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Towards industrial usage of ultrashort pulse welding

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Abstract

Laser welding of transparent materials using ultrashort laser pulses is attracting attention for an increasing number of applications in the field of medical industry, consumer electronics, microelectronics and others. Nonlinear absorption and heat accumulation at high repetition rates allow for local melting the weld partners at the interface. After cooling, a permanent joint with high stability up to the bulk material remains. However, due to basic material properties the (crack-free) weld seam dimension is limited and so the welding performance, e.g. the focus tolerance or gap size that can be bridged requiring high surface quality. In contrast, advanced process strategies such as wobble welding or temporal modulation of pulse energy enable improved welding performance providing tools for tailoring the induced material modification as it will be shown by in situ microscopy. Moreover, these techniques may also serve for in-line control of the welding process and to optimize applications such as material functionalization or high-speed cutting.

Keywords: Micro Processing; Micro Welding; Processing of Transparent Materials;

1. Introduction

Materials processing by ultrashort laser pulses has gained particular interest in recent years due to the confined energy deposition providing versatile functionalities for a multitude of application fields. In particular the processing (e.g. cutting, edging or welding) of glasses with their outstanding chemical, mechanical and optical properties facilitates to build unique devices making use of glass as engineering material of the 21st century. By focusing ultrashort pulses in the bulk of glass allows for high intensities triggering nonlinear absorption mechanism. Besides the principle absorption the laser parameters can be set

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in order to generate isotropic refractive index changes, local birefringence or even localized melting within the focal region [1-3]. For the latter the pulse repetition rate needs to be high enough to accumulate heat from pulse to pulse (so- called heat accumulation) which may result in local melting. After resolidification of the melt a permanent connection is formed if the modification is placed within the interface of two samples (at least one opaque). Several publications in recent years studied the principle process [4,5], the resulting stability [6] or the feasibility for various material combinations [7]. However, typically optical contacting is needed prior the welding process. For industrial usage extensive sample preparation techniques should be avoided while the process should withstand harsh processing conditions or non-perfect sample conditions. To overcome these limitations the bridging of small gaps of a few micrometers was demonstrated [8,9]. Still larger gaps denote a critical issue as well as varying focus positions, e.g. due to complex sample geometries. To this end, we studied welding by temporal energy modulation as well as different beam shapes to resolve these limitations.

2. Experimental setup

For welding experiments an ultrashort laser source (TruMicro 2030, TRUMPF) was used emitting pulses with a pulse duration of 300 fs at a laser wavelength of 1030 nm. A pulse repetition rate of 200 kHz and double pulse bursts (20 ns pulse separation within the burst) was set to ensure heat accumulation. A microscope objective with 10x magnification (NA 0.25) served to focus the laser pulses in shallow material depths. The glass samples (Gorilla glass 3, non-strengthened, Corning) were moved underneath the objective by a high-precision translation stage. For in-situ imaging of the laser interaction zone a high-speed camera (frame rate 50,000 frames per second, exposure time 4 µs, illumination wavelength 810 nm, pulse duration 60 ns) was used.

The pulse energy modulation was directly set within the laser control settings using a sinusoidal modulation shape with a modulation frequency of 500 Hz. Different modulation shapes (sawtooth, rectangle) resulted in similar welding performance (e.g. gap that could be bridged, breaking stability) but always better in contrast to usual welding without modulation.

3. Results and discussion

Figure 1 shows a microscope image of two laser-induced modifications during processing (pulse repetition rate 250 kHz, 8 pulse burst with 20 ns pulse distance in burst, average power 2.5 W, feed rate 10 mm/s) using constant pulse energy and sinusoidal pulse energy modulation (1 kHz modulation frequency), respectively. In the latter case the corresponding size of the molten region is significantly larger as indicated by the dashed lines. This is due to the higher maximum pulse energy in contrast to unmodulated inscription (average power was the same in both cases). Intriguingly also the interaction region shows distinct differences as the plasma region on the right side of the images indicates. In case of energy modulation, the absorption and plasma movement towards the laser happens much more controlled while only a confined plasma spot is visible. In contrast, unmodulated inscription exhibits several absorption regions which may emerge and vanish chaotically.

Furthermore, the welding characteristics using pulse energy modulation was studied by welding of customized glass samples with defined step optically contacted to a plane glass sample (both Gorilla glass unhardened). Due to the sample geometry (samples with different step size were used) the maximal gap that can be bridged could be determined. Again, the same average laser power for modulated and unmodulated welding was used (ca. 1.8 W in this case). The results show that pulse energy modulation allows for the bridging of gaps up to 8 µm while only 4 µm gaps could be bridged by usual welding. This is due to the larger maximal pulse energy and feature size which is beneficial for gap bridging as reported by Richter et al. [9].

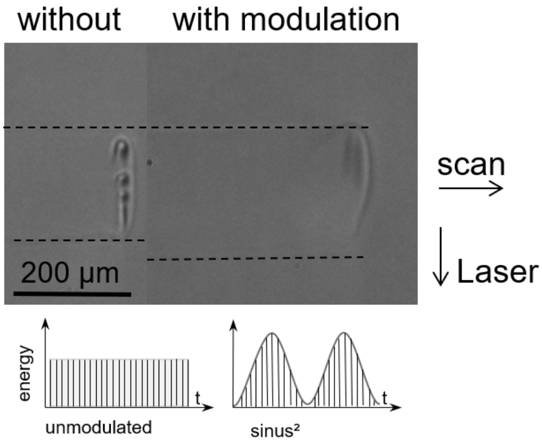

Fig. 1 High-speed camera image of a laser-induced modification without (left) and with (right) temporal energy modulation at the same average laser power (2.5W). The graphs below the images indicate the principle pulse energy distribution. The scan and laser propagation direction is indicated.

In addition, the welding with temporal energy modulation does not prefer crack formation even at higher maximal pulse energy (at a corresponding energy level where cracks would form without modulation). Here, the short interval with defined pause in between two consecutive peaks of the sinusoidal pulse shape does reduce stress as noted by Nakamura et al. [10]. Correspondingly, the stability of welded samples is comparable to the unmodulated welding with ultrashort laser pulses which can be as high as the breaking stability of the volume material.

4. Conclusion

In summary, the welding of transparent materials allows a plurality of applications which enable to revolutionize joining technologies for various fields such as biomedicine, micro- or consumer electronics just to name a few. However, to transfer the technology to wide industrial usage requirements such as durability and ease of use in terms of focus tolerance, sample preparation and handling as well as maximum stability that can be reached need to be fullfilled. In this regard the modulation of pulse energy is a big step towards industrial usage enabling larger feature sizes and crack-free welding of samples with gaps up to 8 µm (4 µm without modulation). In addition, the confined absorption and plasma dynamics allows for better process stability which paths the way for micro-welding under industrial conditions.

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