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Rapid tooling injection molded prototypes: a case study in artificial photosynthesis technology

Joanna Noble[a], Karl Walczak[b], David Dornfeld[a,*]

[a]*University of California, Berkeley,1115 Etcheverry Hall, Berkeley 94720, USA*
[b] *Joint Center for Artificial Photosynthesis, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley 94720, USA*

* Corresponding author. Tel.: +1-510-643-7013; fax: +1-510-643-5599. *E-mail address:* dornfeld@berkeley.edu

Abstract

In this paper we will explores techniques for fabricating optical components for use in an artificial photosynthesis prototype. Specifically, methods were developed for creating rapid tooling to injection mold optics. Three mold fabrication methods were compared: CNC machining of plastic, CNC machining of aluminum, and 3D printing of plastic. For the 3D printed parts, three finishes processes were explored: hot-pressing with a steel shaft, coating with printer resin, and mechanically polishing with a scraper and buffer. Mold fabrication and finishing methods were evaluated based on speed, difficulty and quality. From this preliminary investigation, resin-coated 3D printed molds show promise for use in rapid tooling for injection molding.

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Keywords: Injection molding; Optical prototypes; Rapid tooling; Surface finish; 3D printing

1. Introduction

Standard optical fabrication methods are typically time-consuming and expensive. Some applications require custom optical components even during the prototyping phase. Since prototyping often requires short design-to-part time cycles and quickly implemented design changes, the lead time and expense of custom optics becomes impractical. An easier, faster optical fabrication method that meets prototype standards, if not necessarily final product standards, would be useful for these situations.

Plastics optics are commonly manufactured using machining, casting, compression molding, and injection molding [1]. Machining may refer to single-point diamond turning or to grinding and polishing. These machining processes are slow and precise, often used for prototypes. For larger volumes, casting, compression molding, and injection molding are used. Injection molding is the most common method and allows for greater part complexity.

This paper describes the development of a method for injection molding non-imaging optical components, using rapid tooling. The prototyping methodology presented in this paper is a general method which could be utilized by a number of applications for improving surface finish. In this paper our case study is artificial photosynthesis.

2. Background

2.1. Rapid Tooling and Injection Molding

In a typical injection molding process, plastic resin is melted and then injected under pressure into a mold. The material cools, and the mold is opened to release a plastic part. Mold and part design for injection molding must consider a wide variety of factors.

Molds are typically made from hardened steel for longer tool life [1]. To attain an optical quality surface, the steel can be directly polished. Alternatively, a separate section can be

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inserted into the mold where optical quality surfaces are required. This section can be coated with nickel and diamond-turned to an optical finish. The insert can be easily replaced once the surface has become worn or damaged.

When only a small volume of parts is required, rapid tooling may be used instead. Rapid tooling refers to production tooling that is produced using rapid prototyping, often referred to as additive manufacturing or 3D printing, methods. Rapid tooling may also serve as “bridge tooling” to begin production while the hardened steel mold is being designed and machined. 3D printed parts have successfully been used for short run injection molding [2, 3].

2.2. Artificial Photosynthesis Prototype Development

The optical component developed for this study is for use in an artificial photosynthesis prototype. The Joint Center for Artificial Photosynthesis (JCAP) is a U.S. Department of Energy project, led by the California Institute of Technology and Lawrence Berkeley National Laboratory (LBNL), that is working to develop solar-fuel generators. Artifical photosysthesis is a photoelectrochemical process in which water, CO_2, and sunlight are the system input and fuel grade chemicals are the outputs [4]. This process is expected to provide an advantage over other fuel-generating methods because solar energy is both abundantly available, carbon neutral, and has high energy density. Additionally, artificial photosynthesis reduces the “food or fuel” dilemma of biofuels, in which land and vegetation that would contribute to the food supply are instead used for fuel creation.

Component, subassembly, and prototype level research are being concurrently conducted, to reduce scale-up variables and establish design rules [5]. Prototype construction also allows for development of device structure and manufacturing processes that can be refined for the final product. The optical component of the prototype serves to capture, direct, and potentially concentrate sunlight.

The current prototype, illustrated in Fig. 1, consists of a 3D printed frame, with a molded lens array forming the top, and louvered light absorbers and ionomer membrane sheets across the mid-section. The ionomers membrane separates product gases, in the top and bottom sections of the prototype. The light absorbers are angled to increase the surface area. Since the lens-making process is still being developed, a 3-5 mm thick acrylic window is being used in place of a more complex optical component. In the photo, the translucent white frame is 3D printed and the dark blue slats are coated silicon.

Previous optical prototyping efforts for this project have focused on casting a silicone elastomer using a 3D printed mold [6]. The completed part (Fig. 2) showed inconsistent thickness and multiple voids and bubbles. A finite element analysis of expected displacement of the elastomeric lens array also demonstrated possible excessive stretching at expected operating pressure. Therefore, current work focuses primarily on other materials and manufacturing methods.

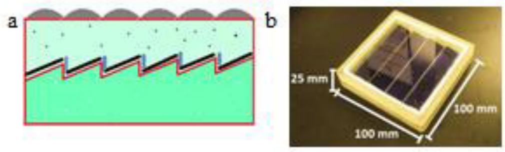

Fig. 1. Artificial photosynthesis prototype device (a) layout; (b) frame model.

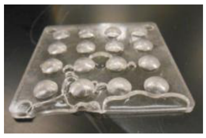

Fig. 2. Cast elastomeric silicone optical array.

3. Methods

3.1. Test Part Design

In order to develop the optical prototype fabrication process, a test part was designed. The optical needs for the device are not currently defined, but are expected to require an array of lenses. The test part consists of an array of cylindrical lenses placed at the same spacing as the silicon plates. After initial testing with machined molds, the test part was modified to decrease the total part volume and to change the radius of the lens cylinder to 9.525 mm (3/8 in). The initial part (Part A) and modified part (Part B) are illustrated in Fig. 3.

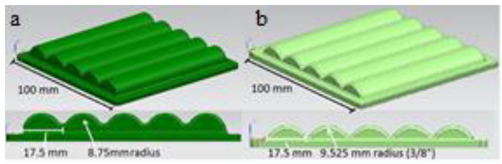

Fig. 3. Cylindrical lens arrays (a) test part a; (b) test part b.

The test parts were molded from Cyclic Olefin Copolymer (COC), grade 5013L-10. This material was selected for its superior optical properties, high service temperature, and low water absorption. These features are important because the optical component will be in constant contact with the electrolyte liquid and exposed daily to temperature changes.

The mold design was adapted from the test part by accounting for shrinkage and adding vents. Vents were added at the recommended depth for COC 5013L-10 of 0.0254-0.0762 mm (0.001-0.003 in). The part cavity was increased by 5%, more than necessary to account for expected shrinkage. For simplicity, the mold was designed with a single combined sprue and gate, which was placed in the middle of the part for symmetric flow. To mitigate marring of the cylindrical lens surface, the mold was designed with the gate and parting line on the bottom side. A draft angle of 1^o was added to the vertical sides, to ease part removal. Additionally, a small radius was added to all sharp corners, to encourage smooth flow.

The only features included in the top half of the mold were the nozzle seat and sprue-gate. The flat-bottomed lens design did not require any other machined features. The nozzle seat and sprue-gate were copied from the purge barrel design in the injection molding machine manual, but without a taper added to the sprue [7]. Three locating pins were included to help maintain the sprue position in the center of the part. Fig. 4 shows the mold design, with Mold A and Mold B corresponding to test parts A and B.

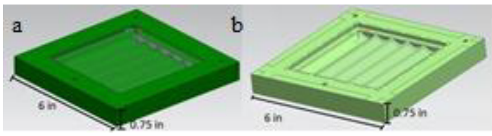

Fig. 4. Mold design for (a) test part a (b) test part b.

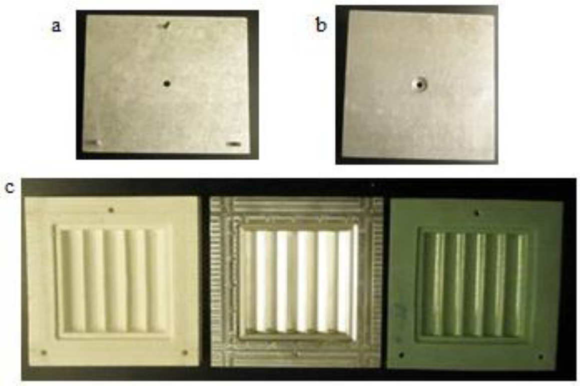

Fig. 5. (a,b) Top half of mold; (c) fabricated molds: VHMW, Al, 3D printed

3.2. Mold Fabrication

Three different rapid tooling mold fabrication methods were explored for comparison: CNC machining of aluminum, CNC machining of plastic, and 3D printing of plastic. The machining was completed with a Haas VF0 vertical machining center at the UC Berkeley Student Machine Shop, and the 3D printing was completed with an Objet350 Connex at JCAP. The machined molds were for Test Part A, and the 3D printed mold was for Test Part B. Since the top half of the mold is in constant contact with the extremely hot nozzle, it was machined from aluminum and used for all three mold bottom halves.

Two molds were machined from 6063 Aluminum (Al) and Very High Molecular Weight Polyethylene (VHMW). The Objet350 Connex is an inkjet-style 3D printer that prints with a UV curable acrylate resin. Numerous acrylate resins are available with different material properties, and parts can be printed with a glossy or matte finish. The mold was printed using a “Digital ABS” mixture of RGD515 and RGD535 resin, with a glossy finish. The final machining path and the print direction were both along the lens cylinder axis. The fabricated molds are shown in Fig. 5.

3.3. Part Fabrication

A Morgan-Press G-100T injection molding machine was used to mold parts from polypropylene (PP) and COC. The Morgan-Press is a ram plunger injection molding machine, with a maximum shot size of 98.3 ml (6in^3), maximum injection pressure of 82.7 MPa (12,000 psi), maximum clamp pressure of 86.2 MPa (12,500 psi) and a maximum mold area of 203.2x279.4 mm [8]. PP was used initially because it’s easier to mold with in the Morgan-Press. The injection parameters were adjusted over several test runs, and the best parts were selected for measurements. The parameters used for these best parts are listed in Table 1. The injection speed know was left at the same setting for all runs (two full turns from zero). COC was not molded in the VHMW mold because the mold already showed deformation and surface damage from molding PP at lower temperature and pressure.

Table 1. Injection molding parameters.

	PP, Al Mold	PP, VHMW Mold	PP, 3D printed Mold	COC, Al Mold	COC, 3D printed Mold
Barrel Temperature (^{o}C)	218	218	218	246	252
Nozzle Temperature (^{o}C)	232	232	232	260	260
Injection pressure (MPa)	20.7	10.3	10.3	51.7	25.9
Clamp pressure (psi)	68.9	75.8	86.2	not recorded	86.2
Pre-injection packing (# times, MPa)	twice, 20.7	twice, 10.3	once, 10.3	none	once, 25.9

3.4. Mold Finishing

A variety of finishing processes could be explored for all three fabrication methods; however, finishing processes were only developed for the in-house method of 3D printing. The Objet350 Connex produces a naturally wavy surface, corresponding to the row of inkjet printer heads. These bumps would deflect light in unplanned directions in a molded lens. Three finishing processes were explored for the 3D printed molds: mechanical polishing, hot pressing, and coating. Single cylinder mold sections were printed for experimenting with these three methods.

In order to mechanically polish the mold, first the cavity surface was scraped by hand using a matching 9.525 mm (3/8 in) steel radius gauge. Next, the cavity was buffed using a Dremel rotary tool with a soft density cylindrical felt polishing bob and polishing compound.

To hot press the cavity, a precision ground steel shaft with an rms roughness of 9 μm was heated in an oven to 200 ^{o}C. The shaft was pressed into the cavity using a vise and left until the system reached room temperature.

The coated cavity was coated in the same acrylate resin as was used for printing, the “Digital ABS” mixture. Before coating, the mold section was first scraped and polished as described above. Less than one gram of resin was poured into the cavity. The cavity was then placed in a vacuum chamber to remove bubbles. To set the resin, the cavity was cured alternatively under a halogen lamp and a 254 nm UV lamp until the coating had fully hardened.

The cavities were evaluated for surface finish, shape error, and behavior during injection molding. To assess possible surface damage during molding, one PP part and one COC part were injection molded into each of the four cavities using the Morgan-Press. Table 2 lists the injection molding parameters used for these single cavity molds.

Table 2. Injection molding parameters for single cavities.

	PP	COC
Barrel Temperature (^{o}C)	218	252
Nozzle Temperature (^{o}C)	232	260
Injection pressure (MPa)	19.0	10.3-20.7
Clamp pressure (psi)	62.1	62.1-86.2

4. Results

4.1. Mold Fabrication

Molds were fabricated using three different rapid prototyping methods: machining of aluminum, machining of plastic, and 3D printing of plastic. Table 3 summarizes limitations and benefits of each method.

PP and COC parts were injection molded into the molds using the Morgan-Press. Molded parts are shown in Fig. 6. The molded parts were measured by staff at the LBNL Central Shops with a Mahr Perthometer M1, a profilometer that automatically calculates average roughness (R_a).

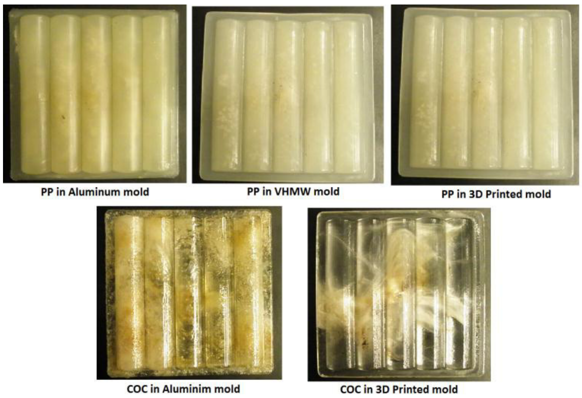

Fig. 6. PP and COC injection molded parts.

The parts were measured at the curve peaks for a distance of 1.75 mm. Beyond this point, the cylinder slope was too large for the profilometer height range. Many of the parts showed minor scabbing or voids on the surface, so these values may reflect more on the injection molding parameters than on the mold fabrication methods.

Table 3. Comparison of rapid prototyping mold fabrication methods.

	Machined Metal	Machined Plastic	3D Printed Plastic
Material Limitations	Easily machinable metals (aluminum)	Easily machinable plastics	Acrylate resins available for Objet350 Connex
Preparation time between mold design and fabrication (approximate)	3 hours	3 hours	5-15 minutes
Machining/Printing time (approximate)	4 hours	2 hours	5 hours
Skills required	CAM software, cutting tool selection, cutting speeds and feeds selection, use of vertical machining center		Minimal training required
R_a Roughness of Molded PP parts (μm)	0.636	0.979	0.547
R_a Roughness of Molded COC parts (μm)	0.621	-	0.462

At least ten parts from PP or COC were molded in the aluminum mold without any visible sign of surface damage or deformation. At least five parts were molded in the 3D printed mold. The cavity surface showed light browning and mild bowing along the borders. The vent surfaces showed small deformations where the COC resin overflowed the mold on some initial runs. The VHMW mold was used for less than five parts as it showed noticeable warping and deformation of the ribs between lens cavities. PP parts from the VHMW and 3D printed mold showed pronounced warping. Additionally, parts were more difficult to remove from the VHMW and 3D printed molds than from the aluminum mold.

4.2. Mold Finishing

Three mold finishing processes were explored: mechanical polishing, coating, and hot pressing. Four single cylinder cavities were printed, for the three finishing methods and one unfinished reference. All four cavities were in the shape of a 9.525 mm (3/8 in) radius cylinder, but two of the cavities were printed with a shorter length and shallower cavity because not enough printer resin was available.

The four molds were measured by the LBNL Central Shops using a Zeiss Accura Coordinate Measuring Machine (CMM) and an Optical Gaging Products Vision Machine, equipped with a TeleStar TTL Laser. The CMM automatically calculates the radius and roundness of the parts. Roundness measures the difference in diameter between the minimum circumscribed circle and maximum inscribed circle [9].

Table 4 summarizes the required time and measurements results for all three finishing methods. Fig. 7 shows the part profiles from the Vision Machine. The parts were measured at the bottom of the cavities because the sidewalls were too steep for the laser to track correctly. A second order polynomial was fit to each dataset and subtracted out. These values are plotted in Fig. 8 and were used to calculate R_a.

Table 4. Time and part quality for mold finishing processes.

	Mechanical Polishing	Coating	Hot Pressing	As Printed
Labor Time (min)	<15	30	<5	-
Total Time (hr)	<.25	2	5-20	-
Radius (mm) (nominal 9.525)	10.7135	9.4484	9.4255	9.4821
Roundness (mm)	0.1302	0.0800	0.0577	0.0786
R_a Roughness (mm)	0.0070	0.0111	0.0118	0.0153

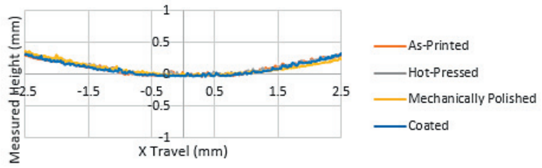

Fig. 7. Finished mold profiles measured across 5mm.

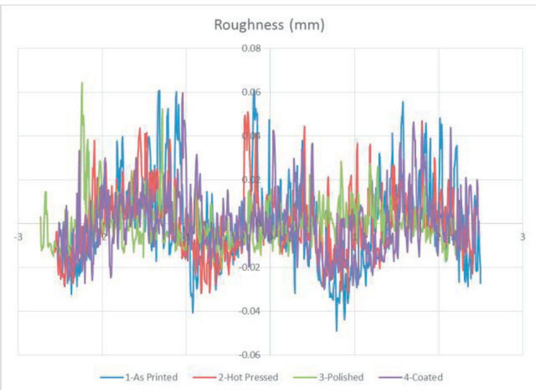

Fig. 8. Finished molds roughness measured across 5mm.

Mechanical polishing and hot pressing require less labor time than coating, but they also require a tool in the shape of the cavity. For standard sizes, a radius gauge or off-the-shelf smooth shaft can be used. For non-standard sizes, a scraper could probably be easily machined using water jet or laser cutting, while a smooth shaft may have to be diamond turned. Coating molds using the 3D printer resin is a much more difficult to control process, and small process errors can easily result in uneven coating, rough sections, bubbles, or curing failures.

All three methods showed a greater deviation from nominal radius than the as-printed reference cavity, but coating had the closest measured radius. Hot pressing showed the best roundness, an improvement over the as-printed part. Coating showed slight disimprovement for roundness, while mechanical polishing made roundness much worse.

To assess possible surface damage during molding, one PP part and one COC part were injection molded into each of the four cavities, as described in the methodology. No surface damage was noticed for any of the cavities except for the hot-pressed cavity. After the first molding with PP, this cavity appeared as-printed and lost the smooth finish gained from hot pressing. The finish of the molded parts closely resembled that of the cavities, with the coated cavity producing the shiniest, smoothest looking parts. Fig. 9 shows the four cavities, and Fig. 10 shows the ridged appearance of the hot-pressed cavity after molding contrasted with the smooth finish of another hot-pressed cavity.

Fig. 9. Finished cavities: as printed, hot-pressed, scraped/polished, coated.

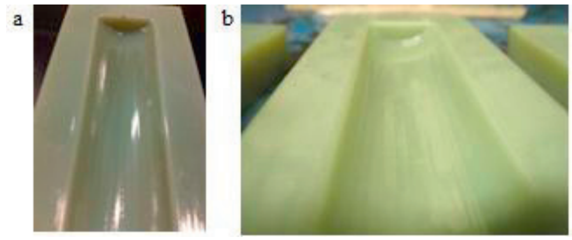

Fig. 10. Hot-Pressed cavity (a) before molding; (b) after molding.

5. Conclusions and Future Work

A method for rapidly fabricating optical components would be useful for artificial photosynthesis device prototypes, among other applications. Methods were developed for creating rapid tooling for injection molding optics to address this problem. Three mold fabrication methods were explored: CNC machining of plastic, CNC machining of aluminum, and 3D printing of plastic. 3D printing requires less skill and labor, while machining provides more options for material selection and optimization of produced shape error and finish.

As printed, 3D printed parts have inadequate surface finish for molding optical components. Three finishing processes were explored, using printed single cavities, to improve the printed surface finish: hot-pressing with a steel shaft, coating with printer resin, and mechanically polishing with a scraper and buffer. Mechanical polishing and hot-pressing took less time than the coating process and are easier to control. The coated and hot-pressed cavities had a closer measured radius to nominal and better roundness than the polished cavity. The coated and polished cavities showed no visible damage from injection molding, while the hot-pressed cavity visually appeared to revert back to the as-printed finish.

Based on this preliminary investigation, 3D printing shows promise as a method for creating rapid tooling for injection molding. At this point, the most viable finishing process explored is coating, based on part quality and injection molding behavior. The heat deflection temperature of the printed parts could be improved using a post-printing oven curing process recommended by Stratasys.

While 3D printing molds requires less skill and fewer man-hours, machining still shows promise. The machining parameters, cutting tools, and mold materials could be further optimized to reduce finishing operations.

Injection molding has many process variables that were not fully explored in this project. Part clarity and surface flaws can be improved by adjusting the injection pressure and speed and the material temperature and by incorporating a pre-molding drying process for the COC. Alternatively, a standard rotating screw injection molding machine would allow for better process control and more consistent material mixing, but require more user training than the Morgan-Press.

Of the three different finishing processes explored, coating showed the best performance from these preliminary results. However, each of the methods can be further developed before drawing final conclusions. Additionally, finishing processes for the machined parts could be explored. If these parts can be finished using a faster and easier process than 3D printed parts, this may offset the relative ease and convenience of 3D printing.

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