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Welding of fused silica with femto second lasers enables new design options

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Abstract

We demonstrate laser based joining of glass parts for industrial manufacturing applications. The work pieces are reliably bonded with very good strength. The best results are obtained using ultra short pulses with high and changing repetition rate adapted exactly to a good thermal management with low stress. The process is based on multi-photon absorption inside the bottom glass resulting in joint welding by heat accumulation. The comfortable process window is suitable for industrial production requirements. A sensor identifies the location of the joint. The welding speed is fast compared to ablation processes. An optical contact between the parts is not necessary. The quality of the welding can be evaluated in a non-destructive way. The glass surfaces near the welding process qualify for high laser power utilization because there is no glue involved. The weldings can hermetically seal a glass casing. A range of production tools is set up to manufacture parts. We are convinced that glass can be used as an engineering material with the necessary flexibility to construct complex unities by utilization of femto second laser welding.

Keywords: Welding; glass; bonding; fused silica; femto second laser; ultrafast

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1. Introduction

Glass welding with femtosecond lasers is now ready for industrial practice. Clever heat management prevents tension and cracks occurring in the material. Laser welding supersedes earlier joining methods such as gluing and offers a number of advantages: no additional materials are necessary, no evaporation and embrittlement of materials take place and, consequently, a greater durability is achieved – As an example for this process we demonstrate laser-welded glass protective caps for laser light cables.

2. Challenge of the Joints

The greatest challenge in laser welding of two glass surfaces lies in the joint, where the two components meet. The two parts must fit together exactly. Ideally, there should be no gap between the surfaces of the adjacent components – at most a few micrometers. It is not necessary to have optical contact bonding but the glass surfaces have to be polished. As the laser beam is directed vertically from above down through the upper component and the joint and is focused in the lower component, it is also essential that all surfaces and bodies of the glass facing the laser do not scatter or reflect the light. In addition, the focus of the laser beam must be positioned at a precise distance from the joint. The joint location can either be measured prior to welding or positioned with an accurate fixture which also serves to bring the parts into close proximity. A favored method uses partial vacuum. The pressure does not have any influence on the solidity of the welding.

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3. Welding glass protection caps

Glass components which were previously glued to each other can now be laser welded together economically and with high quality. TRUMPF demonstrates this in its own manufacture of laser light cables. Fig. 1(c) shows a laser light cable (LLK-B) with a connector. This transports up to 16 kW laser power, for example to a robot for the welding of metal sheets. At the end of the cable there is an LLK-B protection cap made of quartz glass. The protective cap is supposed to prevent dirt from coming into contact with the end surfaces of the fibers, which typically exhibit a core diameter of 0.1mm. The high photon density in the fibers would burn dirt immediately and render the cable useless. Hitherto the lid of the protective cap has been glued on, but now it can be welded by laser. Gluing has proved to be an unsatisfactory solution because during the production process the glue does not remain cleanly on the edge of the glass and some tiny droplets of glue might stray onto the inner wall of the cap. This leads to a high reject rate. Laser welding seems to be the better alternative because the welding takes place inside the glass, therefore there is no emission of particles.

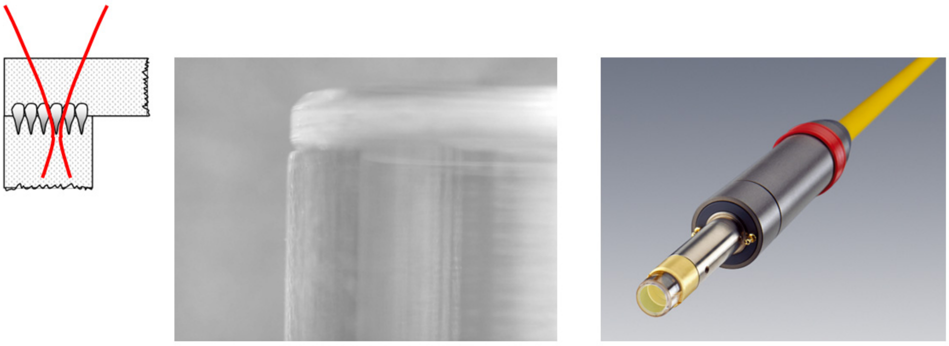

Fig. 1. (a) welding joint with laser beam; (b) protective cap; (c) Laser light cable.

4. Seven-photon absorption starts the melting process

Glass is transparent for wavelengths from ultraviolet to near infrared. This is a major advantage because it enables the process to take place within the glass. The focus of the laser beam is located inside the lower glass component, 270 µm below the joint. A specific density of photons is required to initiate the welding process by seven-photon absorption. For the wavelength of 1030 nm which is used here, at least seven photons or approximately 7 eV are necessary to tear an electron out of its bond in quartz glass. The free electrons released generate an electron gas. This area now becomes opaque to laser light. It works as a process booster; the energy threshold is severely reduced and seven-photon absorption is no longer necessary.

During the melting process different effect zones are created in the glass as shown in Fig.3(c). The highest power density lies deep in the lower glass at the laser beam focus position. The power density is approximately 250 TW/cm². Effect zone 1, which reaches to 15 TW/cm² shows disturbances in the resolidified glass. Below this zone the laser light is scattered without the ability to form melt. Above the first effect zone there is a second zone where, through the creation of free electrons and defects in the glass as well as by the thermal conduction, the isotherm of melting temperature is driven upwards into the upper glass, in doing so crossing the joint.

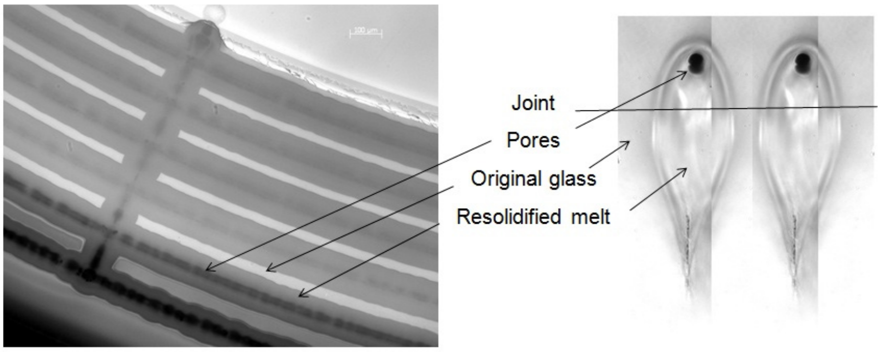

Fig. 2. (a) weld seams from above; (b) melt balloons cross section.

The energy of several thousand pulses causes a melt balloon to be created and extended upwards. Stress regions moving in front of the balloon are located in the upper glass. Stress regions caused by too much power density stay in the bottom glass. The small low-stress zone is positioned in the joint. Stress is prevented further by thermal management. The laser energy is provided in a pulse train with relaxation pauses of different length. Fig. 3(a) shows the temperature progression near to the focus point of the laser beam. The temperature rises to the melt point and then falls and then rises again and then falls away again. This alternation in temperature prevents cracks and tension arising in the welding process because in this way expansion at great heat and contraction when cooling are balanced out.

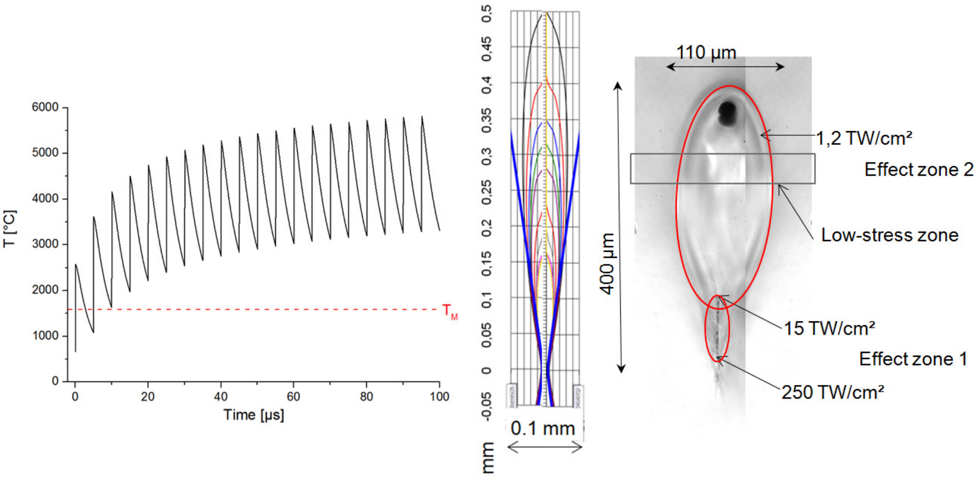

Fig. 3. (a) Temperature graph (source: IAP); (b) Isophotes; (c) Melt balloon.

After several milliseconds the process stops because the photon density at 1.2 TW/ cm² is no longer sufficient and the laser beam has moved on in relation to the work piece to the next weld position where the process begins once again with effect zone 1 in the lower glass. Fig.3 (b) shows the isophotes, which are lines of equal power density. The scale of the isophotes is identical to the scale of the melt baloon picture (c) and is applied to calculate the power densities of the different effect zones.

5. Strength of joint far beyond expectations

The process of laser welding of glass is so reliable that any individual random sample will fulfill quality checks. Breakage tests carried out on welded glass protection caps produced surprisingly positive results. The strength requirement for the test component was set to 35 N. More than twice this strength was achieved on all the samples and the breakage point was not at the welded interface.

The quality of the weld can be checked non-destructively by microscope and in an automated way with the help of image-processing methods. This way, a faulty focus position or gaps caused by dust can be diagnosed.

6. Economic efficiency and new design options

The economic efficiency of the new laser glass-welding process is to be seen first of all in the elimination of all the disadvantages of previous methods such as gluing: optical transparency is no longer obstructed by contamination, there is no evaporation and no long-term embrittlement of adhesives, which means in the case of glass protection caps that they provide much more durable solutions. Furthermore, laser glass-welding makes new options available in the design of optical components or optical housings. Complicated glass geometries can now be constructed of individual parts. This could be a system of – convex or concave – lenses which are inseparably bonded. A further positive aspect is that glass-metal combinations with the disadvantage of different expansion coefficients can now be replaced by glass-glass combinations. In addition, glass housings for electronic or measuring systems can be air tightly welded to maintain a vacuum over extensive time spans. Furthermore, aligned optics can be fixed stably by the glass-welding procedure. The range of applications is enormous and it can already be seen that industrially mature laser welding of glass holds enormous potential for construction engineers and designers in a wide spectrum of industrial branches.

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