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Additive manufacturing of glass: CO_2-Laser glass deposition printing

Philipp von Witzendorff[a], Leonhard Pohl[a,*], Oliver Suttmann[a], Peter Heinrich[b], Achim Heinrich[b], Jörg Zander[b], Holger Bragard[b], Stefan Kaierle[a]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419, Hannover, Germany*
[b]*Quarzglas-Technologie Heinrich GmbH & Co. KG, Im Süsterfeld 4, 52072 Aachen, Germany*

* Corresponding author. Tel.:+49-511-2788-337 ; fax: +49-511-2788-100. *E-mail address:* l.pohl@lzh.de

Abstract

Additive manufacturing is used in several industrial sectors where polymers and metals are established materials. Different academic studies prove that additive manufacturing methods can be applied on glass materials using powder or fiber based material sources. In terms of quartz glass, with melting temperatures around 2200°C, laser sources are used to achieve the necessary intensities. In the present study, additive manufacturing of quartz glass is achieved by melting a quartz glass fiber with a CO_2 laser source. A combined laser head focusses the laser radiation onto the glass fiber in order to melt the fiber. A three axis system is used to move the printing stage and glass substrate. The experimental investigations show that CO_2-laser glass deposition printing allows for the creation of arbitrary 3D quartz glass structures. This method is envisioned to replace conventional manual glass manufacturing processes for production of complex hollow glass structures which are present in the medical sector.

Keywords: Additive manufacturing, glass, laser

1. Introduction

Glass is a versatile material found in many applications where the glass composition or surface functionalization is customized to meet the application requirements. When high chemical inertness, transparency and temperature resistance is required, quartz glass is usually used. For example, artificial kidneys or machines used within semiconductor manufacturing consist of quartz glass components. The manufacturing of these quartz glass components involves machining processes such as milling, drilling and polishing and hot processing such as forming and welding. The latter are mostly performed by manual operation with a hydrogen gas flame as an energy source. Small lot sizes, the hard and brittle material properties and the manual operation lead to a high scrap rate when manufacturing complex quartz glass structures. These challenges motivate the development of additive manufacturing of quartz glass where complex quartz glass structures are manufactured in a single step on one machine.

Several studies prove that additive manufacturing of glass is feasible by different approaches:

- Glass extrusion printing [1,2]
- Selective laser melting/sintering [3,4]
- Wire-fed additive manufacturing [4,5]
- Stereolithography and subsequent oven sintering [6]

First industrial machines are available which are using the glass extrusion printing process for additive manufacturing of borosilicate glass [7]. In terms of quartz glass, temperatures above 2000 °C are required for additive manufacturing which makes the glass extrusion printing process unfavorable due to high energy demand and high temperature stress at the extrusion nozzle. Selective laser melting has shown to allow the creation of 3D printed parts. However, residual pores led to opaque glass parts [3,4]. The authors from [4,5] use glass rods whereas the present study uses endless glass fibers which are coated with a polymer coating. Stereolithography and subsequent oven sintering allows high resolution 3D printing

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of transparent and pure fused silica. However, the part size is restricted by the size of the tank holding the silica-polymer mixture. In addition, shrinkage occurring during sintering has to be considered [6].

The current study aims to produce quartz glass for medical components where the additive manufacturing process also has to be performed on semi-finished quartz glass parts such as tubes. Therefore, wire-fed additive manufacturing of quartz glass is investigated where an endless glass fiber is molten with a CO_2-laser.

2. Experimental Setup and Experiments

A CO_2-laser with a maximum output power of 120 W was used as an energy source. The glass printing head consist of a laser focusing lens with a focal length of f = 190 mm and a self-developed glass fiber feeding system. A three axis system is used to move the printing stage and glass substrate. The laser radiation was applied in defocused position perpendicular to the printing stage/glass substrate with spot diameters between 1-15 mm. The glass fiber was supplied under an angle between 25°-60° degrees with respect to the laser radiation. Printing was performed with fiber feed and axis movement in the same (→ →) and opposite (→ ←) direction. The feed rate of glass fiber and the velocity of the axis movement were kept at the same speed.

The supplied glass fiber diameter was approximately 0.5 mm. The glass fiber has a polymer coating with a thickness of 50 µm. The polymer coating is necessary to feed the fiber without breakage. The coating evaporates during laser processing without affecting the deposited quartz glass quality which was shown for welding of quartz glass [8]. Printing was performed on quartz glass plates (HSQ 100 from Heraeus Quarzglas).

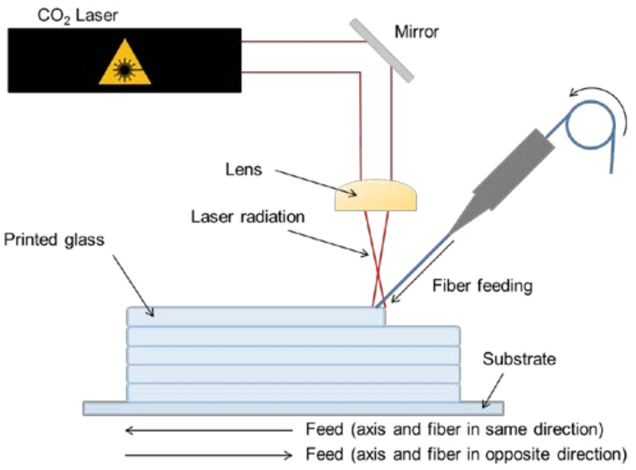

Fig. 1. Sketch of CO_2 laser glass deposition printing setup

The investigations aim to show which combination of glass fiber feeding rate, laser power and velocity of the three axis moving system is suitable to perform reproducible and stable additive manufacturing of quartz glass with glass fibers as supplied additive. Glass layer consisting of five overlying printed glass filaments are produced for each investigated parameter combination. On each glass substrate multiple experiments were conducted with a distance of 20 mm between individual printed glass layers.

The results are classified similar to the investigations of Lou et al. [9] with:

- Evaporation
- Discontinuous printing
- Continuous printing
- Lack of fusion

Nomenclature

f_{fiber} feed rate of glass fiber
f_{axis} velocity of axis movement
P……laser power

3. Results

Figure 2 shows an image which was captured during an additive manufacturing process. The magnification (lower right corner) was taken with a grey filter in front of the camera. The figure illustrates how the experiments were conducted, printing straight glass layers with a distance of 20 mm.

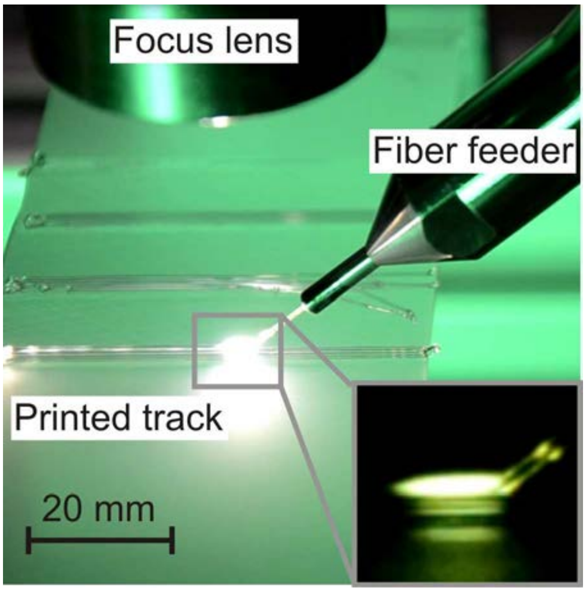

Fig. 2. Process image

Figure 3 shows the results of the process investigations. Two laser powers (P = 90 W and P = 120 W) were used. The feed rate of the glass fiber and the velocity of the axis movement were kept at the same speed. The direction of the axis movement and the fiber feeding was set in the same (→ →) and opposite (→ ←) direction. At low feed rates evaporation occurs due to overheating of the glass fibers. With increasing feed rates the process shifts from strong evaporation to discontinuous printing. The top image of Figure 4 shows a result within the discontinuous printing regime. In this case the glass fiber temperatures are too high which leads to a very low viscosity of the fiber resulting in deposition of single quartz glass droplets. It has to be noted that these droplets are deposited in a very reproducible manner so that the deposition occurs in constant distance and on top of each other.

To achieve continuous printing (see Fig. 4 bottom) where the glass fibers are fused on top of each other, the feed rates have to be increased. The process window is larger when using the higher laser power of P=120 W. At P = 120 W, a wide process window of approximately $f_{axis} = f_{fiber} = 200 – 300$ mm/min was found. Moreover, it was also investigated that printing should be performed with fiber feeding and axis movement in the same direction due to a slightly greater process window. When the feed rates exceed 300 mm/min, heating of the fibers is insufficient so that no fusion occurs between the individual layers.

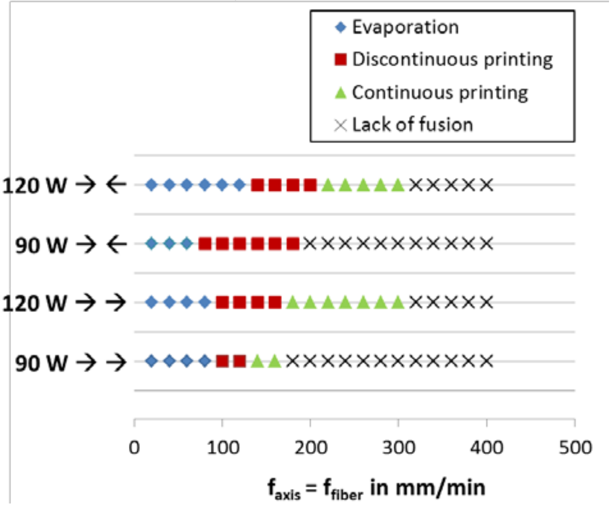

Fig. 3. Process regimes with respect to laser power, f_{axis}, f_{fiber} and direction of axis and fiber movement: → → fiber and axis movement in same direction; → ← fiber and axis movement in opposite direction.

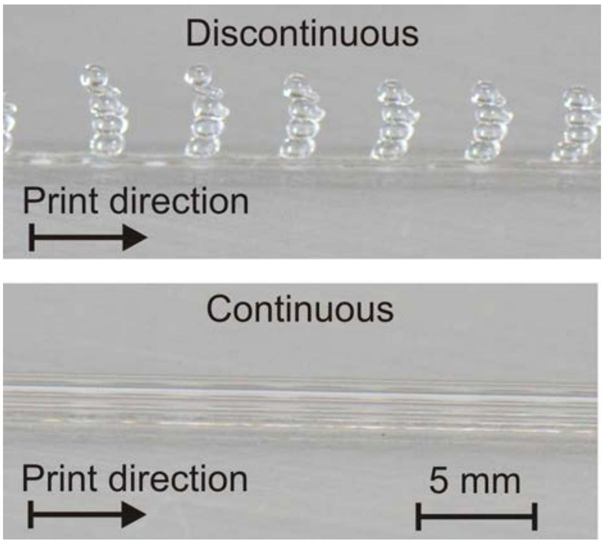

Fig. 4. Top: Printing result within the discontinuous regime (P= 120 W; f_{axis}=f_{fiber}= 150 mm/min); Bottom: Printing result within the continuous regime (P= 120 W; f_{axis}=f_{fiber}=250 mm/min);

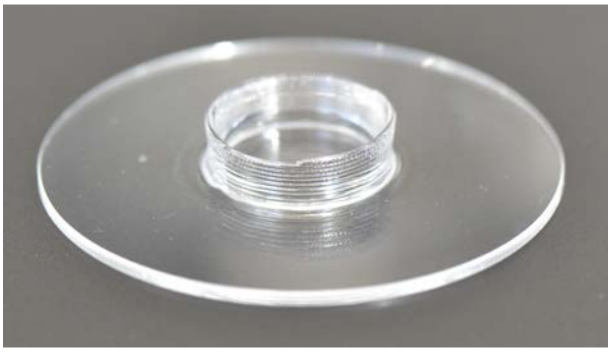

Fig. 5. Printed quartz glass cylinder with a diameter of 20 mm and 10 overlying glass layers, P = 120 W, f_{axis}, = f_{fiber} =250 mm/min, →→.

The process investigations were used to create a cylinder with 20 mm diameter which consists of 10 overlying glass layers, Fig. 5. For this purpose, a rotational axis was used and printing was performed with fiber feeding and axis movement in the same direction. The created cylinder is free of cracks and pores and shows a homogenous connection between the individual layers.

4. Conclusion

Additive manufacturing of quartz glass is feasible by using a CO_2-laser which melts a continuously supplied quartz glass fiber. In order to create overlying structures consisting of multiple glass fibers, the heat input has to be controlled. A too high heat input occurring at low feed rates leads to strong evaporation and discontinuous printing. At high feed rates with insufficient heat input and temperatures, fusion between the individual fibers is not present. A reasonable process window was found which allows the creation of arbitrary printed quartz glass structures. The presented method is aimed to replace conventional manual quartz glass production processes.

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