FIBER-FED PRINTING OF FREE-FORM FREE-STANDING GLASS STRUCTURES

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Abstract

Additive Manufacturing (AM) of low-profile 2.5D glass structures has been demonstrated using a fiber-fed laser-heated process. In this process, glass fibers with diameters 90-125 µm are supported as they are fed into the intersection of the workpiece and a CO_2 laser beam. The workpiece is positioned by a four-axis CNC stage with coordinated rotational/transitional kinematics. The laser energy at $\lambda = 10.6$ µm is coupled to phonon modes in the glass, locally heating it above its working point. The rapid heating and cooling process allows for the deposition of various glasses into free-standing three-dimensional structures such as trusses and other complex geometries. Issues unique to the process are discussed, including the thermal breakdown of the glass and index inhomogeneity between the fiber core and cladding when using single-mode optical fiber feedstock.

Introduction

Additive manufacturing has revolutionized the field of manufacturing in recent years due to the advantages that these processes entail. Traditionally these advantages have pertained to an increased design freedom and the allowance of complicated three-dimensional geometries, rapid prototyping, more efficient material usage, and the capability to manufacture parts from functionally graded materials. As these techniques for additive manufacturing mature however, more manufacturing applications become candidates for adaption to these processes. Specifically, applications for optical systems are emerging as a promising enterprise; applications such as photonics packaging, gradient index (GRIN) and freeform optics, and integrated optics all stand to benefit from the development of a system which is capable of depositing high quality optical materials. This is due in part to the attractive material properties of glass itself. Glass is transparent in the visible spectrum, is amorphous and therefore does not suffer from grain boundary scattering, it is chemically inert, harder than transparent polymer counterparts, and displays a low sensitivity to temperature gradients.

While additive manufacturing has been widely studied for use with polymers, metals and ceramics, there is comparatively little work done in developing AM techniques for glass[1]. Those studies which have been conducted into the AM of glass share a limitation in depositing transparent glass due to bubble entrapment. Several groups utilizing selective laser sintering were able to fabricate three-dimensional glass parts[2,3,4], but these parts resemble sugar cubes in both texture and appearance. The development of continuous melting approaches for glass AM by several groups has been much more successful in depositing transparent glass. A filament-fed laser-heated process developed by Luo et al. demonstrated an ability to deposit void-free transparent glass using a feedstock with diameters ranging from 0.5-3 mm[7]. However, this process requires new cane to be reloaded into the filament feeder intermittently during the deposition process, and even the smallest diameter feedstock used of 0.5 mm cannot be rolled to extend the duration of uninterrupted deposition. Klein et al. developed a gravity-fed molten vat approach[5], after which Micron3dp introduced their high temperature extrusion technique[6]. Both of these platforms are capable of depositing very intricate three-dimensional geometries out of glass, but the inability of these techniques to deposit void-free blocks of glass constrains their use for optical applications.

In light of the limitations with the filament-fed laser-heated process[7], a system utilizing optical fiber as a feedstock is very attractive, as kilometers of fiber may be spooled to allow for a continuous deposition process. In addition, the smaller diameter of optical fiber minimizes issues with thermal diffusion in the feedstock, potentially allowing for a greater volumetric deposition rate than that of the filament-fed process. Optical fibers are widely available, consisting of extremely high quality, low loss glass (<1 dB/km), and are relatively cheap with a prices lower than $180 per km of single mode fiber[8].

Experiential Results

The experimental platform used in this study (Fig. 1) utilizes a CW CO_2 laser (Synrad Evolution 125, λ_0=10.6 μm, 140 μm spot size) which is incident on a soda-lime substrate. The substrate is fixed to a heater capable of reaching temperatures of 650°C, which is utilized to prevent thermal shock during the deposition process. The heater and substrate are in turn attached to a set of *x*-*y*-*z* stages, where the *x* and *y* stages (Aerotech ANT130-160XY) realize the horizontal movements, and a *z* stage (Aerotech ATS100-150) is used to move the platform upwards and downwards. A rotational stage (Aerotech ANT130-360-R) was installed on top of the *x*-*y*-*z* stages to enable rotations of the substrate. The fiber was fed into the melt pool (intersection of laser beam and substrate) by a custom-designed fiber feeder. 1% of the laser energy is reflected into a thermopile type power meter (Ophir 10A-V1) so that the laser power at the printing surface may be determined. Incandescent light is emitted from the melt pool during the printing process, with the spectrum of the radiation being dependent on the temperature of the melted glass. This incandescent emission is collected using an OceanOptics USB-4000 fiber-coupled spectrometer (calibrated with an OceanOptics LS-1-CA 2800 K light source) which has a 0.8 mm diameter interrogation region centered on the laser heated area.

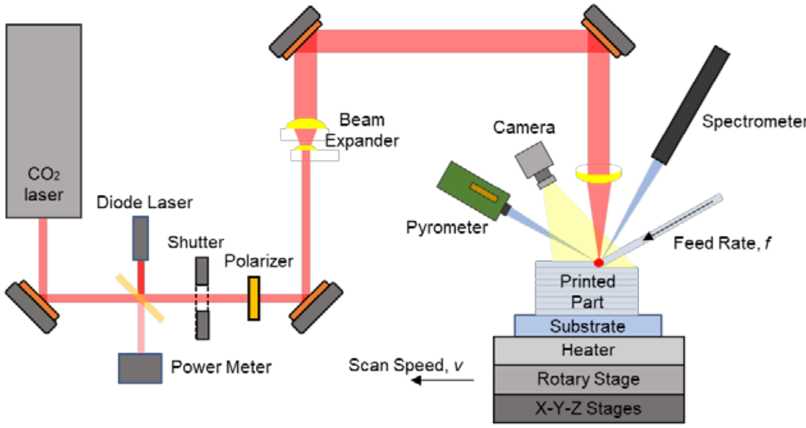

Fig. 1. Schematic of experimental platform

The process parameters investigated in this study for their effect on the deposited glass are specified to be the laser power, *P*, fiber feed rate, *f*, platform scan speed, *v*, and the laser spot size (Fig. 2). The latter two parameters were consolidated into a dimensionless ratio of feed rate to scan speed, *f*/*v*. The feedstock used was SMF-28 optical fiber manufactured by Corning. This fiber has an acrylic coating which is mechanically stripped following a two-hour soak in denatured alcohol, leaving a cladded quartz core which has an outer diameter of 125 μm. The cladding has a refractive index of 1.44681, while the 9 μm diameter core has a refractive index of 1.45205.

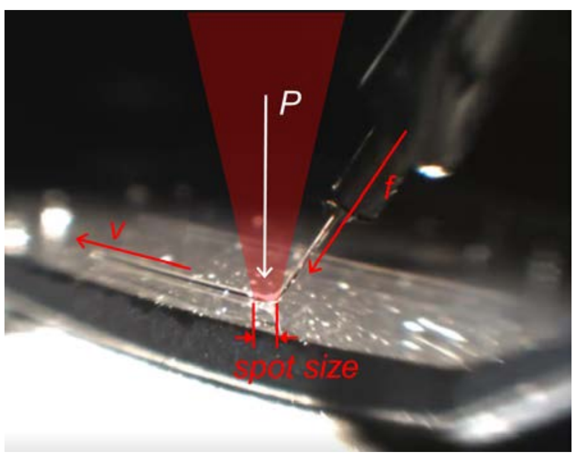

Fig. 2. Process parameters for fiber-printing specified for their effect on the deposited glass

With the ability of the fiber-fed laser-heated process to deposit transparent quartz structures proven in previous studies, it was now attempted to deposit a spherical lens in such a way that the shape of the deposited lens adhered to a design profile (Fig. 3). Each layer consists of a series of concentric circles, starting from the outside and working its way inwards. Each ring is designed to maintain a constant feed rate-to-scan speed ratio of 1:1. After depositing each layer, the CO_2 laser is then defocused, and the layer is reflowed to create a smooth surface.

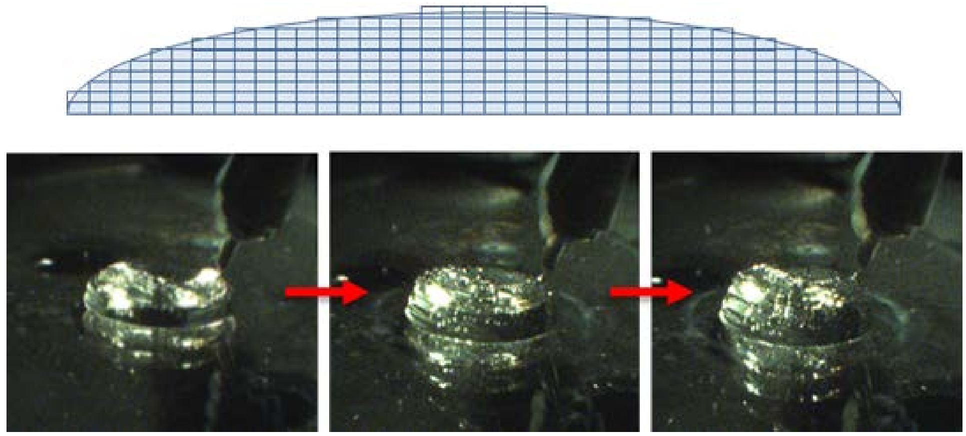

Fig. 3. Cross-Section of Lens Profile Design (top) Progression of Lens Deposition (bottom)

These lenses deposited with Quartz SMF do an adequate job of imaging, be it the pixels on an LCD monitor, or an AFRL Resolution test chart (Figure 4). It is unclear at this time whether or not the quartz glass within the core is mixing with the cladding during the deposition, or if there remains segregation between the slightly higher index of refraction glass in the core, and that of the cladding. Any effects of this index inhomogeneity are soon to be measured and compared with lenses which are deposited using specially drawn quartz fiber, where the entire fiber is comprised of material with the same index of refraction.

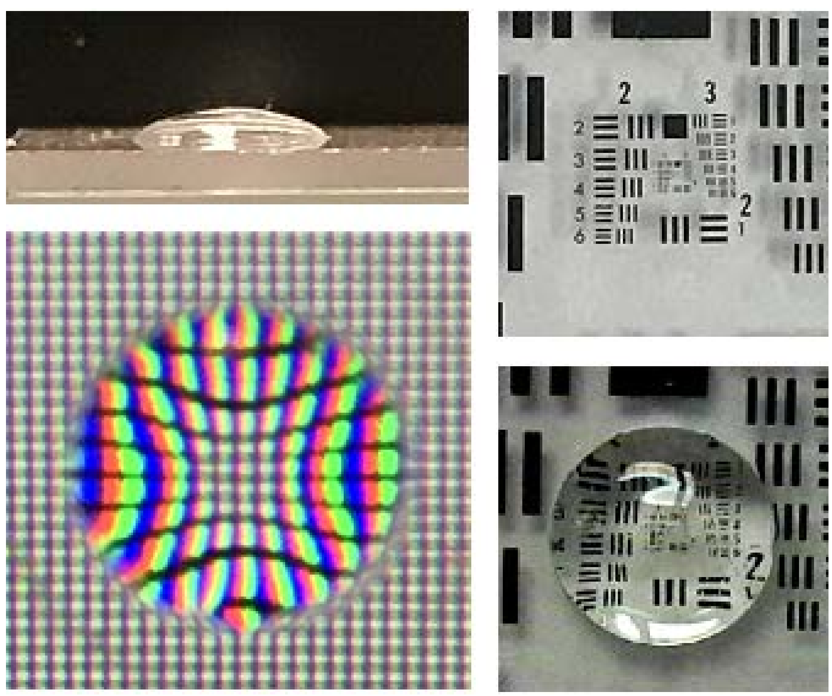

Fig. 4. Profile of spherical lens (top left), lens imaging pixels on LCD monitor (bottom left), AFRL resolution test chart with no lens (top right), AFRL resolution test chart imaged through spherical lens (bottom right)

The fiber-fed process is not limited however to only printing transmissive parts; by printing with a feed rate-to-scan speed ratio of 1:1 and a small spot size of ~200 µm, large 3D parts may be printed with quartz SMF fiber. Simple geometries such as those depicted in figure 5 have been deposited with heights of up to 15 mm, and more complex geometries such as arches (Fig. 6) have been demonstrated with parts successfully deposited up to 20 mm high. The more complex geometries such as that depicted in figure 11 have been made possible by running a 3D model through a slicer program, thus discretizing the shape into a series of points. Then, a G-code generator is used to produce motion commands to move form one point to the next. However, the path planning often requires manual input to select the next appropriate vector when moving from one z-position to the next.

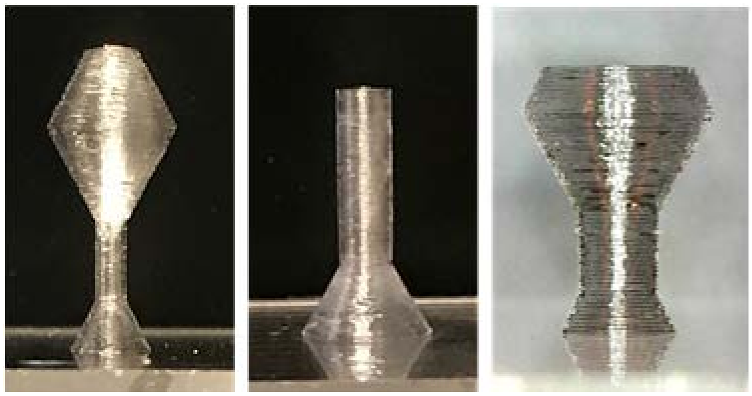

Fig. 5. Simple geometries deposited with quartz SMF

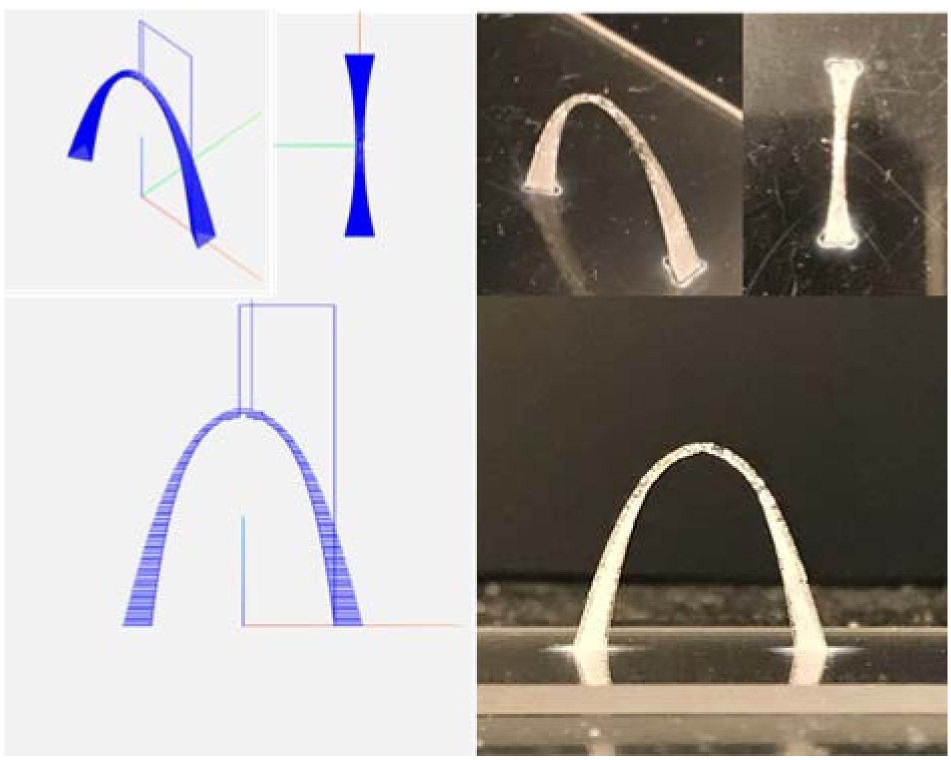

Fig. 6. St. Louis Gateway Arch generated deposition path (left) structure post-deposition (right)

In addition to the continuous structures discussed above, more free-standing complicated geometries involving many starts and stops in the deposition have been accomplished, such as trusses (Fig. 7). These trusses involve the deposition of free-standing fiber in directions which are not aligned with the fiber feeder direction, a disconnect between the substrate and the fiber feeder, and a subsequent reconnection for the next sequence in the deposition. The necessity for consistent disconnects and reconnects which do not damage the already deposited structure requires the use of lead-ins and lead-outs, which often result in unnecessary segments of fiber deposited along the periphery of the truss. The possibility of adding a terminal portion to the deposition code which uses the laser to sever the connections between the intended truss structure and unnecessary segments of fiber deposited to create a lead-in or lead-out will soon be tested.

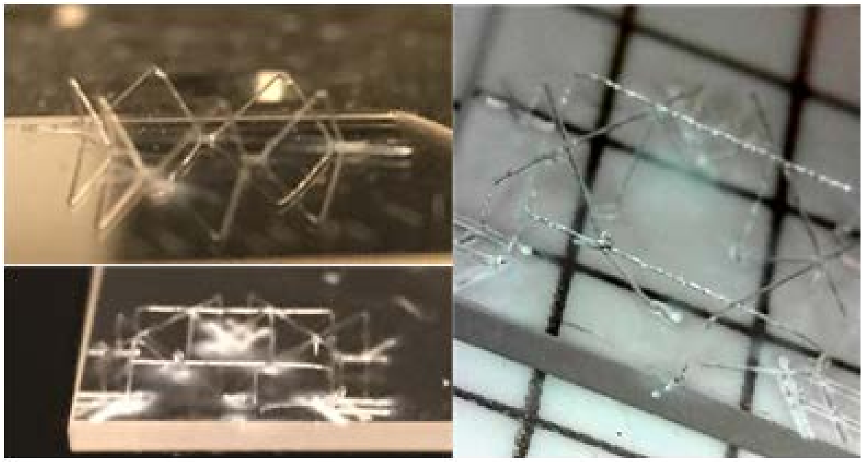

Fig. 7. Fiber truss in various stages of deposition

Finally, it has been demonstrated that with the laser-heated fiber deposition process, quartz SMF fiber may be deposited which is capable of guiding a HeNE laser beam (Fig. 8). A segment of the fiber is deposited in free space, and then is sloped downwards to connect to the substrate while rotating 90 degrees, and the remainder is deposited along the substrate surface. This is done to ensure that any light that appears to be guided by the deposited fiber is done so because the HeNe beam is in fact coupled within the fiber itself, and not simply reflection within the substrate.

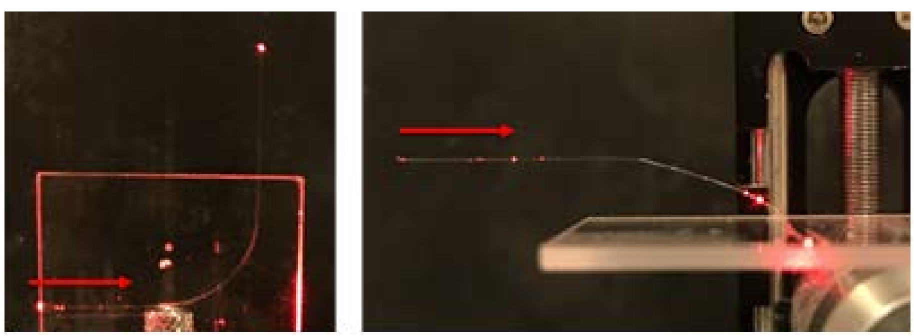

Fig. 8. HeNe laser beam guided through deposited quartz SMF fiber

As proof that these fibers do in fact guide light from one end of the fiber to the other, and that any light coupled into the substrate does not interfere with any signaling, several waveguides were deposited next to each other and illuminated with the HeNe laser individually (Fig. 9).

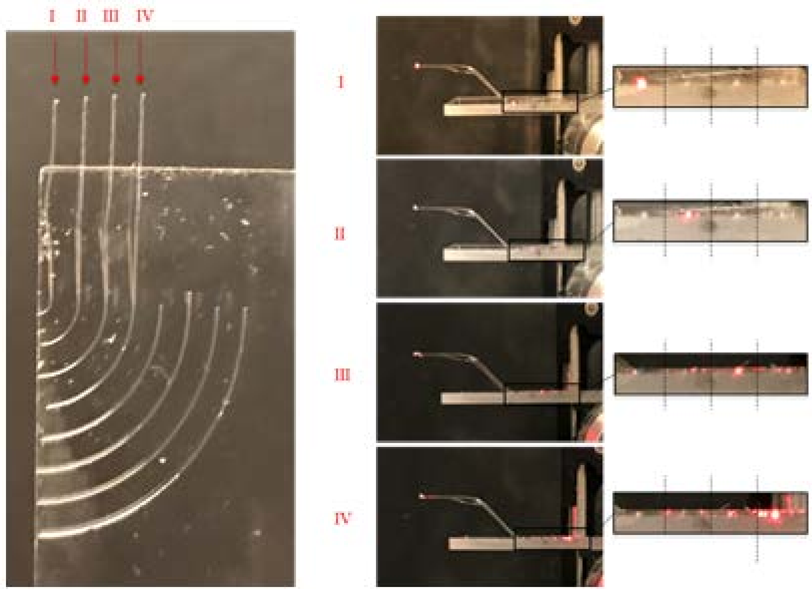

Fig. 9. Four adjacent waveguides demonstrating ability to isolate waveguide illumination

Figure 9 not only shows that the light can be transmitted around a circular arc with a radius of 1mm, but also that each fiber may be illuminated individually. It may be seen in figure 9 that there are some instances where there is a slight illumination in adjacent waveguides, as well as from the substrate as well. This is believed to be due to two factors, the first being dust and other particulate that accumulate on the substrate surface, which scatters light. The second, much less trivial, is the coupling of the laser beam from the waveguide into the substrate. This happens at the spot where the fiber begins to lift off the substrate surface to slope upwards to the diagonal section. This lift off is done at a sharp angle, which is undesirable for waveguides; This is a coding limitation for this platform at this time. There is currently no way to arc the stage in the Z direction, and so the sharp angle scatters light and couples a large percentage of the beam into the substrate. This is a temporary limitation however, as a new program will be introduced soon which will allow for arcing the Z-stage along the X or Y direction.

It was also observed that when the quartz SMF fiber is deposited in free space, certain portions of the fiber will scatter light. This is clearly an undesirable characteristic for a waveguide, so the causes behind this phenomenon are being investigated. Sections of the free-standing fiber which scatter light were observed under a microscope, revealing that these areas appear to be necking, while segments which did not scatter light have a more uniform cross-section (Fig. 10). At this time it is speculated that the fiber necking is due to small interruptions in the fiber feed, due either to slipping in the feed wheels or backlash in the bevel gears used to drive the feed wheels. A new fiber feeder is currently being designed therefore which will address these issues and hopefully prevent them in the future.

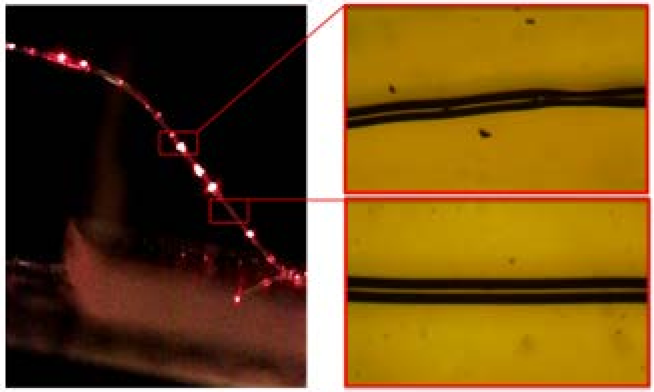

Fig. 10. Freestanding fiber observed under a microscope: Necking site which scatters light (top right), uniform segment which does not scatter light (bottom right)

Conclusions

The fiber-fed laser-heated process is capable of depositing quartz SMF that has a nominal diameter of 125 µm, where $f=v=1$ mm/s. The fiber-fed laser-heated process was used to deposit simple spherical lenses which demonstrated the ability to optically focus light. The deposition approach for the spherical lens was improved by depositing the lens one layer at a time, where each layer consists of concentric rings deposited with a feed rate-to-scan speed ratio of 1:1. The fiber-fed process was then used to print three-dimensional structures ranging from complex continuous shapes such as the St. Louis Gateway Arch, to discontinuous free-standing structures such as simple trusses. Lastly, it was demonstrated that the deposited quartz fiber is able guide light, prompting further investigations into the utility of using this process for printing waveguides in the future.

Acknowledgements

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