Optics & Laser Technology 83 (2016) 59–66

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Review

Laser welding of glasses at high repetition rates – Fundamentals and prospects

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ARTICLE INFO

Article history:
Received 4 November 2015
Accepted 17 March 2016

Keywords:
Ultrashort laser pulses
Welding
Bonding
Micromachining
Heat accumulation

ABSTRACT

We report on the welding of various glasses with ultrashort laser pulses. Femtosecond laser pulses at repetition rates in the MHz range are focused at the interface between two substrates, resulting in multiphoton absorption and heat accumulation from successive pulses. This leads to local melting and subsequent resolidification which can be used to weld the glasses.

The fundamental interaction process was studied using an in-situ micro Raman setup to measure the laser induced temperature distribution and its temporal decay. The induced network changes were analyzed by Raman spectrocopy identifying an increase of three and four membered silicon rings within the laser irradiated area. In order to determine the stability of the laser welded samples a three point bending test was used. Thereby, we identified that the maximal achievable breaking strength is limited by laser induced stress surrounding the modified material. To minimize the amount of stress bursts of laser pulses or an post processing annealing step can be applied. Besides fused silica, we welded borosilicate glasses and glasses with a low thermal expansion coefficient. Even the welding of different glass combinations is possible demonstrating the versatility of ultrashort pulse induced laser welding.

Contents

1. Introduction

Glass plays a dominant role in our daily life due to its excellent optical, mechanical and chemical properties. For the processing of glass numerous techniques as drilling, cutting, or polishing are well known and established. In contrast, the reliable and stable bonding of different glasses is still a demanding problem. All the established methods e.g. optical contacting, direct bonding or anodic bonding exhibit certain disadvantages as these methods were not designed for the bonding of glasses [1,2].

However, in the last decade ultrashort laser pulses have proven to be a powerful tool to locally modify transparent materials [3,4]. The extremely short pulse duration allows nonlinear absorption

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http://dx.doi.org/10.1016/j.optlastec.2016.03.022

processes that fundamentally differ from traditional light-matter interaction leading to an extremely non-equilibrium state in a confined volume. Due to the highly localized energy deposition machining of sub micron features and full three dimensional processing of transparent materials become feasible [3]. In fused silica three different types of modifications can be induced: isotropic and anisotropic index changes [3–9] and the generation of small cavities [10]. In addition, multiple ultrashort laser pulses with a short temporal distance yield the possibility to locally melt the processed material [11]. In this case, the laser pulses act as thermal point source increasing the temperature of the irradiated volume stepwise. Due to heat diffusion also the temperature of the surrounding material increases leading to the melting of the focal region and a well-defined vicinity [12]. This so-called heat accumulation of ultrashort laser pulses provides a powerful tool to locally bond transparent materials [13–17]. Potential applications for laser induced welding of transparent materials are manifold in fields such as microfluidics, optofluidics, healthcare, and small satellites.

Although the first reports about locally induced heat accumulation and melting of transparent materials are published about one decade ago [11,13,18], all the capabilities of ultrashort pulse induced laser bonding are far from entirely explored. There are also demanding issues which have to be resolved in order the use local laser welding for industrial mass production. One example was to avoid the requirement of an intimate contact between the glass samples prior the welding process, which was only recently achieved [19–21]. In addition, the laser induced temperature distribution and the subsequent induction of transient and permanent stress in the glass is of great interest in order to maximize the stability of ultrashort pulse induced welds.

In this paper we want to summarize our results of ultrashort pulse induced laser welding, starting from the analysis of the laser induced heating process, to the subsequent local structural changes and the realization of strong and reliable bonds in various glasses and even different glass combinations.

2. Experimental procedure

For most of the weldings results presented here a femtosecond oscillator providing pulses at a wavelength of 1030 nm, repetition rate of 9.4 MHz, an average output power of 5 W, and pulse duration of 450 fs (Amplitude Systems, t-Pulse 500) was utilized [16] (except otherwise stated). The repetition rate and pulse energy were varied by an external acousto-optic modulator and a halfwave plate followed by a polarizer, respectively. For all experiments an LBO crystal was used to generate the second harmonic (515 nm). An aspheric lens with a focal length of 8 mm (NA 0.5) was used to focus the laser pulses slightly under the interface of two previously optically contacted samples. The principle processing geometry is shown in Fig. 1a. In general, the laser irradiates the sample from the top, however even irradiation from the bottom of the sample is possible, too. The size and shape of the molten region depend on the processing and material parameters. A cross section for a typical thermally induced modification shape is shown in Fig. 1b for both conditions: focusing from the top and from the bottom. Here, we used a pulse energy of 150 nJ, a repetition rate of 9.4 MHz and a translation velocity of 1 mm/min. In both cases, the absorption starts at the initial focal point. After the first seed electrons are produced by nonlinear ionization these free electrons can linearly absorb single photons. Thus, the position of the main absorption moves towards the focusing lens and the laser modification volume becomes elliptic [15]. The large dark spots in the modified area are so-called disruptions consisting of a foam-like inner structure with hollow cavities ranging from a few hundreds of nm up to 2 μm which are formed during the rapid cooling of the glass after laser irradiation [22]. These disruptions are always located in the part of the modification which is close to the focusing lens as this area possess the highest temperature and quenches at last. In addition to the large disruption, Fig. 1b shows even smaller dark modifications within the molten zone above the large disruption when focusing from the bottom. These might be gas bubbles formed during the laser irradiation. Subsequently, the gas bubbles rise within the molten pool due to buoyancy force [23]. However, even when focussing from the top, multiple of voids and disruptions can be formed within the molten area depending on the processing conditions [22]. Thus, more experimental results are required to resolve this issue.

To inscribe continuous welding seams the samples were translated (translation velocity between 1 and 200 mm/min) with respect to the laser focus. In fused silica, the induced welding seams exhibit a bright color reducing the transparency of the modified area due to scattering (as shown in Fig. 1c).

For the results presented here, the samples were optically contacted prior the laser welding to ensure an intimate contact between the surfaces. Optical contacting requires a sample roughness of 2 nm and a flatness below 125 nm. Recently, several groups succeeded in local welding of various glasses without optical contacting [19–21]. In our work [20], we placed the laser focus in the lower sample and generated a large pool of molten material. As soon as this molten material hits the upper surface of the lower sample the molten material is ejected filling the gap between the samples. By this technique even a gap of up to 3 μm could be bridged [20]. Fig. 2 shows the bulged surface and the ejected material atop of the initial surface. For this experiment, we utilized the above mentioned Amplitude t-pulse system, but here the amount of ejected material is rather low. In order to bridge larger gaps one has to increase the pool of molten material, which can be done by a more powerful laser system (TRUMPF, TruMicro 2020) as described in [20].

To analyze the stability of bonded samples different tests can be utilized. However, the typically used blade [24], shear [15,25,26] or tensile tests [18] are difficult to compare and allow no conversion between the different results [27]. Thus, we used a three point bending test allowing us to compare the determined breaking strength to the value of the pristine bulk material [28]. To this end, the blanks were cut into rectangular rods with defined dimensions after the welding process. In a next step, the bonded interface was placed at the center between two bearings directly below the stress pin applying a defined force F. Each set of parameters was used several times to estimate mean value and standard deviation. The breaking strength σ can be calculated from the force F required to fracture the bonded samples [16,28].

3. Results and discussion

3.1. Laser induced temperature distribution

To understand the welding process, a detailed knowledge of the real temperature dynamic is required. So far, only a few experiments are reported, which are capable to measure some aspects of the temperature distribution [29]. For example, Shimizu et al. presented a method to calculate the temperature distribution within a special glass after the laser irradiation by changing the ambient temperature during the laser irradiation [30]. However, this method is limited to a few special glasses and yields no information about the temperature dynamics.

Another very promising technique is to measure the ratio between Stokes I_S and Anti-Stokes I_{AS} Raman scattering [31] which depends basically on the temperature T reflecting the Boltzmann