained significant attention for its ability to produce intricate glass structures.[3–6] One such method, Digital Glass Forming (DGF), has shown promise for optics manufacturing.[3] DGF operates by selectively heating filament-fed glass relative to glass substrates, using CNC-based forming and shaping techniques. This process facilitates the fabrication of complex geometries through precise path planning and layer-by-layer deposition, making it particularly suitable for producing optics with non-standard shapes.[3] During the DGF process, glass is either reflowed in situ or post-processed to achieve optical-grade surface roughness.[3] However, a key challenge lies in the reflow step, which often compromises the form accuracy of the optical components. In contrast, subtractive manufacturing techniques maintain excellent machining precision but are limited in their ability to handle complex geometries. There is a need for hybrid manufacturing for lens making and a technique compatible with the DGF.

Direct machining of glass for precision shaping is difficult due to its brittle nature, which limits the use of simple, single-step methods like those used in metal forming.[7][8] Traditionally, glass artisans heat glass to its softening point, where it becomes viscous enough and shape it to form intricate artworks. At the softening point, where the glass becomes sufficiently viscous, forming tools can be employed to perturb, drag, or reshape the material, effectively "sculpting" it. A forming tool with a suitable cross-section can be used as a plow to clear out viscous glass and conformally shape complex shapes such as lenses. This is the basis of laser-heated sculpting.

This paper introduces a novel manufacturing approach where a CO_2 laser selectively heats glass to lower its surface viscosity, allowing a forming tool to deform the softened material. Using CNC stages, the tool carves out desired shapes in the melt pool. A conceptual model is presented that examines key parameters such as temperature, dragging speed, number of passes, and plow forces, and their effects on shaping accuracy. As a proof of concept, a simple cylindrical lens was fabricated. Laser-heated sculpting offers potential for precision shaping, enabling hybrid manufacturing that combines the complex form capabilities of DGF with the accuracy of the sculpting process.

2. Conceptual Model

Viscosity reduction in glass due to localized heating to high temperatures allows bulk deformation from applied stress without causing brittle fracture. When a forming tool is plunged into laser-heated glass maintained at Temperature, T with force, F to a depth of cut, Δz, deformed glass is dragged to the sides and endpoint, and a sculpted depth of h is achieved. If the substrates were moved at a velocity, v against the forming tool, h will be a function of F, T, and v as shown in equation 1. The schematic of the conceptual model is shown in Fig 1a.

$$h = f(F, T, v) \tag{1}$$

The error between the sculpted depth and the applied depth of cut is equal to the elastic deformation of the tool. The error, ε is defined in Equation 2.

$$\varepsilon = h - \Delta z \tag{2}$$

With multiple passes, the elastic deformation of the tool decreases due to reduced deformation volume, and eventually, the sculpt pass conforms to the assigned depth of cut. Equation 3 holds for multi-pass sculpting.

$$\varepsilon \to 0, n \to \infty \tag{3}$$

The applied force on the substrate dictates the extent of plastic deformation in glass. Excessive stress can lead to brittle fractures. The applied force, F, can be modeled using a force-spring system, where the combined stiffness of the forming tool and CNC stages is in series with the stiffness of the glass. Localized heating reduces the glass viscosity, introducing a damping effect that can be modeled using a Maxwell Spring system in series with the tool and stages. The force during the process is a function of the applied depth of cut, Δz, and in this study, force control is managed by adjusting Δz.

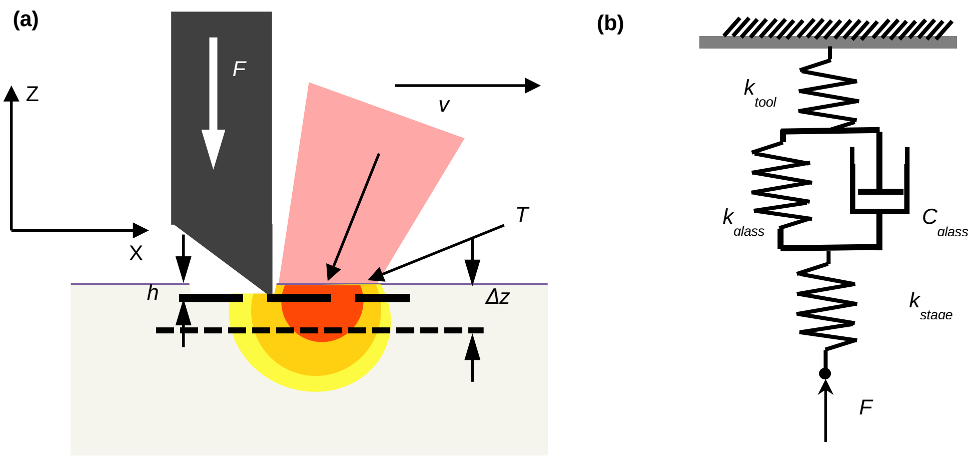

Fig 1. (a) Cartoon showing the conceptual model of laser-heated sculpting. (b) Force-spring system for relating force to depth of cut in the system.

3. Experimental Methods

3.1 Experimental Setup

3.1.1 Laser Processing Setup

The laser-heated sculpting setup is shown in Fig 2. Borosilicate glass substrates (2”×3”×1/8”) were mounted on 4-axis CNC stages (ANT130XY, ATS150, and ANTI130R) from Aerotech. A CO_2 laser (λ = 10.6 μm) with a maximum power of 120 W was used to irradiate and heat the glass substrates. The substrate was placed on a heater plate capable of maintaining temperatures up to 550°C to prevent thermal shock during the sculpting process. An Optris PI 640i thermal camera was positioned overhead for in-situ temperature monitoring. A closed-loop temperature control system, integrated with the thermal camera and A3200 controllers, ensured a constant temperature during sculpting. Additionally, an in-plane visual camera was used to monitor elastic deformation of the forming tool throughout the process.

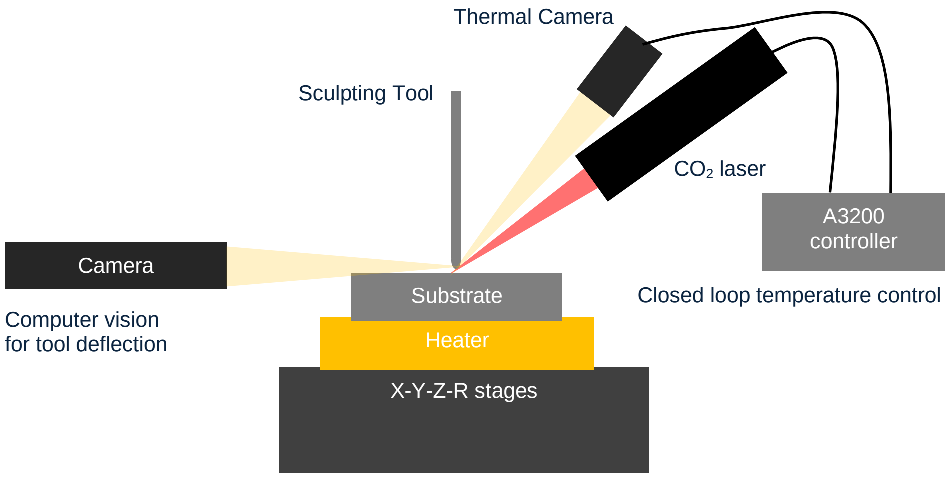

Fig 2. Schematic of the laser-heated sculpting setup

3.1.2 Sculpting Tool

The sculpting tool is mounted perpendicular to the glass substrate, initially making contact with the top surface under zero-force conditions. Graphite rods with a diameter of 10 mm (McMaster) were used to fabricate the sculpting tool. Fig 3 illustrates the sculpting tool and its cross-section.

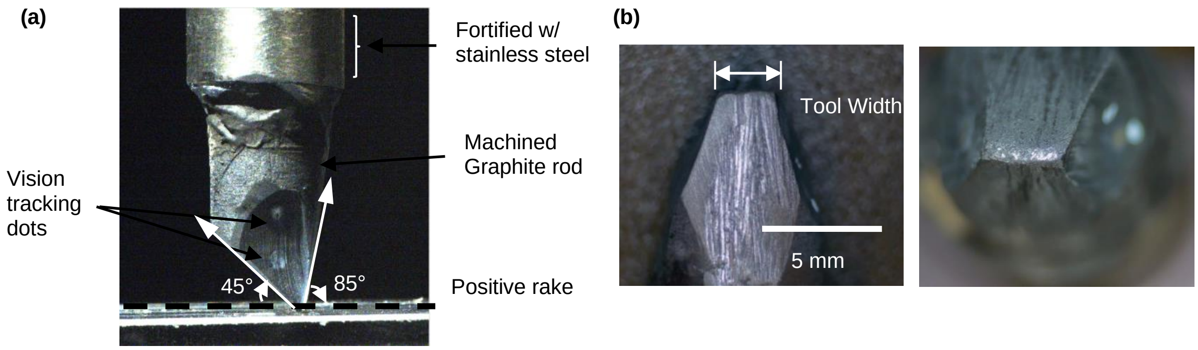

Fig 3. a. In-plane view of the sculpting tool and b. images showing cross-section of the tool tip

The graphite rod was ground to achieve a positive rake angle of 85° and a clearance angle of 45° in the vertically mounted configuration. The tip was shaped to a line with a minimum thickness and a width of 5 mm. To enhance rigidity, a stainless-steel sleeve with a 10-mm internal diameter and a 12.5-mm external diameter (304 stainless steel, McMaster) was added. The tool was secured within the stainless steel collar to reduce compliance during the sculpting process. Additionally, the flank of the tool was marked with high-temperature white paint to facilitate tracking of deflection.

3.2 Experimental Procedure

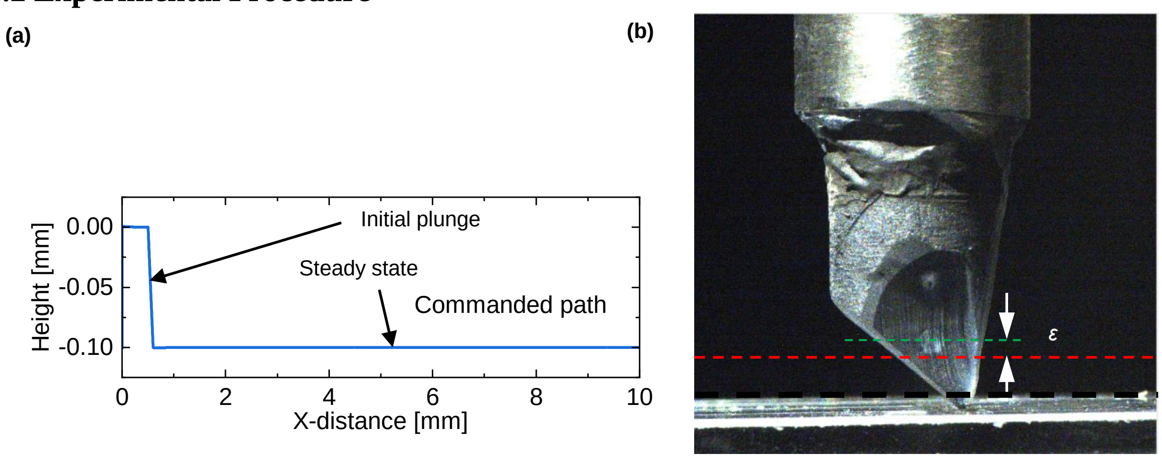

Fig 4. a. Commanded path for the experimental procedure b. in-plane view of the sculpting tool showing datum and deflection

Using CNC stages, glass substrates were moved relative to the CO_2 laser and the sculpting tool while pushing against it for a commanded depth of cut. A laser spot, Ø = 5 mm, irradiated glass substrates, leading the sculpting tool by 5 mm along the CNC path. A simple path was used for model validation with a linear segment followed by a 0.1 mm depth of cut tool plunge and a linear segment at 0.1 mm. This is shown in Fig 4a.

The laser beam is activated and allowed to dwell until a steady-state temperature is reached before starting the sculpting path. This temperature is maintained throughout the process using closed-loop temperature control. During the sculpting path, the elastic deflection of the tool is monitored with the in-plane camera, which tracks vision-marked dots relative to the datum, as illustrated in Fig 4b.

4. Results and Discussion

4.1 Effects of Temperature and Scan Speed

The steady-state temperature was varied along with the scan speed for the path shown in Fig 4(a). Elastic tool deflection, ϵ, was monitored during the steady-state path using the in-plane camera and vision tracking dots. ϵ was normalized with Δz and plotted as a function of temperature (T) and scan speed (v), as shown in Fig 5.

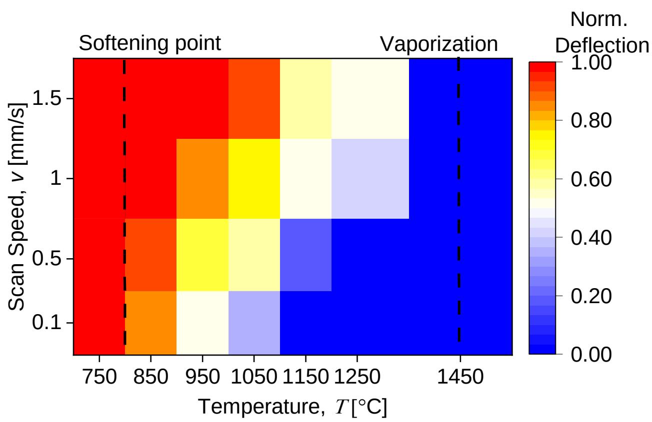

Fig 5. Plot of elastic tool deflection at steady state as a function of the temperature and scan speeds

The softening point of Borosilicate glass is around 800 °C below which the sculpting tool experiences full deflection or deformation isn't observed on the substrate. Above 1400 °C, vaporization was observed. The non-trivial ablation of the material's top surface results in zero tool deflection but renders the sculpting process non-deterministic volumetric losses result in alteration of the sculpted profile. Between 800-1400 °C, the increase in surface temperature results in lower tool deflection or improved sculpting accuracy as the viscosity is sufficiently lowered at high temperatures allowing lower forces to deform and displace glass. Slower scanning speeds also resulted in reduced tool deflection as slow speeds allow longer laser dwell per spot increasing volumetric heat transfer and reducing viscosity in bulk glass.

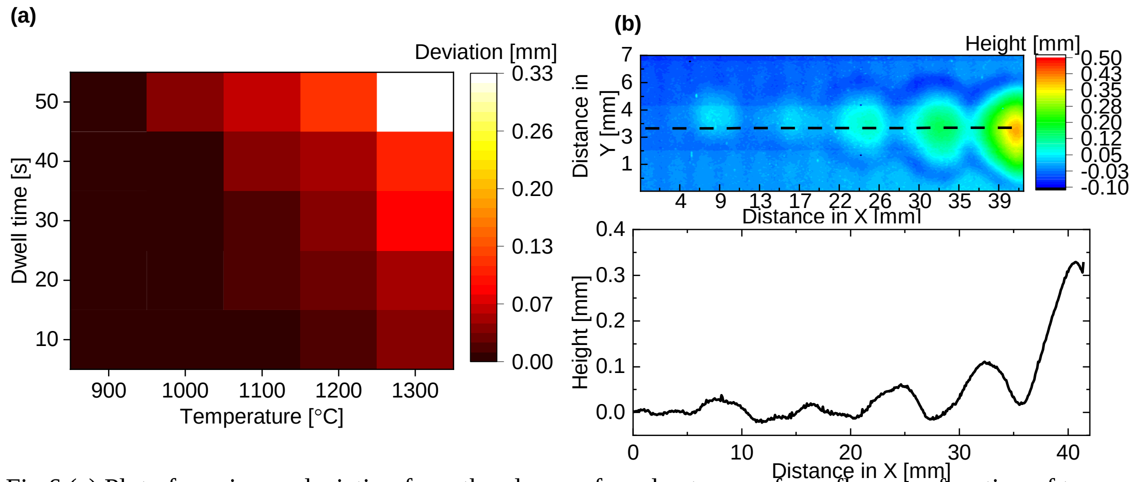

Fig 6 (a) Plot of maximum deviation from the glass surface due to zero-force flow as a function of temperature and dwell time. (b) Surface map of features sculpted at 1300°C with different dwell times, including the cross-section of the machined features.

It should be noted that while higher temperatures and slower scan speeds generally reduce tool deflection, this does not always equate to improved sculpting accuracy. At elevated temperatures, localized heating can cause glass to exhibit zero-force flow behavior, leading to material accumulation or "balling up" around the laser spot upon cooling. This phenomenon can result in significant deviations from the intended glass surface. Fig 6.a. plots these deviations as a function of temperature and dwell time for the laser spot. Fig 6.b. presents a surface map and line-scan cross-section for sculpting at 1300°C with varying dwell times. The surface map was captured using a VIEW benchmark metrology microscope, illustrating the effects of temperature and dwell time on the sculpted features.

4.2 Effects of Tool Width or Applied Stress

Tool deflection studies were conducted for various tool widths using the sculpting path shown in Fig 4a. The sculpting was performed at a scanning speed v = 0.5 mm/s and a commanded depth of cut Δz = 0.1 mm. The tool deflection at steady state was measured at different temperatures for several tool widths, as illustrated in Fig 7.

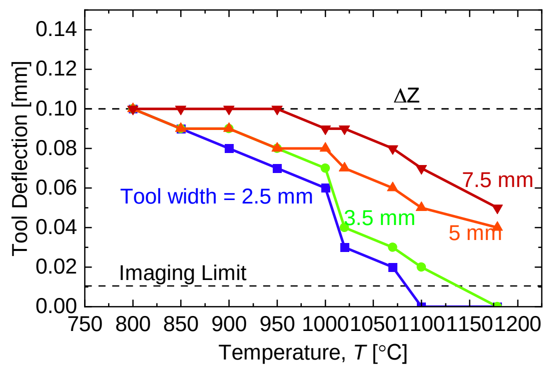

Fig 7. Plot showing the steady-state tool deflection at various temperatures for sculpting tools with different widths.

At the softening point of borosilicate glass, around 800 °C, full deflection was observed. Beyond this temperature, it was noted that tools with wider cross-sections exhibited higher tool deflection as a function of temperature. For each temperature point, tools with narrower widths demonstrated lower deflection and, consequently, higher accuracy in the sculpted profile. This phenomenon occurs because reducing the tool width decreases the cross-sectional area in contact with the glass, resulting in increased applied stress for the same amount of force (depth of cut).

4.3 Convergence to Zero Error

The path shown in Fig 4a was sculpted using multiple passes. A temperature of 1000 °C, a scan speed of 0.5 mm/s, and a depth of cut (Δz) of 0.1 mm were employed with a sculpting tool of 2.5 mm width. Fig 8a illustrates the tool deflection both at steady state and during the initial plunge, plotted as a function of the number of passes.

With multiple passes, the tool deflection is reduced, improving sculpting accuracy. This improvement is attributed to the decreased force required as the finite volume of glass is progressively deformed and displaced in each pass until the desired depth of cut is achieved.

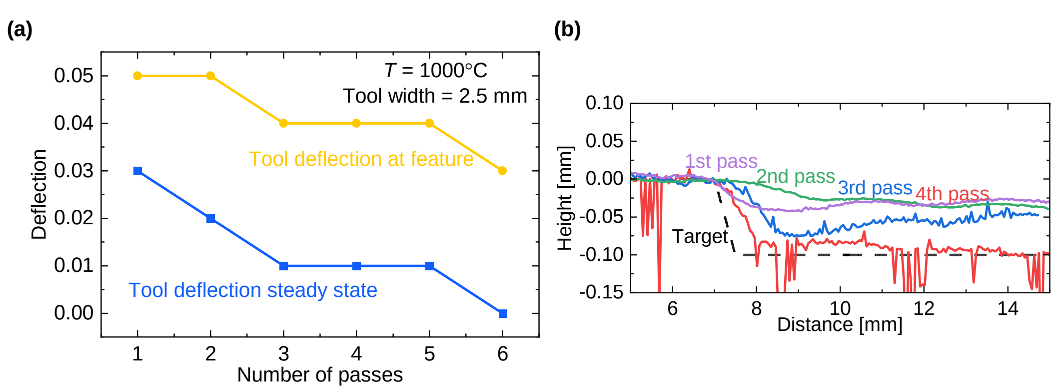

Fig 8a. Tool deflection as a function of the number of passes and the cross-section of the profile at each sculpting pass.

4.4 Sculpting Cylindrical Lens

Laser-heated sculpting was employed to create a cylindrical lens with a profile featuring a radius of curvature of 5 inches and an aperture of 14 mm. The sculpting path was adjusted to form a half-lens profile by making multiple passes, each with a 0.1 mm depth of cut to achieve zero error. The process utilized a temperature of 1000 °C, a scan speed of 0.5 mm/s, and a 2.5 mm wide sculpting tool. The lens profile and the corresponding path plan are illustrated in Fig 9 (a) and (b), respectively. The half-lens profile was sculpted, followed by a linear section to remove excess material along the Y-axis. This process was repeated along the X-axis to achieve the desired length. A stepover distance of 1.5 mm was selected, with each subsequent pass staggered by 0.75 mm to minimize scallop height resulting from glass displacement around the tool.

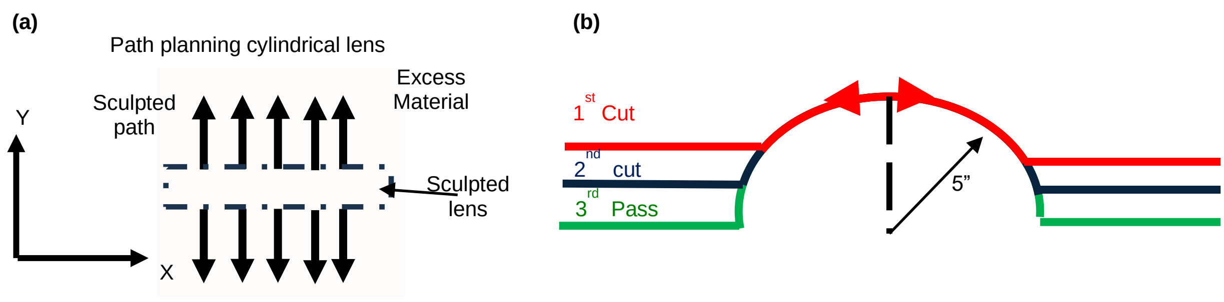

Fig 9. (a) Path plan for sculpting the cylindrical lens and (b) Cartoon showing the cross-section profile and path for sculpting the cylindrical lens.

After the completion of the sculpting process, the artifact was mapped using the VIEW benchmark metrology microscope. The photograph of the sculpted lens, along with the surface map is presented in Fig 10.

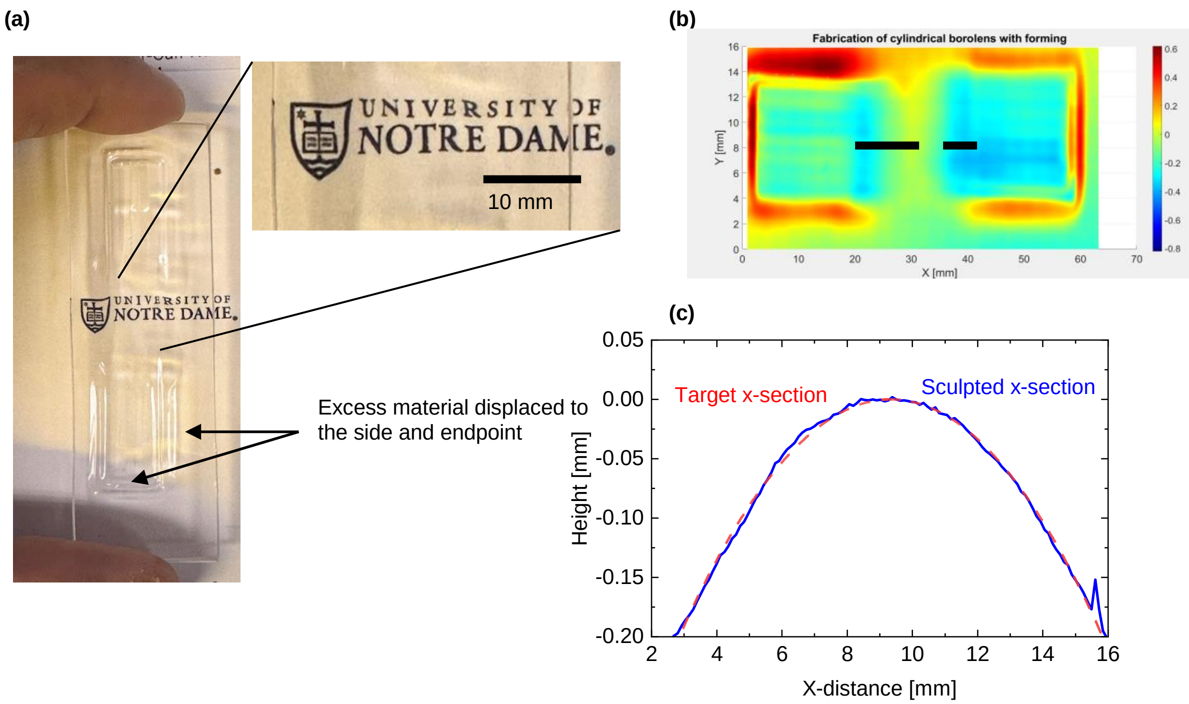

Fig 10. (a) Photograph of the sculpted lens, showing the university mark. (b) Surface map of the sculpted lens. (c) Cross-section of the sculpted profile compared to the target.

Image distortion is noted towards the end of the sculpted profile and at the beginning of the steady-state linear path, primarily due to residual scalloping, as shown in the surface map in Fig 10b. However, when cross-sectioned and compared to the target, the sculpted lens profile conforms closely to the intended shape, indicating minimal error.

5. Conclusions

This study demonstrates the utility of laser-heated sculpting in the fabrication of complicated form factors with high accuracy. Localized laser heating reduces glass viscosity, allowing deformation via a graphite sculpting tool along a controlled path. A simplified model based on the depth of cut on each pass, temperature, and linear travel speed can be formulated for sculpting accuracy or conversely, the error which is equal to elastic tool deformation during the sculpting process. Between temperatures of 800-1400 °C, and travel speeds between 0.1 mm/s to 0.5 mm/s, a non-trivial reduction in tool deflection was observed or increased accuracy in the sculpting profile. The temperature and speed are limited by the zero-force flow effects at temperatures above 1100 °C and longer laser dwell. Multi-pass sculping enables asymptotic convergence of the sculpting profile to target due to reduced force requirements which was used to demonstrate simple optical form: cylindrical lens of 5” radius of curvature with a 14- mm aperture with sub noise floor accuracy. This validates laser-heated sculpting as a promising technique for precision optical manufacturing or as a complement in hybrid processes.

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7. References

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