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We demonstrate that the use of low energy but high repetition ultrashort laser systems can be advantageous for glass laser cutting using method of controlled fracture propagation. In specific regime using low numerical aperture objective, elongated zone of energy deposition induces high mechanical stress allowing single-pass full cutting of 1mm-thick soda-lime glass. The crack can follow straight as well as curve trajectories with a radius down to 1 mm with a 1mm/s feedrate. In order to achieve high quality precise control on the fracture propagation we have studied the effects of experimental parameters such as numerical aperture, repetition rate, pulse energy, pulse duration, but also regimes of irradiations by single pulses or bursts.

DOI: 10.2961/jlmn.2016.01.0012
Keywords: laser materials processing, ultrashort laser pulses, glass, heat accumulation, glass cutting.

1. Introduction

Glass represents a wide market for fabrications of optics elements or cover glasses in consumer electronics, flat display, architecture, medical devices, *etc.* Despite the great demand, glass cutting techniques, including laser-based, still have limitations in terms of quality, geometries and versatility of method for different materials. Thus, a need of improving quality and speed of glass laser cutting arises.

Among the other glass laser cutting techniques, method of controlled fracture propagation [1,2] has great potential in cutting brittle materials such as glass or sapphire. This method is based on the ability to produce a mechanical stress profile by the absorption of the laser radiation (usually of CO_2 or Nd:YAG lasers) on the surface or in the volume of the exposed material. Under specific conditions thermal stresses cause initiation of a top-down through crack which propagates along the laser beam trajectory. The cut parts are released without any mechanical assistance. The cutting sidewalls are smooth and free from any surface defects and debris. Despite its advantages in the quality of the performed laser cuts, this method did not receive a wide range of applications because of several inconveniences. It shows relatively poor precision and low rate of processing (tens of mm/s). Frequently at high processing speeds, it is difficult to control the crack propagation inside the glass and crack propagates in some arbitrary direction. Such laser cutting uncertainty results in too high amount of broken parts. In addition, in conventional method the laser radiation is absorbed in a thin subsurface region of a material, thus for proceeding of the glasses and other dielectrics, which are transparent for the selected laser wavelength additional high absorptive coating of the surface is required.

There were attempted considerable efforts to improve both precision and quality of the cut (for example by irradiation of two laser sources [3], by absorption of single laser in the glass volume [4], by prescribing trajectory with another laser [5]) and proceeding speed (by applying an additional performance of ultrasonic wave [6], a jet of cool water, or air [7]). Such improvements, however, add extra-cost and complexity to the process. Thus, it still remains the question how in the same time to make this technology fast, precise and versatile for the different materials.

In this article we demonstrate that the use of ultrashort and high repetition rate pulsed laser sources may be advantageous since it allows to overcome presented drawbacks. It results from nonlinear light absorption and nonlinear Kerr effects when the pulses form rather long and narrow laser affected zone (LAZ) [8]. We have achieved a regime, when laser modification reaches a length comparable with the glass thickness with the diameter of ten of microns. At high repetition rate (typically higher than 100 kHz) absorbed energy does not dissipate when the next pulse arrives, and temperature around LAZ rises [9-11]. Eventually, such narrow heat source elongated from the front to the rear glass surface is able to produce intense stress fields in its vicinity [12] and initiate the crack formation along the whole glass thickness, when thermal tensile stress overpasses mechanical strength of the material.

Nonlinear character of pulse propagation results in an elongated zone of high aspect-ratio regulating volume energy deposition and, as a consequence, provides better control on the crack propagation along the glass thickness. On the other hand, the intrinsic property of nonlinear absorption makes this cutting method suitable for wide range of glasses and transparent ceramics, without any need of prior treatment of the samples.

2. Experimental setup

Ultrashort laser pulses were generated by an Yb-doped fiber femtosecond laser Satsuma by Amplitude Systèmes. It operates at 1030 nm wavelength, delivering 300 fs pulses with variable pulse repetition rate up to 2 MHz. Maximal average power of the laser system of 5W provides energy up to 10 µJ per pulse for 500 kHz repetition rate. In addition to the mode delivering single pulses, the laser can operate in a burst-mode, generating groups of amplified femtosecond pulses following each other at 25 ns time delay. Bursts were generated by selecting different number of pulses (between 1 and 10 pulses per burst, ppb) from the oscillator working at 40.5 MHz and amplifying them in the fiber. The maximum power after amplifier working in burst-mode was kept at 5W. Thus, energy per burst is conserved and redistributed between the pulses in each burst.

Glass processing was performed by focusing the laser beam with a long working-distance objectives having low numerical aperture (5x Mitutoyo M Plan Apo NIR, NA=0.15) inside the glass sample (see Fig. 1a). The beam diameter was handled using the variable beam expander (Jenoptik). In this case, if the beam diameter is less than the entrance pupil of the objective, it is equivalent to the focusing with effective NA less than 0.15. Samples of soda-lime glass of 1 mm thickness (Duran group) was mounted on the translation stages, while the beam was fixed during laser processing. Positioning of focal point with high precision 3-axis system, makes possible machining with micrometric accuracy.

Laser modification was imaged and characterized by optical transmission microscopy (MF176 measuring microscope by Mitutoyo). Quality of produced cuts was monitored by optical confocal microscope (Leica DCM3D).

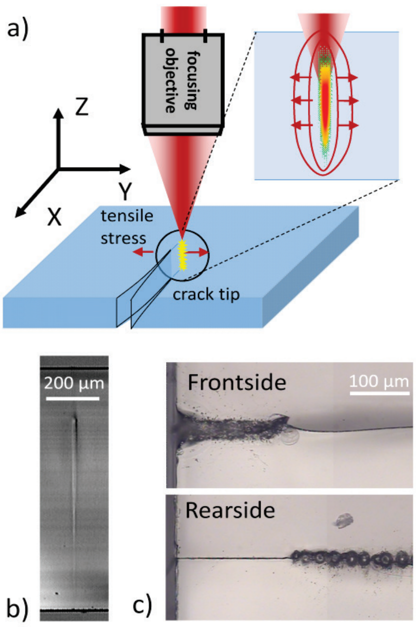

Fig. 1 a) Scheme of ultrashort laser induced controlled fracture propagation with illustration in the inset of the principle of laser induced thermal stresses in the vicinity of LAZ. b) Microscopy image of LAZ representing elongated energy deposition performed by E_p=4µJ pulses, at 500 kHz, focused with NA=0.04. c) Front and rear surfaces of the cut produced with such a spot, translating the focus at velocity v=1mm/s

3. Results

We have investigated the effect of the laser parameters, such as numerical aperture, pulse energy (E_p), single pulse or burst-mode, and repetition rate on the laser affected zone. The detailed description of these parameters will be discussed in the subsequent sections. Here, it is important to indicate two essential parameters which determine fracture initiation and subsequent propagation of crack: (i) energy distribution along the sample thickness and (ii) operating repetition rate.

Firstly, it is necessary to create elongated LAZ which is uniform across almost the whole sample depth. Due to nonlinear light absorption determined by high peak intensities of ultrashort laser pulses and nonlinear propagation realized in loose focusing conditions, a zone of primary energy deposition takes a form of a long and narrow filament, as shown in Fig. 1b. We demonstrate that in our focusing conditions using objectives with NA<0.1, filament reaches its length of about 800 µm and a diameter of 20 µm in its widest point.

Secondly, at high repetition rate the absorbed energy does not dissipate when the next pulse arrives. That results in heat accumulation and raising of the temperature [11] and associated thermal mechanical stresses in the vicinity of LAZ. In soda-lime glass this regime is realized for repetition rate higher than 150 kHz [11]. When tensile elastic stresses surpass the mechanical strength of the material, they cause initiation of a through crack from the upper to the bottom surfaces of a glass which propagates along the scanning trajectory of a laser beam (see Fig 1c). Therefore, the cutting of 1mm-thick glass was achieved by a single-pass without prescribing the trajectory.

To assist crack initiation, surface defect was created by laser ablation in the initial point of the trajectory (ablation part produced on the front side is shown in Fig. 1c). So the protocol is firstly to prepare a surface defect at the initial point of trajectory which will help to control the fracture initiation and then focus into the bulk in order to initiate and propagate the fracture by focus movement. The crack follows straight and curve trajectories with a radius down to 1 mm with a feed rate of 1mm/s. It is important to note, that crack tip is usually delayed with respect to the actual focal position to a distance less than 1mm. This can cause deviation of the crack from the cutting trajectory. Such deviation is bigger for small radii of the trajectory curvature. Typically, it is less than 10 µm for straight cuts and can reach hundreds of microns for curved trajectories.

3.1 Cut optimization.

Since the amount of deposited energy and its spatial uniformity are essential to induce a fracture, we have studied the influence of different irradiation parameters on the LAZ. Firstly, we have studied the dependence of the filament size and length on the pulse energy. Irradiation was performed at 500 kHz repetition rate using objective with effective NA=0.04. In addition to visual observation of laser modification, time-averaged nonlinear absorptivity of the laser pulses was measured. Absorption measurement was performed by detecting transmitted power by the laser power sensor before and after the focal point during irradiation while sample was translated at constant velocity of 5 mm/s.

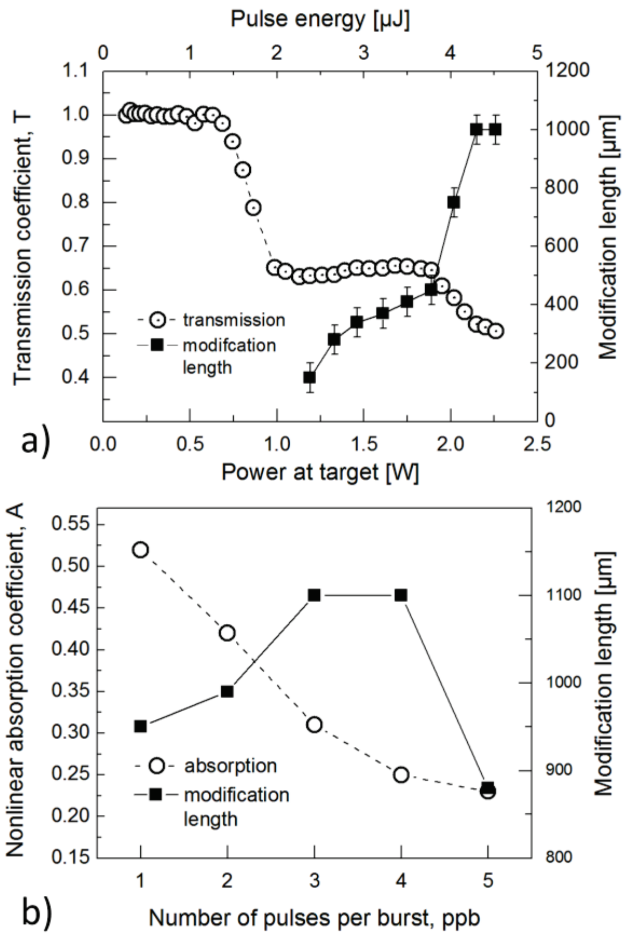

Fig. 2 a) Dependence of transmitted energy and modification length as a function of energy of pulses at target focused with NA=0.04 objective at 500 kHz. b) Absorption and modification in the burst-mode as a function of number pulses per burst focused with NA=0.08 objective at 500 kHz with burst energy of 3.6μJ. In both cases, modification and transmission measurements were performed, while translating the sample with v=5mm/s.

As shown in Fig. 2a by a drop in transmission, photoionization starts for pulse energies higher than 1.5μJ, however at such energies significant heating of sample was not achieved and only color centers are generated resulting in the photodarkening of the sample. They can be successively removed by placing the sample in an oven at 150 °C during 10 minutes. Only at the energies higher than 2 μJ per pulse when transmission T reach a plateau at T=0.65, we start to observe significant refractive index changes induced by glass transition above the melting point. The length of modifications increases further with energy up to of 4μJ per pulse. At such pulse energy filament starts to damage rear surface of the sample (see the rear side of the sample depicted in the Fig. 1c) since modification length increases suddenly achieving its length of 800 μm (as shown in Fig. 2a). This is connected with the second drop in transmission. This behavior can be attributed to a certain light diffusion on the rear surface. However, we associate this drop rather with an increase in absorption, since it is associated with the increase of the modification length. The latter can arise from the back-reflection of the laser pulse on the plasma generated on the rear surface. Thus, in the range from 2.5 to 4 μJ per pulse, where nonlinear absorption is maintained on the constant level of A=0.35, the increase of energy results mainly in the increase of the modification length. Pulse energy of E_p=4μJ seems to be optimal for cutting since long filament of 800 μm favors uniform energy deposition along almost the whole depth of the sample. Furthermore, slight damage of the rear surface facilitate crack guiding. Higher energy per pulse results in strong damage of the rear surface.

Further optimization was performed on the energy deposition over time. Here we tested two strategies: (i) to explore ns-burst mode, when energy of pulse is shared between sub-pulses in groups separated by nanosecond time interval, (ii) to optimize energy deposition at picosecond (ps) and sub-ps timescale by pulses duration.

It was shown that ultrafast burst-mode micromachining allows enhanced control of thermal effects and increases processing speed [13-15]. In addition, during the burst at ns time delays the material exhibits transient optical and electronic properties. Despite the electron system is almost relaxed the changes in these properties can be caused by local temperature increase, presence of residual point defects or unrelaxed electronic states. Transient optical changes affect the propagation of the subsequent pulses in the bursts and results in different spatial energy deposition. For example, it was demonstrated that use of burst for volume modifications can induce waveguiding character of pulse propagation defined by such transient optical changes and may lead to higher length of the modification [13,15].

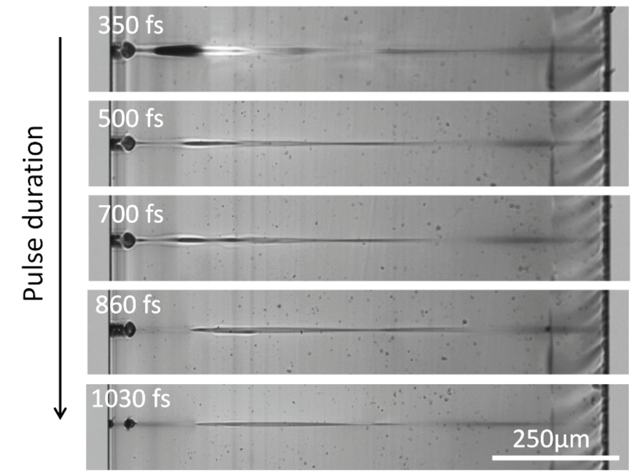

Fig. 3 Microscopy images of irradiations produced at different pulse durations. The side view of the dynamic irradiation is taken when sample was translated at v=5mm/s in the plane perpendicular to the screen (laser comes from the left). Laser parameters: pulse energy of E_p=4 μJ at 500 kHz, NA=0.04.

We investigated this effects using the bursts with 25 ns delay between pulses in group monitoring the modification length and nonlinear absorption coefficient. Modifications were performed by focusing bursts of E_p=3.6 μJ at 500 kHz with NA=0.08 objective. Note, that experiment was performed at higher NA to effectively process the glass even for high number of pulses in burst. Results demonstrate that for our bursts, energy absorbed by the glass decreases while the number pulses in burst increases (see Fig. 2b). This observation matches the intensity-driven mechanisms of absorption. Indeed, each pulse in the burst is less intense and, consequently, has lower possibility to ionize the glass matrix. In the same time, the filament-like LAZ is longer, has smaller diameter, and have the maximal length for 3 pulses in a burst. Therefore, this regime can be advantageous in order to provide longer filaments or higher increase of local temperature. However, it needs higher energy per pulse, since absorption of pulses in bursts is less efficient.

At ps and sub-ps timescales nonlinear absorption and propagation can be directly addressed via interaction with free electrons produced by photoionization which have not relaxed yet [16,17]. Fig. 3 shows the side view of dynamic irradiations (sample translation at v=5mm/s in the plane perpendicular to the screen, laser comes from the left) by laser pulses of E_p=4 µJ at 500 kHz, NA=0.04, produced at different pulse durations. Results show that uniformity of LAZ decreases for shorter pulse durations. The shortest pulse durations produce zone with a strong energy deposition in the frontal part of the LAZ. In the same time, longer pulse durations produce uniform modifications, however its length decreases with the pulse duration. Such uniform energy deposition produced by longer pulses leads to better quality of the cut, as it will be shown in the next section.

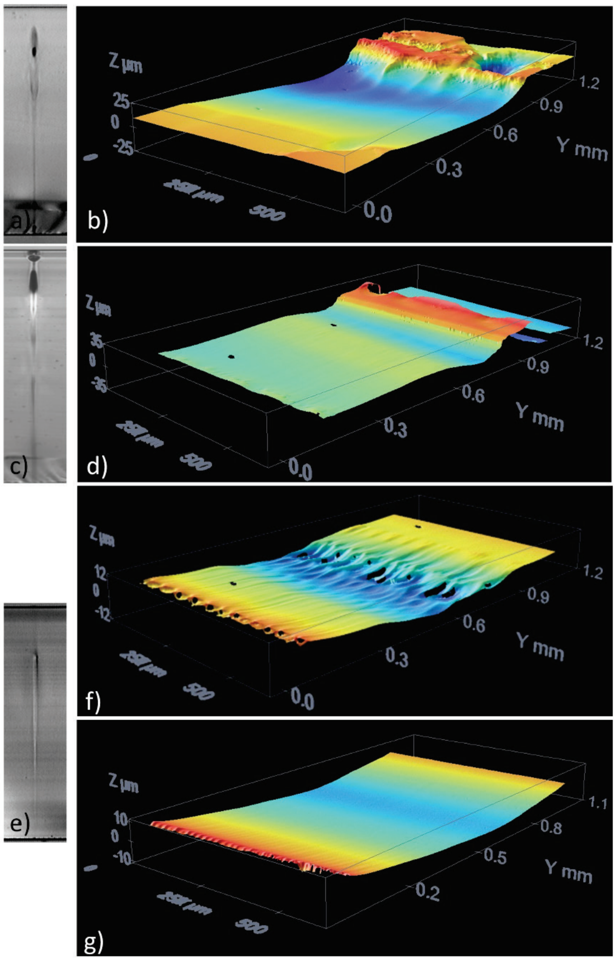

Fig. 4 Microscopy images of LAZ and corresponding profile of the sidewall in the middle of the cut produced at different experimental parameters. a)-b) E_p=3.6 µJ, t_p=300 fs 500 kHz, NA=0.08 at 1mm/s. c)-d) E_p=4 µJ, t_p=350 fs, 500 kHz, NA=0.04 at 1mm/s. e)-g) Optimal parameters representing uniform energy deposition: E_p=4 µJ, t_p=500 fs, 500 kHz, NA=0.04 at 1mm/s. f) Sidewall profile in the beginning of the cut. g) Sidwall profile in the middle of the cutting trajectory in stationary regime.

3.2 Sidewall quality

Cutting edge and sidewall have been characterized using confocal optical microscope. First we have studied influence of the irradiation parameters on the quality of the cut. Fig. 4 shows the influence of the numerical aperture on the roughness of the sample.

For higher NA of 0.08 sidewall is rather rough (Fig 4a,b). The rugosities of the sample in this case reach the size of 50 µm. We connect it with nonuniform character of energy deposition in the glass volume (see microscopy image of LAZ on Fig 4a.). We assume that in the point of overexposure in the front part of laser affected zone, more defects are induced, that highly modifies the stress profile around them. Thus, control on the cut is more difficult, that results in rough surface of sidewall.

For lower NA of 0.04 (Fig. 4c,d) energy is distributed more uniformly along the LAZ resulting in the less surface roughness. However maximal peak to valley rugosities have the same order of 50 µm.

The real improvement of the cut quality appears when pulses with pulse duration higher than 500 fs were used. In this case, because of the difference in nonlinear propagation, distribution of energy along depth of sample is much uniform than for fs case (see discussion in previous section and corresponding image of modification shown in Fig 4e.). Use of ps and sub-ps laser pulses results in smooth separation of the parts of the sample. Typically, sidewall represents a shallow valley or a bump on the other part of the sample of the height less than 10µm as presented in Fig. 4e,f. Deviation from a flat plane can be directly attributed to variation of the LAZ diameter along the sample depth and to the stress profiles generated by the laser absorption. The cut should follow the line of maximum stress which is defined by the highest temperature gradient in the laser affected zone. That line is located either on the left or on the right side from the focal point that in addition brings some incertitude on the cut behavior.

One should note, that surface quality along the whole trajectory also varies. In the beginning, when deviation of the crack from the laser trajectory is minimal, we have measured sidewall roughness Ra=1µm with deviation from the flat surface of 10 µm and waviness of 30 µm. Corresponding sidewall profile is shown in Fig 4f. In the middle of trajectory, cutting achieve stationary regime and the crack deviation is less than 10 µm. At this point sidewall becomes smooth as presented in Fig. 4g. In this regime we have measured the roughness Ra<100nm and zero waviness. Front surface (regarding laser arrival) of the sample is flawless with no chipping, however rear surface was subjected by slight laser attack resulting in small craters.

This behavior can be explained by differences of the mechanical stress field. When the crack does not deviate from the laser trajectory, stress profile is strongly affected by spatio-temporal fluctuation of temperature taking place in the close vicinity of the filamentary-like modification in the heat accumulation regime [18]. As a result, wave patterns shown on Fig 4f. are imprinted on the sidewall, which result in sufficient waviness. On the other hand, in stationary regime, when crack slightly deviates, stress profile is highly uniform, that results in smooth sidewall with very low roughness and negligible waviness.

4. Conclusion

In this paper we have studied the capabilities of ultra-short pulse laser systems for glass laser cutting using the method of controlled fracture propagation. Using laser processing at high repetition rate and using low numerical aperture focusing objective, the energy can be deposited in rather elongated zone due to nonlinear propagation and induce high temperature increase via pulse-to-pulse energy deposition and heat accumulation effect. As a result, high mechanical tensile stress is induced along the whole depth of the sample and eventually leads to the crack formation. By controlling the mechanical stress distribution, we have demonstrated capability of single-pass full cutting of 1mm-thick soda lime glass. The crack can follow straight and curve trajectories with a radius down to 1 mm with a 1mm/s feedrate. In order to achieve highest quality of the cut and better control on the fracture propagation we have studied the effects pulse energy, pulse duration, but also regimes of irradiations by single pulses or bursts. These laser parameters have the influence on the nonlinear energy deposition, affect uniformity of energy deposition and the length of the laser affected zone, thus, leading to better quality of cutting. In the optimal irradiation regime with pulses of E_p=4 μJ, t_p>500fs, NA=0.04 at a repetition rate of 500 kHz, sidewall of performed cut has remarkable quality. Being slightly curved with deviation from flat surface less than 10 μm, it has roughness less than 100 nm with negligible waviness.

Acknowledgments

This publication has been performed in the framework of FEMTOWELD project funded by the French government which is gratefully acknowledged by the authors.

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(Received: May 27, 2015, Accepted: January 18, 2016)