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Experimental investigation on lateral path overlay and the degree of mixing of additively manufactured soda-lime and borosilicate glass structures.

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Abstract

In the presented paper, the influence of the lateral distance between the deposited lines on the geometric dimensions and the degree of mixing of additively manufactured glass structure is investigated. Initial experimental investigations have shown that additive manufacturing of quartz, soda-lime and borosilicate glass is possible when material- and process-specific process parameters are taken into account. Using a CO_2-laser, the silicate glasses and the rod-based additive material are melted. For this experimental investigation, the ratio between welding and feeding speed of the filler material, as well as the laser power, is kept constant. The fabricated structures are subjected to post heat treatment to relieve thermally induced stresses and are examined with photoelasticity. Geometrical dimensions, such as layer height, width and bond angle, as well as the degree of mixing are quantified after materialographic sample preparation. The knowledge is used to optimise near-net-shape additive manufacturing of glass components.

Keywords: soda-lime-glass; borosilicate glass; CO_2-laser; 3D-Printing;

1. State of the art and motivation

The application range of additive manufacturing technologies extends from the production of prototypes to functional and real parts. Characteristic is the layer-by-layer production, which offers many advantages in the implementation of complex geometries, combination of different materials and the processing of materials that are difficult to process [1].

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Examples include glass construction, optics, electrical engineering, semiconductor, chemical, pharmaceutical and food industries when silicate glasses are used. Fused quartz or/and borosilicate glass is used when chemical resistance, thermal shock resistance and optical properties are required. Soda-lime glass is used in the food industry as hollow glass and in glass construction as flat glass. For complex glass constructions, simple glass components represent the initial state, which are processed and joined using mechanical and thermal processes. Especially for small batch sizes and complex glass constructions, the processing is carried out in a manual and multi-stage process. Generally, a gas flame serves as the energy source for the thermal processes, such as forming and joining. The increase in energy efficiency, machining and processing with one process and the reduction of the necessary process steps motivate the development of additive manufacturing processes for the production of individual fused quartz, borosilicate and soda-lime glass structures.

Additive glass structures were produced by Klein et al. [2] using the principle of fused deposition modelling (FDM). The clear visibility of the applied fused layers is a characteristic feature of the process. To create a flat surface, an additional post-processing step is necessary. The process temperature required to process the different silicate glasses in the FDM process leads to a high energy input and a high thermal load on the technical periphery.

A process for the additive manufacturing of geometrically fine quartz glass structures based on stereolithography was shown by Kotz et al. [3]. Glass particles are added to a UV-curable polymer mixture and preformed into green parts. In a subsequent sintering process, the polymer mixture is debinded and a transparent quartz glass structure is created. Special attention is paid to shrinkage during sintering.

Selective laser sintering (SLS) and selective laser melting (SLM) are based on powder materials and are among the most common processes to produce complex three-dimensional structures, especially for metals [4, 5]. In both processes, a laser beam that moves relative to the powder bed serves as the energy carrier. The powder material is heated locally until it sintered (SLS) or melts (SLM). In both processes, the challenge of a continuous process is due to the high energy absorption of the laser beam in a thin layer of a few µm and the associated risk of sublimation of the material. Powder adhesions are found at the edge areas of the additive structures, which lead to target geometry deviations and rough surfaces. The density of borosilicate glass structures after laser sintering and the subsequent annealing process was investigated by Klocke et al. [5]. The investigations showed that densities of up to 97% can be achieved. Increasing the density in a subsequent annealing process leads to greater shrinkage and thus to greater geometric deviation of the component.

Using the SLM process, Khmyrov et al. [6] produced three-dimensional quartz glass structures. In the experimental investigations, defects in the form of imperfections were found in the structure. The challenge for the SLS and SLM processes is the densification of additively manufactured components to produce transparent structures without defects.

The advantage of wire-guided processes over powder-based processes in the additive manufacturing of transparent structures was demonstrated by Kinzel et al. [1]. The focus of the investigations was on the adjustment of optical properties of additively manufactured structures made of fused quartz [8], borosilicate glass [1] and soda-lime glass [7]. The geometric accuracy of the layers for an additive structure build-up was not the focus of the investigation, as the components are mechanically reworked for the optical evaluation. A special wire feeder was developed for the wire-guided process. In the case of fused quartz, the wire diameter was 0.5 mm. For a non-destructive feeding of the thin wires, a coating with a polymer was necessary. The feasibility of continuous deposition welding of a fused silica fiber with polymer coating was confirmed with a similar setup by von Witzendorff et al. [9]. In both [1,7,8] and [9], a CO_2 laser serves as the energy source for heating the base and filler material.

This paper presents an experimental study on the influence of the distance of the deposited lines on the layer geometry of a one-layer-structure. With respect to the complex handling and process control of a wire-based feed material with polymer coating, soda-lime glass rods with a diameter of 3 mm and borosilicate glass rods with a diameter of 2 mm without coating are used. The additional material is fed into the resulting melt pool, which is realised by a CO_2-laser beam. Based on the findings of previous experimental studies, these are considered as the initial condition of this study [10]. In the first experiments one-layer-structures are generated. In order to show effects on the geometry during the layer-by-layer build-up in height, multi-layer-structures with three layers are generated.

2. Experimental Setup

The experimental setup is shown schematically in figure 1. The object table is moved in the three-room directions by linear axes driven by stepper motors. CO_2-laser, feeding unit, furnace bell and object table are controlled by a CNC card controller. The operating point of the laser remains constant. Due to the low thermal shock resistance of soda-lime and borosilicate glass compared to fused quartz, the process chamber inside the furnace bell is heated to approximately 774 Kelvin and the temperature is maintained during the process with a variance of +/- 15 Kelvin. The types of glass used for the experiments are soda-lime glass (AR-Glas®) and borosilicate glass (Duran®) produced from the SCHOTT AG. The substrate plates used have dimensions of 50 mm in length, 50 mm in width and 3 mm in height. The additional material is a glass rod made of soda-lime glass with a diameter of 3 mm and borosilicate glass with a diameter of 2 mm.

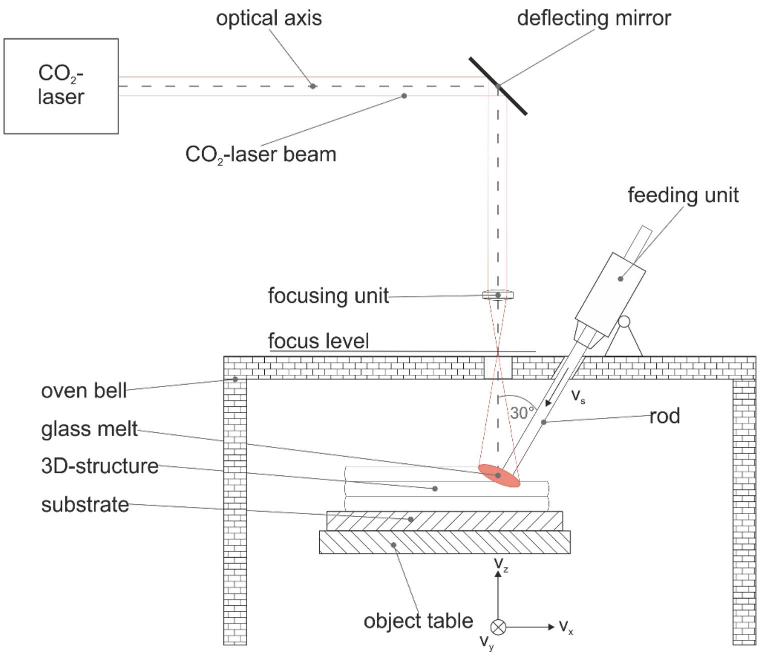

Fig. 1. Schematic sketch of the experimental setup for the experimental investigation

The CO_2 laser beam source used (Synrad firestar f201, λ = 10.6 µm,cw) is aligned perpendicular to the substrate. The interaction area between defocused laser beam and substrate has a diameter of 10 mm.

The stepper motor feeds the additional material into the melt pool at a constant speed of 1 mm/s via a linear guide. This is a proprietary development. The angle at which the additional material is fed is kept constant at 30° in the experimental investigation. The feed direction is perpendicular to the direction of movement of the object table. After additive manufacturing in the process chamber, all specimens have been stored in an annealing furnace. The specimens were thermally treated at 854 K +/- 10 K over a period of three hours. Afterwards, the specimens were cooled down to room temperature in a closed furnace.

From the previous investigations [10], an optimal process parameter was selected for the geometric dimensions and kept constant throughout the tests. A laser power of 79 Watt with a variance of +/- 4 Watt, an object stage speed of 1 mm/s and a height adjustment of Δz = 1 mm proved to be optimal.

3. Results

The experimental begin with determining the geometric dimensions of the specimen with the process parameters mentioned in Chapter 2. Fig. 2 depicts the cross-section of an applied layer. Based on an average layer width b of 5 mm, a layer height h of 1.2 mm and a bond angle of approximately 70°, the experimental plan was set up.

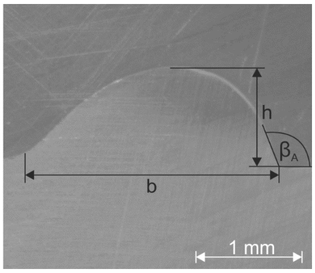

Fig. 2. Geometry drawings of the additively manufactured layer, with the width b, the height h and the bonding angle β_A

Two printing strategies were selected for the additive manufacturing of a one-layer-structure and the variation between the deposited lines. In the first printing strategy, all deposited lines have the same processing direction, while in the second printing strategy the following deposited line has the opposite processing direction (see figure 3).

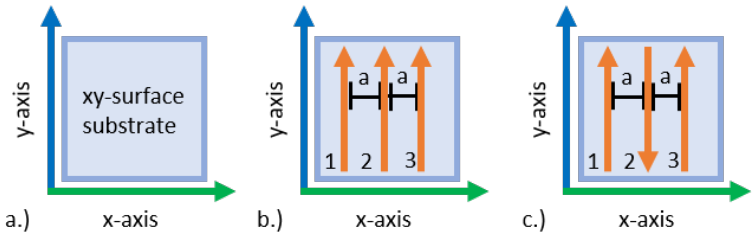

Fig. 3. a.) explanation of the symbols, b.) print job with the same direction of the deposited lines, c.) print job with different directions of the deposited lines, in the subfigures b.) and c.) the a stands fort the distance between the deposited lines

The distance a between the deposited lines was varied as shown in Table 1, based on the already mentioned geometry of the optimal process parameters. The result of one run is a bead-on-plate or a a sort of cladding, which is the starting for additive manufacturing. The number of claddings was adjusted in each case to the maximum number in relation to the substrate width. The length of a deposited line is 35 mm. The structure was build up to a height of three layers.

Table 1. Variation of the distance a between the deposited lines of a one-layer-structure

Experiment number	Distance a (mm)	Number of deposited lines
1	5	8
2	4,5	9
3	4	10
4	3,5	11
5	3	14
6	2,5	16
7	2	18

After the investigation was carried out, the resulting specimens were measured non-destructively using the principle of stripe light projection with a GOM ATOS system. The measuring head is an ATOS Core 45 and has a measuring volume of 45 mm x 30 mm x 25 mm (L x W x H). The measuring point distance and thus the accuracy of the system is 0.018 mm.

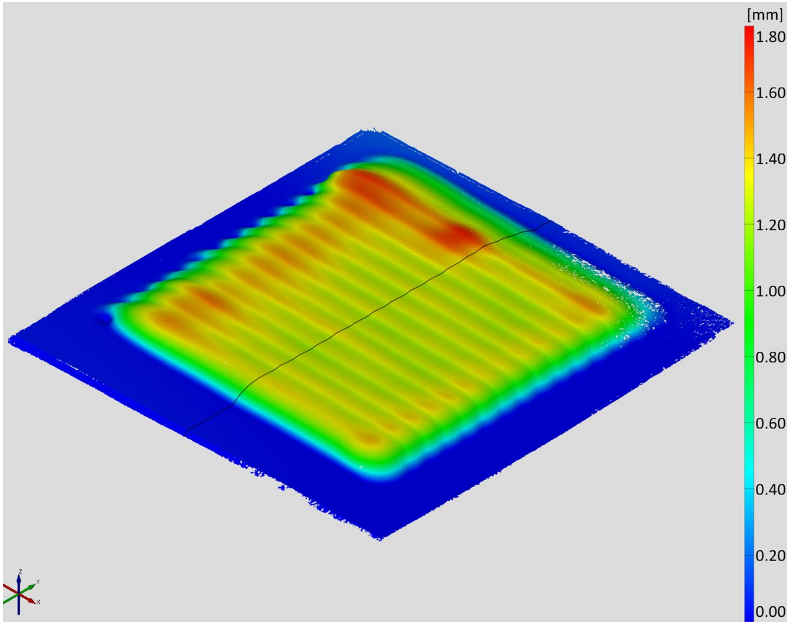

Fig. 4. Plot of a measured borosilicate glass specimen with a weld line distance a of 2.5 mm in false colors to show the layer height in relation to the substrate surface. The black line in the middle of the deposited lines shows the measuring points for the following evaluation of the layer height.

Figures 5 and 6 contain the cross-section profile measured by GOM of the specimens broken down by glass type, processing direction, deposited line distance and number of layers. The geometric dimensions of the individual layers can be reproduced well in the experimental set-up with soda-lime glass and borosilicate glass. The bond angles of the outer right and left layers are between 100° and 110° for both processing directions and glass types. All borosilicate glass specimens show no stress crack. Soda-lime glass specimens were exposed to a large temperature gradient when moved from the processing chamber to the annealing furnace, so that some specimens show stress cracks.

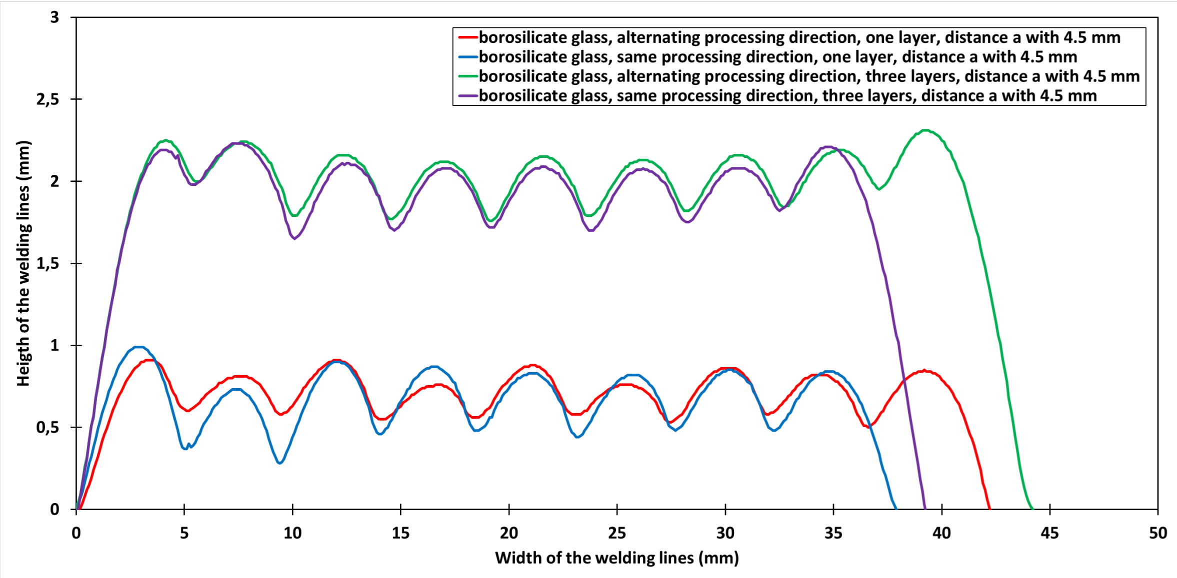

Fig. 5. Cross section of borosilicate glass specimen with a line distance a of 4.5 mm, one layer and three layers. The height was measured as shown in Figure 4, by the black line in the center of the specimen.

The cross-sections in figure 5 of the alternating processing direction the deposited lines with one layer and three layers show that every second deposited line has a lower layer height than the previous deposited line. With increasing number of layers, the overall width of the structure increases.

If the distance between the deposited lines becomes smaller, the layer overlap each other and the filling of tales between the layers becomes evident (see figure 6). The overlap also increases the layer height in relation to the initial geometry and the lower distances between the deposited lines. This shows that in relation to the overlap of the deposited lines, the height adjustment for adding more layers must be adjusted as well. Likewise, the bond angle becomes smaller with an increase in the number of layers to 3.

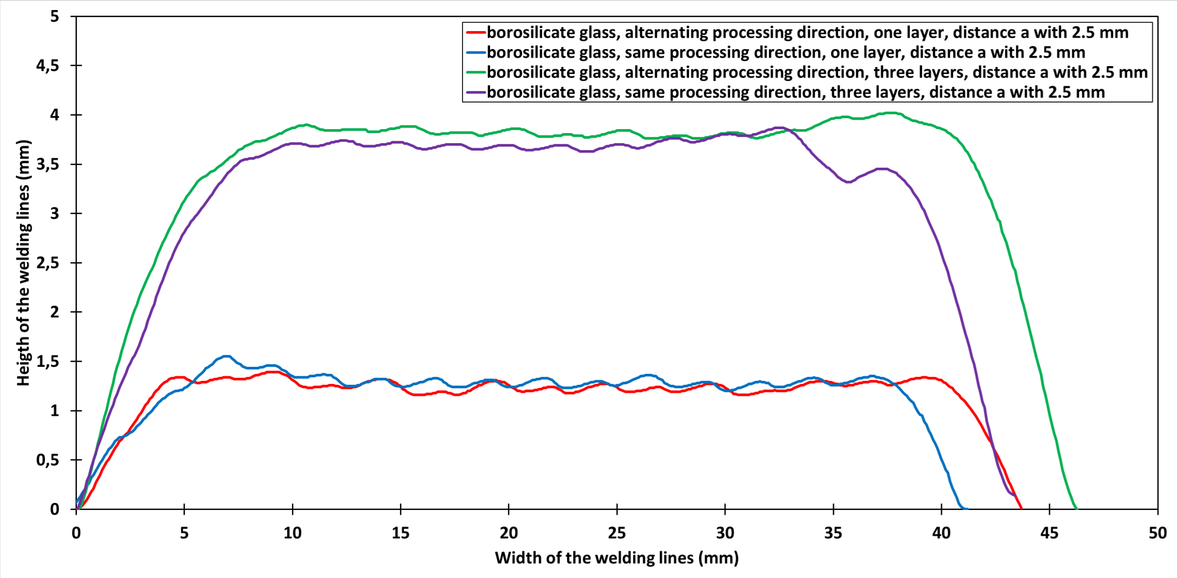

Fig. 6. Cross section of borosilicate glass specimens with a welding line distance a of 2.5 mm, one layer and three layers. The height was measured as shown in Figure 4, by the black line in the center of the specimen.

With the aim of near-net-shape production of a multi-layer-structure, it is shown that for borosilicate glass and soda-lime glass a line spacing of a = 2.5 mm can achieve good results with a small range of the layer height (see Table 2).

Table 2. Average, minimum, maximum and range of the height of the additively manufactured specimens

Specimen description	Average height (mm)	Min. height (mm)	Max. height (mm)	Range of height (mm)
borosilicate glass, same processing direction, one layer, distance a with 2.5mm	1,31	1,2	1,55	0,35
borosilicate glass, alteranting processing direction, one layer, distance a with 2.5mm	1,26	1,16	1,39	0,23
borosilicate glass, same processing direction, three layers, distance a with 2.5mm	3,7	3,55	3,87	0,32
borosilicate glass, same processing direction, three layers, distance a with 2.5mm	3,84	3,73	4,02	0,29
soda-lime glass, same processing direction, one layer, distance a with 2.5mm	2,94	2,78	3,07	0,3
soda-lime glass, alternating processing direction, one layer, distance a with 2.5mm	2,94	2,88	3,17	0,29

4. Conclusion

The investigation show that a near-net-shape multi-layer-structure can be implemented by additive manufacturing of soda-lime glass and borosilicate glass with rod-based base material. Continuous geometries and layer bonding could be produced. The results are the basis for the additive manufacturing of individual three-dimensional structures. Taking the process parameters into account, the geometric dimensions of a multi-layer-structure can be adjusted. The results suggest that larger volumes can be manufactured additively.

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