3D Printing Optical-Quality Glass

Livermore development team for tailored glass using direct ink writing (from left to right): Du Nguyen, Jungmin Ha, Timothy Yee, Becca Walton, Oscar Herrera, Rebecca Dylla-Spears, Michael Johnson, Nik Dudukovic, Koroush Sasan. Not pictured: Megan Ellis. (Photo by Garry McLeod.)

FROM beads to telescope lenses, glassmaking methods have been honed over millennia to achieve new physical forms with specific optical properties. A glass object is usually created by melting silica powders and hardening the molten mixture in a mold; afterwards, the form can be further modified through subtractive techniques.

Although time-tested, conventional processes limit the range of achievable structures and can introduce structural inconsistencies that corrupt the desired material and optical properties. Instead of subtractively altering glass components after casting, a Livermore research team headed by Rebecca Dylla-Spears has developed glass “inks” to additively manufacture—that is, 3D print—glass components with nearly limitless forms and gradated optical properties.

Breaking the Mold

The team’s revolutionary process emerged from a Laboratory Directed Research and Development (LDRD) Program project to bolster optics and laser technology know-how by optimizing the size, weight, and power of integrated components. Until now, glass production methods could not support simultaneous tailoring of complex geometry and refractive index—measurement of the way optical media interact with light. The limited form and performance of traditional optics often requires several individual components be used in combination rather than employing a single, tailor-made component, thereby raising production costs, wasting excess material, and compounding possible error.

The tailored glass using direct ink writing (DIW) method is the first extrusion-based glass fabrication technique to offer the precision of 3D printing alongside the freedom of spatially varying optical properties. DIW is a process of mixing and extruding liquid-phase substances similar to 3D polymer printing (for example, fused deposition modeling). However, far beyond 3D polymer printing, DIW supports a diverse range of materials including ceramics, metals, and now, silica glass. “This technology unlocks a new parameter space ripe for exploration. What we’ve learned through this work can serve as a springboard for further advanced manufacturing approaches including glass and other multimaterial compositions,” says Dylla-Spears.

The process first combines multiple liquid-phase inks into a single glass-forming substance. These specialty inks are composed of solvent (removed post-print) with nanoparticles composed primarily of silicon dioxide and a variety of dopants, for example titanium dioxide or germanium dioxide, that impact the glass’s resulting density and refractive index. Carefully controlled flow rates ensure the correct volume of each ink is released to achieve the desired relative concentration at each time step. The separate inks are combined in a micromixer to produce a homogenous substance that is extruded through a nozzle along a programmed path to construct the object. Once printed, the low-density preform, called a green body, undergoes a series of heat treatments to strengthen and condense the build.

The adaptable printing process yields specialty glass structures and optics to work within precise constraints on size, weight, and performance. Structures with variable optical properties address, for instance, the need for intricate, lightweight components in airborne laser–mirror systems. Elsewhere, employing a single flat, refractive index-graded lens in place of an aspheric lens could reduce finishing costs up to 90 percent because fewer unique resources and facilities are needed to produce specialized parts. Maximizing operating parameters while minimizing cost is appealing to aerospace manufacturers and collaborators in the Joint Munitions Technology Development Program between the Department of Defense and Department of Energy. However, the utility of tailored glass goes beyond defense-related purposes. For gemstone purveyor Swarovski, which joined the Livermore team under a cooperative research and development agreement, the technology promises pristine crystal glass with high refractive index and optical dispersion to increase the luster of luxury goods.

The tailored glass by direct ink writing technique preserves fine features while exercising free-form flexibility, as in this 3D-printed helical glass structure.

Convention-Shattering Fabrication

Dylla-Spears’s team has already produced an array of complex objects once unthinkable using traditional approaches. The process’s free-form flexibility enables fine lattices, solid monoliths, liquid-tight containers, and microfluidic channels, all capable of supporting smooth gradient transitions in color, density, and refractive index. While the components are manufacturing marvels in their own right, Dylla-Spears explains, “I expect the technology will complement conventional optics fabrication processes. Customers are likely most interested in custom containers, gradient optics, and lightweight mirror blanks.” The process’s high customizability will allow manufacturers to rapidly prototype and improve glass-based designs.

Developing the technology was all but straightforward. Dylla-Spears says that preventing cracks posed a significant challenge when printing at large scales and with composition gradients. “Initially, we sought to optimize handling and heat treatment protocols around a proven ink formulation,” she says. “Recently, however, we shifted focus to making the ink formulation itself more robust to cracking, which has allowed us to increase the optical area by almost 10 times.”

After establishing feasibility of 3D-printed glass, Livermore materials engineer Du Nguyen focused on multimaterial patterning and extrusion consistency. Achieving an accurate multimaterial composition profile proved particularly challenging because ink deposition rates must continually fluctuate to yield gradient properties. “Effects such as residence time in the nozzle and capacitance throughout the system impact ink deposition rate,” says Nguyen. The team attempted to match ink rheology and to minimize air bubbles but found that minute inconsistencies are inevitable. Nguyen explains, “We countered these effects by using a microfluidic circuit analogy to program deposition to actively compensate for encountered inconsistencies.”

Staff scientist Timothy Yee, who worked alongside Nguyen, also concentrated on post-print processes. “Fine tuning the heat treatment process was vital to converting printed parts into fully dense, transparent glass,” says Yee. The heating process required careful design to ensure that all solvent and organic contaminants are removed and to minimize cracking and warping during sintering. Once cooled, mechanical engineer Megan Ellis characterized the products using dimensional analysis to validate printing accuracy and understand structures’ reactions to applied forces. “Due to factors such as interstitial spacing and residual stresses, 3D-printed parts sometimes exhibit more structural flaws than a comparable piece of the bulk material,” says Ellis. “We iteratively improved aspects such as formulation, printing orientation, and consolidation to ensure higher quality products.”

Nguyen maintains that the award-winning process could only have been achieved through the project’s multidisciplinary team effort. He says, “Glass manufacturing is an ancient process, a part of human history, and continuing that history by developing new ways of working with the material is incredibly exciting.”

—Elliot Jaffe

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