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Direct bonding of transparent PMMA using an ultrafast fiber CPA laser system

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Abstract

Laser welding of transparent materials with micrometer precision is attracting growing interest in several application fields, especially for the assembly of biomedical devices.
In this work, we exploited the flexibility of focused laser light to weld two transparent 1-mm-thick layers of polymethyl-methacrylate (PMMA) in a lap-joint configuration. A high repetition rate ultrafast fiber CPA laser system delivering pulses ranging from 15 ps to 650 fs at the wavelength of 1030 nm was used for our experiments. Non-linear absorption and heat cumulative processes originated in the focal volume by the high repetition rate (> 200 kHz) produced localized melting of the polymer at the interface between the two layers.
The influence of the pulse width on the morphology of the laser-induced modifications in the bulk PMMA was evaluated exploring a wide range of repetition rates and pulse energies.
An appropriate set of process parameters was found able to generate continuous and localized melting of the material. Based on these results, ultrashort pulsed laser lap welding of two 1-mm-thick PMMA layers was demonstrated. A simple microfluidic polymeric device has been then assembled taking advantage of this novel joining technique and the effectiveness of the sealing has been proved by a static leakage test with injected fluid pressures up to 1 bar.
The intrinsic flexibility of the proposed ultrashort-laser micro-welding technique to seal microfluidic devices with complex geometries without the need for any absorbing layer or chemical additive which could in principle contaminate the

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biological samples, make this technology very promising for the direct laser fabrication of transparent polymeric microfluidic devices.

KeyWords: Fiber laser, Welding, Ultrafast laser micromachining, Transparent Materials, PMMA

1. Introduction

Polymethyl methacrylate (PMMA) has lot of potential applications in optics, electrical and biomedical fields due to its high optical transparency, processability and low cost (Becker and Locascio, 2002). The disadvantages is that for PMMA, such as for glasses, only few joining techniques are available. Generally, these techniques involve the use of adhesive agent or interlayer, which could cause poor mechanical, thermal and chemical stability and the contamination of the sample. Direct ultrashort pulsed laser lap bonding is considered to be one of the most promising method for joining transparent materials, as it provides high precision, small thermally affected zone while eliminating the effect of creep and the need for any interlayer material. In fact, among the advantages of ultrashort pulsed laser systems is the possibility to precisely position the optical absorption region in the bulk material exploiting non-linear interactions at the beam focus, thus leaving the rest of the sample unaffected (Mingareev et al., 2012). In case of lap joining, the ultra-short laser pulses are focused at the interface between the two layers, generating a heated zone which is highly localized. Through melting or micro-plasma generation any small gap between the layers is filled and a solid joint is created with minimum thermal stress of damage of the surrounding material (Watanabe et al., 2006).

To date most research has focused on the use of both femtosecond (Tamaki et al, 2005) and picosecond pulses (Carter et al., 2014) for weld similar and dissimilar glasses exploiting either multiphoton ionization or avalanche ionization, which are the two mechanisms responsible for the non linear absorption of ultrashort laser pulses,. Picosecond pulses have been shown to be more attractive than femtoseconds thank to the higher simplicity of the laser source and the higher melting and joining efficiency as a heat source for welding glasses. Moreover, the picosecond regime provides higher nonlinear absorptivity due to the larger contribution of avalanche ionization (Miyamoto, 2007).

Ultrashort laser lap-welding of two transparent layers of PMMA was recently reported using fs laser pulses at high repetition rate taking advantage of non-linear absorption and heat accumulation (Volpe et al., 2015).

In this paper, we deeply investigate the laser-induced melting process of bulk PMMA by ultrashort pulses, focusing on the comparison between the fs and the ps regime using a 1030 nm high repetition rate fiber CPA laser system. Firstly the ultrashort laser induced modification are investigated with single lines scanning in the bulk PMMA exploiting non linear absorption and heat accumulation. Finally, a window of appropriate process parameters is identified and used to seal a PMMA laser fabricated microfluidic device.

2. Experimental setup

The experiments were performed at room temperature in ambient air. We used a chirped pulse ultrafast fiber laser amplifier from Active Fiber Systems GmbH, delivering an almost diffraction limited beam (M^2~1.25) at a wavelength of 1030 nm with pulse durations in the range from 650 fs to 20 ps, repetition rate varying from 50 kHz to 20 MHz, maximum pulse energy of 100 μJ or maximum average power of 50 W. The beam was magnified with a beam expander and then focused into the sample through a 0.3 numerical aperture lens mounted on a computer controlled motorized stage (Aerotech Pro115), which enabled precise positioning of the beam focus inside the bulk of the PMMA work-pieces. The samples were fixed on a XY motorized translation stage (Aerotech Pro165LM) with micrometre resolution.

High purity PMMA specimens (Vistacryl CQ, Vista Optics Ltd) with high surface quality (Ra≈2nm) were used without any pretreatment of the samples. The preliminary screening tests were performed on 3-mm-thick

specimens, while the laser-lap-welding experiment on two 1-mm-thick layers clamped together by a mechanical fixture ensuring a uniform adherence between the two plates over the entire irradiated area. In the latter case the laser bonding was performed in the in the region where the air gap was below approximately λ/4 by observing white light fringe pattern in the sample from the above.

After laser irradiation, the ultrashort laser induced modifications were analyzed through optical microscopy. In order to test the quality of the weld, static leakage tests have been carried out on a microfluidic device which consisted of two laser-bonded layers comprising a microchannel connecting two reservoirs. The weld region surrounded the entire contour of the channel. One reservoir was connected to a microfluidic pump (MFCS-EZ, Fluigent) while the other was closed. The sealing test consisted in injecting a blue-colored fluid at increasing pressures, from 100 mbar to 1 bar with 100 mbar steps (each pressure value was maintained for 3 minutes) while any fluid leakage was monitored during the experiment by inspecting the welded area with an optical microscope.

3. Results and discussion

3.1. Single line melting experiments

For the single line experiment the laser beam was positioned 1.5 mm beneath the surface of a 3mm-thick material. Several tests were conducted at 200 kHz, 500 kHz, 1 MHz, 5 MHz and mean power ranging from 0.1 W to 10 W. The scanning speed was 0.1 mm/s.

Each test was performed with 650 fs pulses and 18 ps pulses, respectively, in order to compare the influence of the pulse duration on the material modification. Figure 1 shows the microscope top view of single lines produced in the bulk PMMA with both investigated pulse lengths at a speed of 0.1 mm/s and a repetition rate of 500 kHz at different pulse energies ranging from 0.2 µJ to 12 µJ.

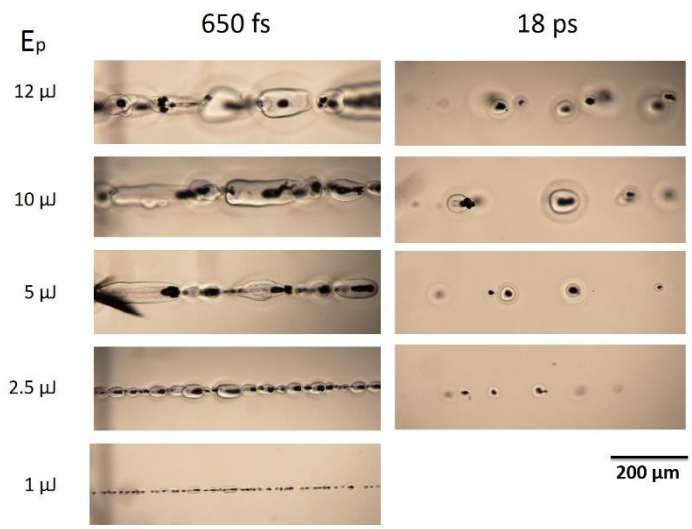

Fig. 1. Microscope top view of single line modifications obtained with 650 fs and 18 ps laser pulses at different pulse energies E_p. The repetition rate is 500 kHz, the translation speed is 0.1mm/s .

Dark spots are observed in each track. These laser induced defects are typically attributed to a fast laser-matter interaction generating a micro-explosion that occurs within the focal volume (Gamaly et al., 2006). The line modification becomes more continuous increasing the pulse energy for both pulse durations. This is probably due to the photoionization rate increase with the laser intensity. At 1 μJ in the ps regime no modification of the specimen has been observed. This clearly demonstrates that the peak power has a significant role in triggering changes of the materials. Indeed, for a given pulse energy at a pulse duration of 650 fs the peak power is two order of magnitude greater than for 18 ps of pulse length.

A steady material modification using longer pulses can be obtained only by increasing the pulse energy in order to have enough peak power to overcome the modification threshold. However, for higher pulse energies the enhanced thermal stress induced into the material produces cracks propagating towards the beam incidence direction up to the sample surface, as exemplarily shown in Fig. 2.

Fig. 2. Microscope top view of cracks in a single line modification obtained with 18-ps laser pulses at 20 μJ of pulser energy. The repetion rate is 500 kHz, the translation speed 0.1mm/s.

Figure 3 shows the comparison between two modification traces obtained for a given average power of 2 W, a repetition rate of 1 MHz and different pulse length of 650 fs and 18 ps, respectively. A more continuous modification is obtained with shorter pulses, due to the higher peak power. The side view of the same tracks shows that in both cases the modifications are buried in the bulk material.

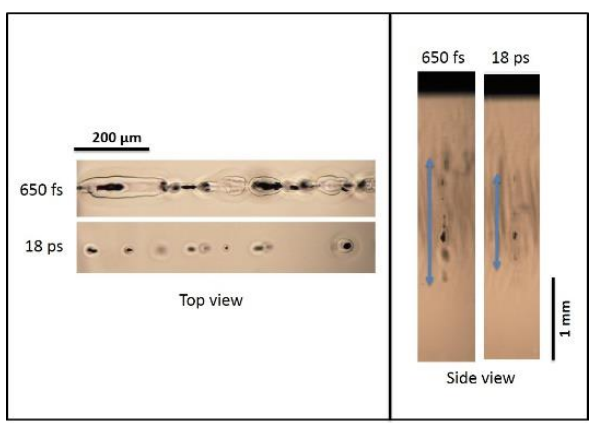

Fig. 3. Microscope top view and side view of single line modifications produced with 2 W of average power with different pulse durations. The translation speed is 0.1mm/s. The repetition rate is 1MHz. In the side view the laser beam hits the sample from the above.

Fig. 4 shows the line modifications produced in the bulk PMMA using 650 fs laser pulses at a pulse energy of 1 µJ for variable repetition rates. The pulse energy is significantly above the material modification threshold.

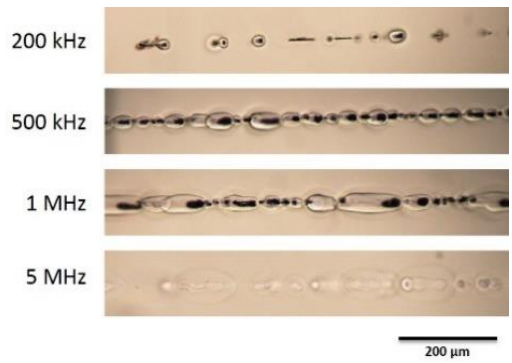

Fig. 4. Microscope top view of single line modifications with different repetion rates at 1 µJ of pulse energy. The pulse duration is 650 fs, the translation speed is 0.1mm/s.

Here, it is evident the contribution of heat accumulation which helps to produce more continuous melting at higher repetition rates.

Analogous results are presented in Fig. 5 with 18-ps-laser pulses at a higher pulse energy of 2.5 µJ. For longer pulses the heat accumulation contribution comes into play at much higher repetition rates. Below 1 MHz the line modification looks similar and very discontinuous, whereas at 5MHz heat accumulation compensates for the low peak power and a continuous melting trace can be noticed.

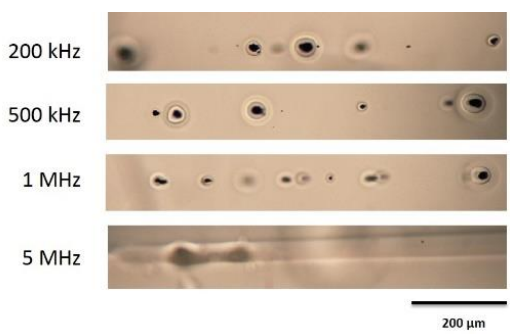

Fig. 5. Microscope top view of single line modifications at different repetion rates at 2.5 µJ of pulse energy. The pulse duration is 18 ps, the translation speed is 0.1mm/s.

At high pulse energies and repetition rates the line modifications obtained in the ps and fs regime become similar and continuous for both pulse lengths (Fig. 6). However, the enhanced thermal load to the material causes thermal stresses which frequently originate cracks, propagating towards the sample surface. Furthermore, the melted zone is not anymore buried in the bulk material, but extends almost over the entire thickness of the specimen. This results in losing the main advantage of ultrashort laser pulses to produce a melted area limited to the focal volume, thus enabling sealing of microfluidic devices with a micrometer precision and minimized thermal distortions.

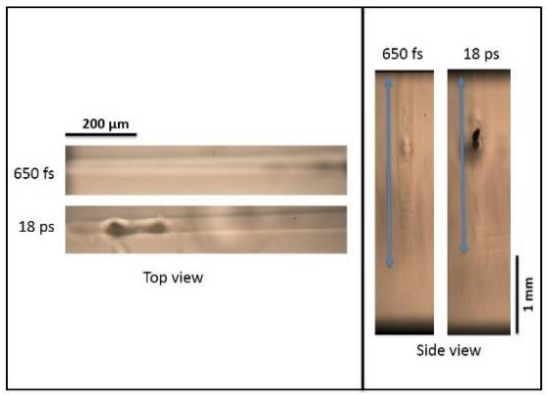

Fig. 6. Microscope top view and side view of single line modifications produced with different pulse durations, an average power of 10 W atranslation speed of 0.1mm/s and a repetition rate of 5MHz. In the side view the laser beam hits the sample from the above.

3.2. Lap-welding experiments

Based on the results obtained in the bulk material, we selected the fs laser pulses as the most convenient approach to obtain a continuous and localized melting of PMMA, avoiding as much as possible the occurrence of cracks. So we keep constant the pulse duration at 650 fs and performed the laser welding experiments of two 1-mm-thick layers of PMMA at 5MHZ, 0.1 mm/s of translation speed and 0.4 µJ of pulse energy. In this condition, we obtain a continuous and localized melting at the interface. Figure 7 shows an example of fs-laser bonding achieved over a wider area by moving the beam along a squared pattern with a lateral displacement between closely spaced lines of 5 µm.

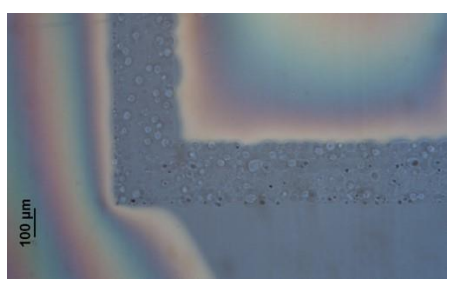

Fig. 7. Microscope detail of a ultrashort laser welded sample along a square path.

With the same strategy, we sealed a simple microfluidic device fabricated by femtosecond laser ablation of a 1-mm-thick PMMA plate. The microfluidic network consists of a 1-mm-length channel with a squared cross section of side 80 µm, which connects two reservoirs of 1-mm diameter (Eaton, 2012). This micromachined layer is clamped and fs-laser welded to another bulky PMMA layer. The welding path completely surrounds the device (Fig. 8).

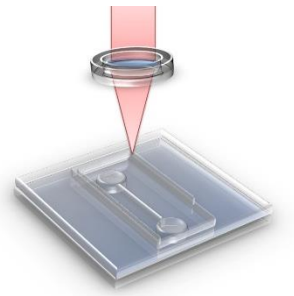

Fig. 8. Schematic view of the laser lap-welding around the microfluidic network.

Following the procedure described in the experimental section, a blue liquid was pumped in the channel through the hole up to 1 bar of liquid pressure. This test was performed several times and in no cases the liquid leaked outside the microchannel (Fig. 9).

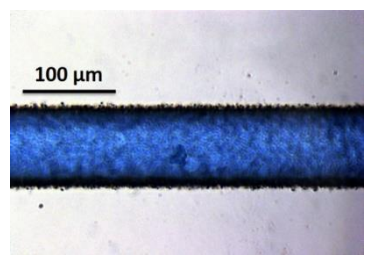

Fig. 9. Microscope image of a section of a microfluidic channel afetr 5 cycles at 1 bar of liquid pressure. No leakeges of the blue fluid are observed.

4. Conclusions

Local modifications of bulk PMMA using 650 fs and 18 ps laser pulses at several repetition rates and pulse energies were analyzed. In the ps regime higher pulse energies than in the fs regime need to be used to modify the sample, as result of the lower peak power. Furthermore, the modifications at 18 ps at low pulse energy are discontinuous, but, as soon as the energy grows, they become non–localized in the material and the occurrence of crack increases. Conversely, working with fs-pulses allows a continuous melting of the PMMA even at low energies, avoiding the crack formation and non-localized melting typical of higher pulse energies.

Therefore, we have found that the fs-regime is more convenient than picosecond pulses to obtain a continuous and localized melting of the PMMA, at least in the experimental conditions presented in this work. Subsequently, keeping constant the pulse duration at 650 fs, we have demonstrated the feasibility of ultrashort laser lap welding of two 1-mm-thick layers of PMMA by exploiting heat accumulation at high repetition rates. This technique was employed to successfully seal a transparent microfluidic device.

We are currently working on some thermal simulations using different theoretical models which are present in literature (Ancona, 2008)(Bauer, 2015) based on the analytical solution of the heat diffusion equations, which could better explain our experimental findings, shedding light on the role of the pulse duration on the modifications produced in the bulk of transparent polymeric materials.

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