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CO_2 laser based welding of borosilicate glass by Laser Glass Deposition

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Abstract

Due to its thermal and chemical resistance, borosilicate glass finds a wide range of applications in optics, chemical laboratories and in glass apparatus engineering. For the manufacturing of complex glass components, the welding of semi-finished glass products is essential. In the majority of industry, this is realized by operating gas burners in manual processes with low efficiencies. Here, laser-based processing offers the advantage of local heating with high efficiency, since borosilicate-glass has a high absorption for CO_2-laser radiation. For this purpose, the welding partners are heated with the CO_2-laser, while a borosilicate rod is fed under an angle into the welding zone. In this paper, the welding of borosilicate glasses in butt and 90°-angles using CO_2-laser irradiation is demonstrated. Prior to the manufacturing of the weld seams with additional material and the examination via 3-point bending tests, parameter studies are performed for the welding of blind weld seams with regard to the weld seam geometry.

Keywords: Laser Glass Deposition; Glass Welding; Laser Welding; Borosilicate Glass; Direct Energy Deposition

1. Introduction

Most of the complex glass components are manufactured by joining. There are a number of joining methods for glass components, including adhesive bonding, anodic bonding, optical contact, eutectic bonding, diffusion bonding, and welding [1]. However, the most common of these processes, like the adhesive bonding and the welding, use filler materials for joining, which cannot provide the required joining performance because the filler materials have low temperature and chemical resistance compared to the glass material [1]. The welding process is based on local melting of the joining partners and inclusive joining and cooling [2]. The advantages of glass welding include the monolithic joint, which results in high thermal and chemical stability [3]. Other advantages include the mechanical strength and transparency of the weld [3]. However, despite the superiority of welding in principle among existing joining methods, glass is one of the most difficult materials to weld based on its properties that lead to cracking due to thermal stress [1]. Compared to polymers, glasses have higher optical transmissivity, lower coefficient of thermal expansion, and high chemical resistance [1]. Therefore, they are often used in optics, chemical apparatus engineering, and architecture. For example, borosilicate glass has applications in fields such as optics, chemistry, electronics, and for hermetic seals [4].

Laser beam welding has been applied mainly for metals and polymers since 1984 [2]. The advantages over conventional welding processes include high power density, high welding speeds, local heating of the workpiece, and good automation [3]. Crack-free welds have already been produced for fused silica glass due to its low coefficient of thermal expansion [3][5][6]. Therein, heat conduction welding was used by Pohl et al. [3] to weld fused silica glasses. Due to the low optical penetration depth of the CO_2 laser radiation in the glass, the method of heat conduction welding is suitable and works well for the following investigations. The same setup was later used

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by [5] [6] for the additive manufacturing of fused silica glass. With this in mind, the following results will also be used in future studies on the additive manufacturing of borosilicate glass.

At the present time, no investigations on the CO_2 laser based welding of borosilicate glass have been carried out. For laser material deposition with borosilicate glass, only investigations for additive manufacturing [7] and with short pulse lasers in the micro welding process [8] have been carried out so far. The microwelding process offers the advantage of low thermal stresses, but is limited in gap bridging and alignments of the joining partners.

2. Methods

The general experimental setup is shown in Fig.1. It includes of a CO_2 laser (Coherent Rofin DC045) with a maximum output power of 4.5 kW. The laser beam is directed onto the surface of the borosilicate glass joining partners (Präszisions Glas & Optik GmbH, 2 mm thickness) by the optical beam delivery system. The laser beam is incident via a deflection mirror on a adjustable focusing lens with a focal length of 195 mm. The laser beam is defocused with an adjustable beam diameter of 4 - 8 mm. Due to the laser radiation, the joining partners are heated by radiation absorption and a subsequent energy conversion. To join the glasses, a borosilicate glass rod (1 mm diameter) is inserted laterally under an angle of 45 ° into the process zone at a feed rate v_F. The joining partners are located on a heating plate at 550°C in order to reduce the temperature gradient during the proces, to specifically cool the welded semi-finished product and reduce the thermally induced stresses. The temperature is measured in the process zone by means of a pyrometer (Maurer GmbH) for control purposes, but is set up at a greater distance of approx. 30 cm to protect the electronics due to the high ambient temperatures. The joining partners are located on a motorized linear axis, which travels along the joining zone at a constant speed v_A = 50 mm/min.

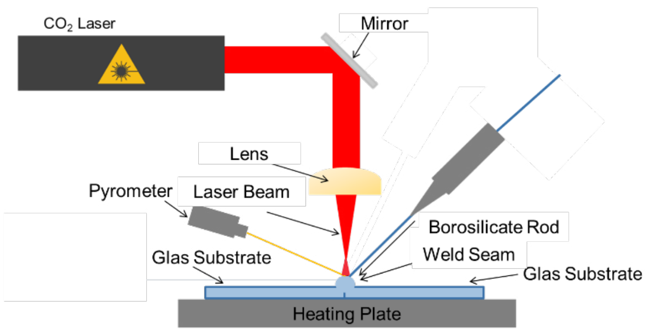

Fig. 1. Sketch of the experimental setup for the laser based welding of borosilicate flat glasses.

To investigate the laser-based weldability of borosilicate glass, blind welds were first performed on the surface of borosilicate glass substrates. The laser power as well as the feed rate are varied. The process parameters and respective value ranges are summarized in Tab. 1. The welded blind seams are qualified based on the weld geometry and process temperature. An example cross-section of a blind weld seam is shown in Fig. 2. The weld geometry is measured by a caliper gauge so that the contact angle can be calculated from the width and height of the path. From the results of these tests, parameters for welding two flat glasses are taken. Welding in butt joint as well as in angle joint are investigated, the welding scenarios are schematically shown in Fig. 3. The thermal stresses are quantified by an imaging polarimeter of the company ILIS GmbH, which uses the principle of stress birefringence for measurement. For the complete release of thermal stresses, the welded parts are annealed in a furnace. Subsequently the flexural strengths of the welded parts were investigated in 3- point bending test.

Table 1. Overview of the process parameter ranges for the described welding process

Process Parameter	Value Range	Dimension
Laser Power P_L	60 – 90	W
Axis velocity v_A	50	mm/min
Rod Feed rate v_F	50 – 200	mm/min
Laser spot diameter	6	mm
Feeding angle	45	°
Temperature heating plate	550	°C
Temperature measurement range	300 – 2500	°C

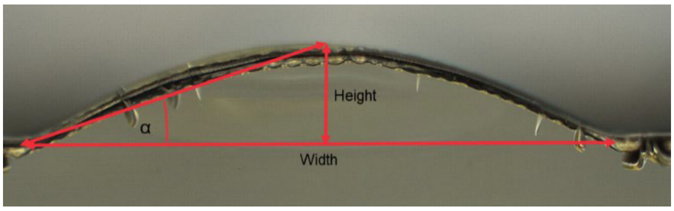

Fig. 2. Image of a cross section of a borosilicate blind weld seam. The typical geometrical aspects, such as the height, width and the contact angle are specified.

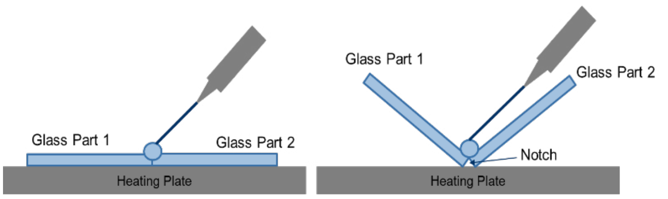

Fig. 3. Sketch of the different laser based glass welding scenarios. Left: Glass parts are positioned in butt formation leaving no gap in between. Right: Glass parts are positioned in 90 ° angle to each other while the corner is located at the heating plate, resulting in the formation of an empty notch.

3. Results

In a first series of experiments, blind welds were performed. Both the laser power P_L = [62, 67, 72, 78, 84, 90] W and the rod feed rate v_F = [50, 100, 150, 200] mm/min were varied. Each experiment was repeated four times to increase the accuracy of the results.

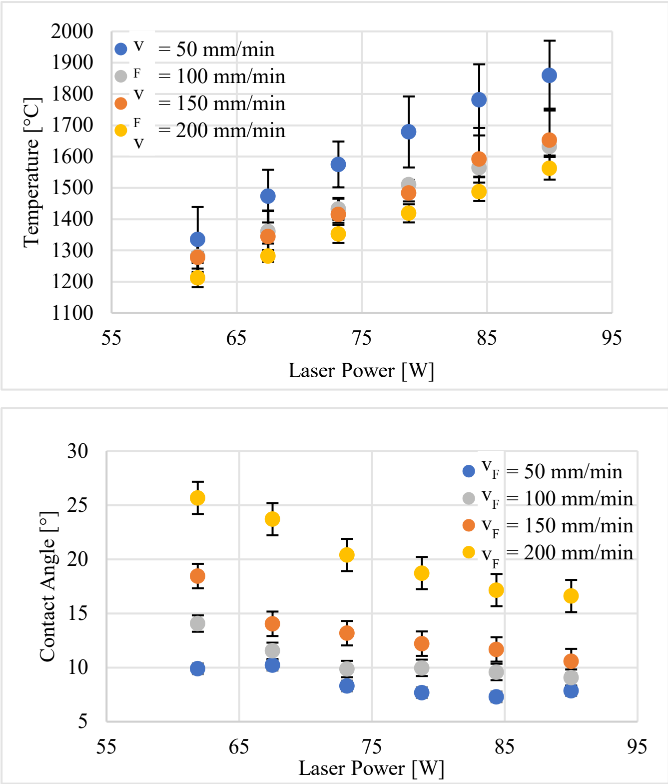

Fig. 4. Graphical representation of the results for blind seam welding with borosilicate glass rods. Top: Graphical representation of the temperature dependence on the laser power for different feed rates v_F. Bottom: Graphical representation of the contact angle dependence on the laser power for different feed rates v_F.

In Fig.4 (Top), the temperature measurements of the process zone are shown graphically. It can be seen that the temperature in the process zone increases linearly with the increasing laser power, because the heat input to the glass also increases. Similarly, a decreasing temperature with increased rod feed rate is observable, since less heat is generated with increasing material deposition, constant heat input and specific heat capacity. Temperatures of 1200°C to 1800°C are reached, which according to [9] corresponds to viscosities below the softening point at 9 dPas and the flow point at 4 dPas.

The deposition morphology of the applied welds was then measured by using a caliper gauge. The contact angle of the blind welds is shown graphically in Fig. 4 (Bottom). It can be seen that the contact angle decreases exponentially with an increase in laser power. The raising heat input due to the increase in laser power leads to a reduction in viscosity, causing the glass to melt further. From Fig.4 (Top) it can be seen that from a power of 78 W a temperature of 1400°C to 1500°C already prevails, which according to [9] corresponds to a viscosity of below 104 dPas. At this viscosity, borosilicate glass is already in the flow range, so that the filament does not melt any further. Further heating above 1500°C would consequently lead to evaporation of the material. These high temperatures can be observed for the low feed rate of v_F = 50 mm/min at already low laser powers of P_L = 67 W. Evaporation is also accompanied by potential contamination of the weld and increased material loss. The high temperatures also lead to process instabilities and spherical deposition of the filler material.

Furthermore, it can be observed that for an increasing feed rate, a generally higher contact angle is achieved at constant laser power. Accordingly, with an increase in vF, the material deposition in the process zone also increases. Since the weld width is limited by the heat-affected zone (the laser spot diameter), the weld width does not succeed 6 mm, resulting in increasing the contact angle. A contact angle below 30° is achieved across all tests, which signifies complete melting of the filament [1].

For the following investigation of the flexural strengths, welds were realized for v_F = [150, 200] mm/min and P_L= [78, 84] W in both, angle and butt joints. These were again repeated 4 times to reduce the error variations. The specimens were tested for strength in a 3-point bend test after annealing. The specimen were annealed in furnace at a temperature of 650°C, which is over the glass transition temperature, and cooled uniformly to room temperature over a period of 8 hours. A polarimeter measurement shows the stresses of a welded specimen before and after furnace annealing and is shown in Fig.5. It can be seen that after oven annealing the thermal stresses were reduced to about 1 MPa at the weld.

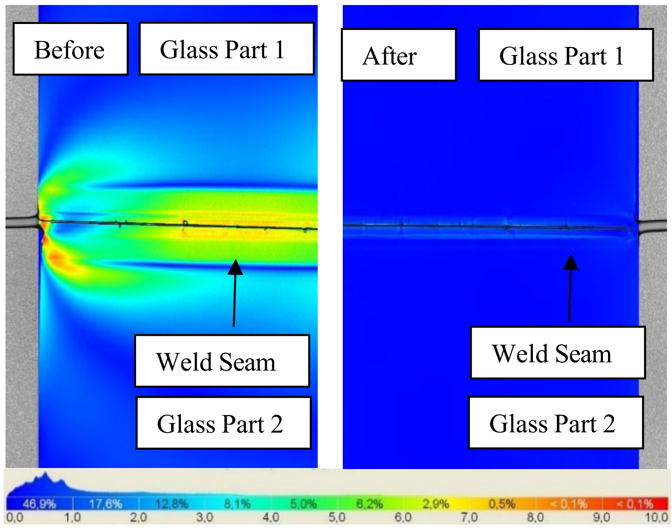

Fig. 5. Polarimeter images of a butt-welded specimen. Left: Before furnace annealing. Right: After furnace annealing. The blue area shows the measuring range and the color scale indicates the respective stress values in MPa.

The results for the flexural strengths tests are shown for the angle specimens in Fig.6 (Top) and for the butt specimens in Fig.6 (Bottom).

For the angle-welded specimens, an average flexural strength of 15 MPa can be measured, which corresponds to 50% of the flexural strength of the reference material, which is a single 2 mm borosilicate substrate, and no change is observable over the P_L and v_F.

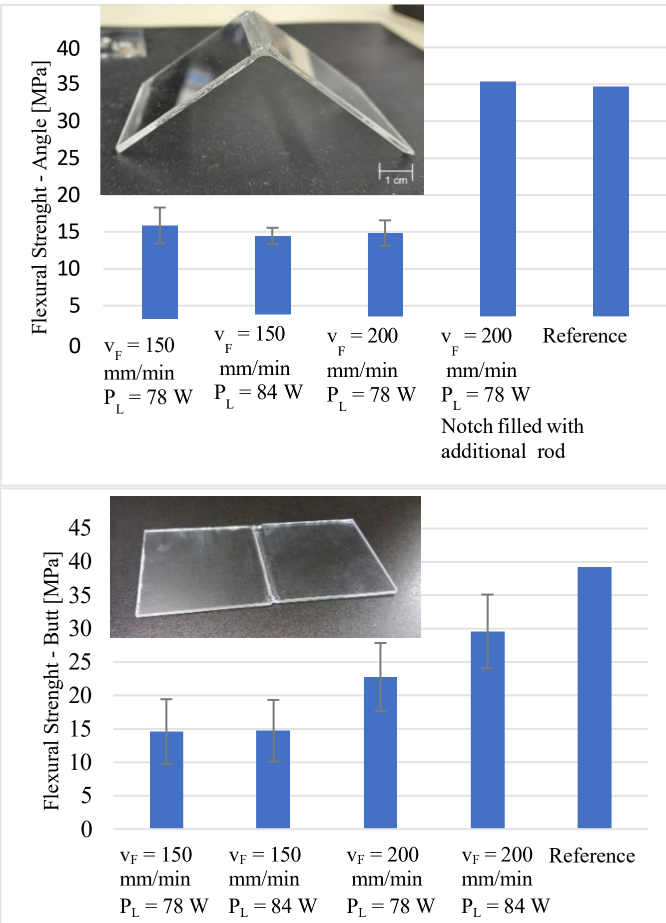

Fig. 6. Graphical representation of flexural strength for different pairings of feed rate and laser power in a 3-point bending test. Top: Specimens welded at an angle of 90°. Bottom: Specimens welded in butt joint. In each case, a reference measurement was taken with a 2 mm thick flat glass as a comparison.

This can be justified by the fact that no through-welding was possible for the angle welding, due to the positioning of the angles on the heating plate, which can be seen in Fig 3 (Right). Indeed, it was only possible to weld on the inside of the angle, since the weld must rest on the heating plate to reduce thermal stresses. By filling the empty notch manually with a piece of glass rod, a through-weld can be simulated. The result of this experiment shows a good approximation to the flexural strength of the reference material. For the specimens welded in the butt joint (Fig 6 Bottom), on the other hand, an increase in flexural strength with increasing v_F and P_L is observable. With the increasing heat and material input, an increasingly higher weld depth could be achieved, resulting in a flexural strength close to that of the reference material. The flexural strength is 30 MPa, which is 75% of the reference material. The achieved bending strengths of 30 MPa or 30 N/mm^2 are in a range which is common for the daily use of glasses.

4. Conclusion

Angle and butt welds of flat borosilicate glass substrates were performed to investigate the weldability using CO_2 laser radiation. For this purpose, blind welds were first performed to identify the process parameters for the welding tests. The blind welds were characterized based on their morphology, process temperature and thermal stresses. Similar to the studies in [7], it was observed that with increasing laser power, the contact angle decreases. The most suitable parameters, resulting in both a low contact angle < 30° and the lowest possible process temperatures < 1500°C, are obtained at rod feeding rates of [150, 200] mm/min. Thermal stresses occurred for all specimens and had to be subsequently annealed. The welded specimens were investigated with respect to their flexural strength in a 3-point bending test. For the angle specimens, an average bending strength of 15 MPa was measured, which corresponds to 42% of the strength of the reference material. For the butt joint specimens, up to 30 MPa could be achieved, which corresponds to 75% of the flexural strength of the reference material. In comparison to the micro welding even higher flexural strength of 95% were achieved in [8]. In further studies, full penetration welding of the specimens can be investigated, as this yields higher strengths. The results of the investigations can find future applications in glass apparatus construction in the chemical and medical industries, where complex semi-finished glass products are usually still welded by hand. Another possible area of application is the additive manufacturing of borosilicate glass for the production of structural components. Here, the additive manufacturing of glass components can be used for structural construction or optical systems such as optical lenses with new shapes and geometries.

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