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Throughput scaling by spatial beam shaping and dynamic focusing

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ABSTRACT

With availability of high power ultra short pulsed lasers, one prerequisite towards throughput scaling demanded for industrial ultrafast laser processing was recently achieved. We will present different scaling approaches for ultrafast machining, including raster and vector based concepts. The main attention is on beam shaping for enlarged, tailored processed volume per pulse. Some aspects on vector based machining using beam shaping are discussed. With engraving of steel and full thickness modification of transparent materials, two different approaches for throughput scaling by confined interaction volume, avoiding detrimental heat accumulation, are exemplified. In Contrast, welding of transparent materials based on nonlinear absorption benefits from ultra short pulse processing in heat accumulation regime. Results on in-situ stress birefringence microscopy demonstrate the complex interplay of processing parameters on heat accumulation. With respect to process development, the potential of in-in-situ diagnostics, extended to high power ultrafast lasers and diagnostics allowing for multi-scale resolution in space and time is addressed.

Keywords: Ultra-short pulse, laser, materials processing, beam shaping, pump-probe, nonlinear absorption

1. INTRODUCTION

Ultra short pulse laser processing offers a manifold of procedures for precise machining procedures, applicable to a plurality of materials. Throughput scaling is attractive for industrial applications and becomes feasible with the availability of ultrafast lasers offering average power in the kW range [1]. For throughput scaling of ultra short pulse laser processing, typically accompanied with average power scaling, some aspects have to be taken into account in order to achieve the quality as known from low power processing.

Ultrafast laser processing typically benefits from avoidance of detrimental heat accumulation, requiring appropriate spread of energy deposition at scaled average power [2,3]. Levers to control the heat accumulation are the overlap between successive pulses and the duration and temporal interval of energy deposition in the region relevant for heat accumulation [4]. Furthermore the process should be optimized for minimum heat generation by adaption of the applied fluence [5,6].

The same fluence at scaled power under standard focusing can be realized at the same spot diameter via scaling repetition rate or alternatively at increased spot diameter but scaled pulse energy. At similar relative spatial overlap of successive pulses, this requires beam positioning with scaled dynamics and typically furthermore an enlarged region addressable, if scaling is not realized by parallel processing.

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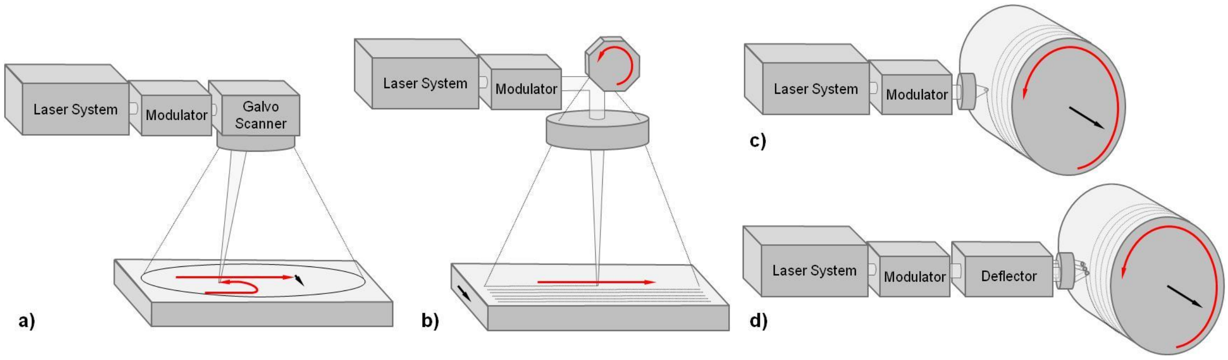

Figure 1: Systems for raster based ultrafast laser processing. A highly dynamic beam positioning (indicated by red arrow) is combined with a translation of the work piece with respect to the beam path (indicated by black arrow), as appropriate. The beam from the laser system is passing a modulator. The modulator may be integrated into the laser system and include a pulse picker, an amplitude modulator and a correction unit for improved straightness, feed rate, focal position and/or phase adaption. A galvo scanner system allows flexible 2D beam positioning for random access and raster scanning without the requirement of additional axis, as indicated in figure 1a [9]. In figure 1b, a polygon scanner based solution is shown [8,10], in figure 1c a helical processing by fast rotating cylinder [10], both combined with additional obligatory positioning device. As indicated in figure 1d, an additional deflector, e.g. chirped acoustic deflector, may be used for further spatial separation of the pulses in different directions [7,11].

For repetition rates in the MHz range and spot diameters of more than 10 µm, adequate feed rates exceed 10 m/s. This is hard to achieve by typical galvo scanners in random access or vector scanning mode (Fig. 1a). Electro-optic or acousto-optic scanners might offer higher rate of resolvable spots, but so far suffer from insufficient number of resolvable spots, efficiency or power handling capability [7]. Polygon (Fig. 1b) or galvo scanner systems in raster scanning mode (Fig. 1a) may offer sufficient speed but realization results in challenges to achieve adequate accurate positioning of the desired huge number of addressable spots at high processing speed [8,9,10]. Another raster based approach is helical processing on the surface of a rotating cylinder (Fig. 1c) [11]. For such raster processing it is beneficial to machine at constantly feed rate on straight paths in one direction, and superimpose a translation oriented differently. Since for precision the exact positioning of the pulses is crucial, scaling the repetition rate is resulting in high demands regarding dynamical stability, synchronization and modulation speed. Within the last years promising progress was achieved on ultrafast laser proceeding based on these raster processing approaches, e.g. by additional axis or deflectors for correction and further spatial separation of successive pulses (Fig. 1c). The options towards improved flexibility, quality and processing speed are on the other hand associated with increased complexity, reduced efficiency or improper power handling capability [7,11]. Therefore the application is typically restricted to 2D surface processing with large fill factor or to structures essentially coinciding with axis of high dynamics, e.g. in roll to roll technology.

Taking into account, that heat accumulation effects get more pronounced at elevated repetition rate, typically the relative spatial overlap between successive pulses has to be reduced at increased repetition rate [2]. Therefore the requirements on the dynamics of the beam positioning may increase even more than linear with the repetition rate.

Scaling the pulse energy instead, thereby adapting the spot diameter to keep appropriate fluence, might reduce the requirements on the dynamics of the positioning system compared to scaling by repetition rate. Under the assumption of the same number of resolvable spots of the beam positioning system, furthermore the region of energy deposition might be increased by longer focal length or alternatively by smaller deflection devices allowing improved dynamics. However, this often means unacceptable reduction of spatial resolution. In addition, depending on the geometry of heat source and flow, an increased spot may result in a prolonged diffusion time, causing additional thermal effects of an individual pulse or for elevated repetition rate.

2. BEAM SHAPING APPROACHES FOR THROUGHPUT SCALING

Beam shaping offers throughput scaling for high quality ultrafast laser processing even at moderate dynamics of the beam positioning system without constraints in precision, if properly adapted. Figure 2 illustrates groove engraving of increased depth by multi-pass compared to a multi-spot approach. For efficient high quality engraving, the desired depth of a groove might not achievable in a single pass (Fig. 2a). In order to generate the desired groove, a sequential engraving on the same path can be applied (Fig 2b). Alternatively several spots can be generated by beam shaping, generating the desired groove in a single pass. In a similar manner the width of a structure can be increased in a single pass (Fig. 3). Detrimental heat accumulation has to be avoided by choosing the distance between the individual spots properly [12].

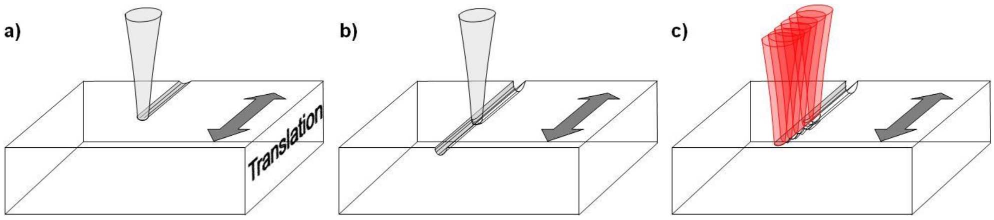

Figure 2: Increasing the depth of laser engraving beyond the depth achievable in a single pass (a) by multi-pass (b) and multi-spot ablation (c).

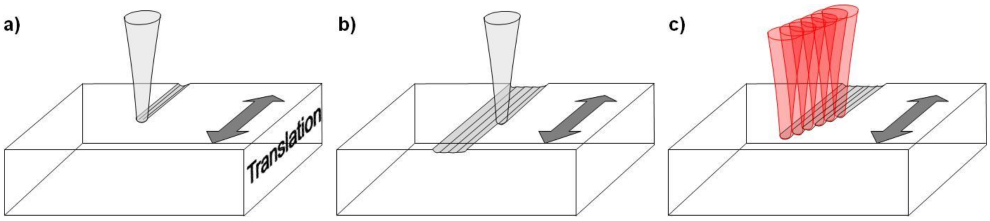

Figure 3: Increasing the width of laser engraving beyond the width achievable in a single pass (a) by multi-pass (b) and multi-spot ablation (c).

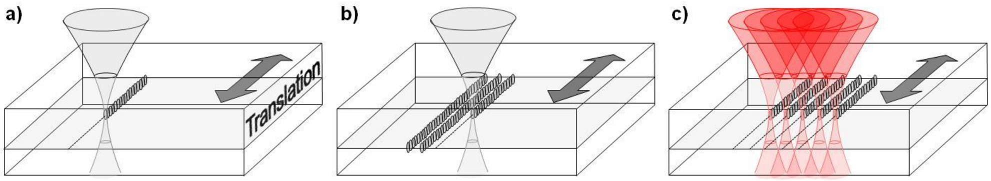

Figure 4: Ultra short pulse welding, single track (a) increasing the number of welding tracks by multiple passes (b) and by multi-spot arrangement (c).

For processing of materials induced by nonlinear absorption inside of the transparent volume, tight focusing is essential [13]. Therefore the volume processed by standard focusing with a single spot is hard to scale and throughput scaling is limited even at elevated repetition rates and even in case the processing does not suffer from but is based on heat accumulation. For ultra short pulse welding by absorption of ultra short pulses, a melt volume is generated directly in the interface region by heat accumulation (Fig. 4). Typically joining tracks are generated (Fig. 4a), several tracks are inscribed sequentially to achieve sufficient joining area (Fig. 4b). By multi-spot arrangements a larger joining area can be generated in a single pass (Fig. 4c). It has to be pointed out, that the process additionally benefits form a simultaneous absorption. Even if the heat accumulation between the individual absorption regions may not be used to form a common melt region, coexisting melt volumes may support gap closing.

The latter exemplifies the proposed beam shaping by generating a formed tool, incorporating the influence of simultaneity on the process itself. This is in contrast to multi spot arrangements for parallel processing [14].

Beside raster based, vector based laser processing is a common technique. Since under vector based processing high precision at complex paths is hard to achieve at constantly high feed rate, throughput scaling usually requires machining under acceleration in order to achieve high quality at complex geometries (Fig.5a). For processing not dominated by accumulation, the distance of successive pulses might be adapted to the feed rate, resulting in a variable repetition rate or in pulse on demand operation triggered by the positioning system. Again, multi-pass procedures (Fig. 5b) or multi-spot arrangements (Fig. 5c) may be used for scaling the processed volume. Often, the beam shape will show a pronounced preferred direction with respect to the feed direction. In case the extension of the preferred direction is not small compared to the radius of curvature of such a complex path, careful attention has to be paid on the handling of these details (Fig. 5c). The same holds for the start and the end of such a processing path. The complexity of the process may be further increased if accumulation effects have to be controlled.

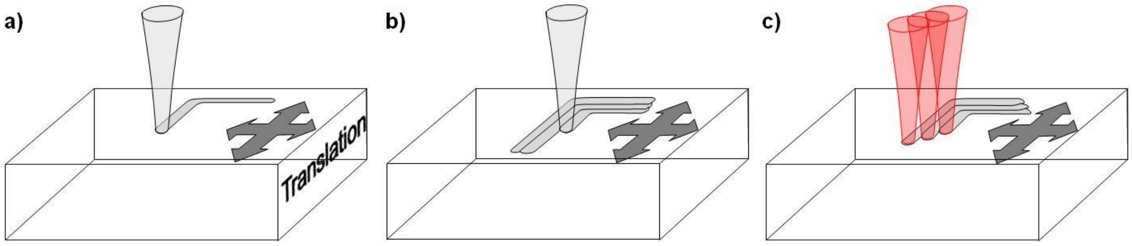

Figure 5: Vector based processing, by standard focusing in a single pass (a), in multi-pass procedure (b) and by applying multi-spot arrangement.

Ultra short pulse processing of transparent materials offers the potential for processing by beam shapes effectively extending into the volume (Fig. 6). The elongated profile in figure 6a is characterized by rotational symmetry, avoiding any preferred direction with respect to the feed direction, thereby allowing processing along complex contours through the complete thickness in a single pass. An inclined incidence, varied along the contour, allows for example to remove an inner contour without a need of a gap (Fig. 6b). Figure 6c illustrates single pass processing applying a complex 2D intensity profile. It has to be pointed out, that typically the lateral extension of such absorption profiles is in the range of 1 µm and that the extension of the affected volume is in the same range. Therefore, a processing by multi-pass approach would require huge number of passes and a positioning of the spots written in the following pass with an accuracy better 1 µm with respect to the preceding. This clearly demonstrates the advantage of beam shaping approaches.

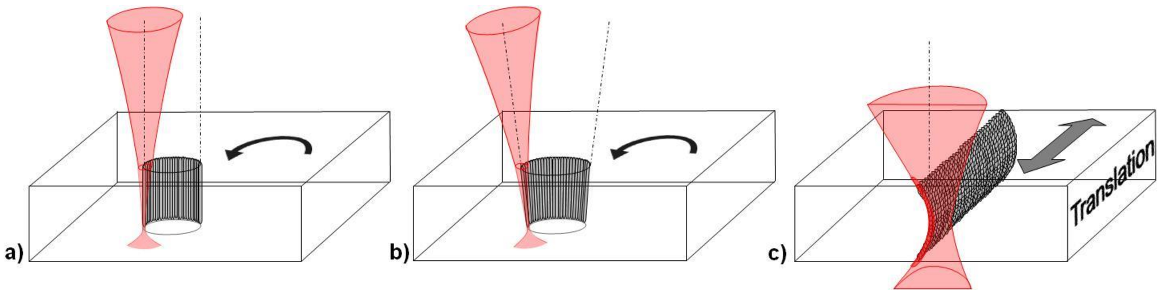

Figure 6: Processing of transparent materials by 3D beam shapes. Example for an in direction of beam propagation elongated intensity profile of small lateral extend at normal incidence (a), the same inclined incidence (b) and for a complex 3D-shape [15] (b).

Processing of transparent materials by inducing nonlinear absorption inside of transparent materials by shaped beams not just requires tight focusing. Furthermore the direction of beam propagation has to be controlled. Applications of scanners are therefore restricted to small field of work. Most applications would therefore require stitching or on the fly concepts by applying additional mechanical axis. The same holds for other applications preferably using tight focusing. Throughput scaling by beam shaping in combination with fixed optics often is a more economical solution, furthermore offering improved precision. Therefore beam shaping approaches should not be excluded from consideration, even if complex beam shaping is often not compatible with scanner applications.

3. EXAMPLES AND DEMONSTRATION

3.1 Engraving lines in sheet steel

A demanding application is engraving of burr free grooves of width and central depth exceeding 10 µm in steel with a processing speed above 2 m/s in a roll to roll processing environment. The measurement of the energy specific ablation volume of steel (Fig. 7) shows, that for wavelength of 1030 nm the best efficiency could be achieved for pulse duration of 900 fs at a fluence of about 1 J/cm². Starting from these parameters tests on multi-pass engraving with pulse duration of 900 fs at repetition rate of 800 kHz and spot diameter of 15 µm resulted in a groove with a depth about 12 µm without inacceptable burr for 81 passes with a feed rate of 2 m/s.

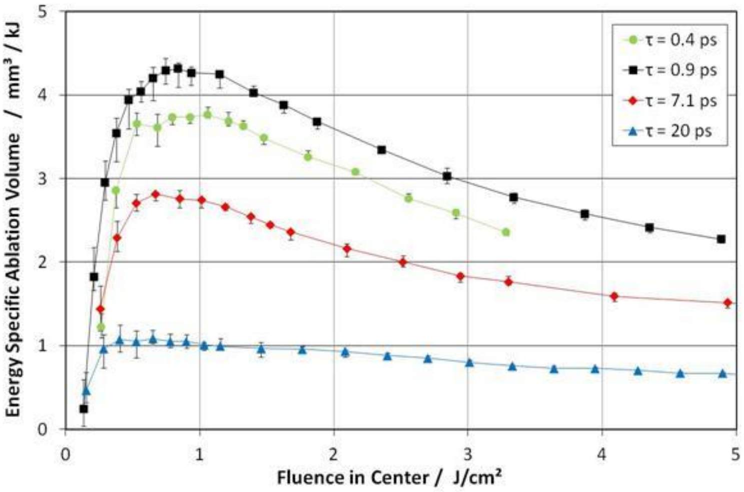

Figure 7: Energy specific ablation volume of steel as a function of the fluence in the center of a Gaussian beam profile of diameter 30 µm, deduced from multi -pass laser engraving of steel of an area of 1 x 1 mm² and Depth > 10 µm with ultra short pulse lasers of wavelength 1030 nm. At a repetition rate of 100 kHz, a scan speed of 0.4 m/s and a hatch of 8 µm were applied.

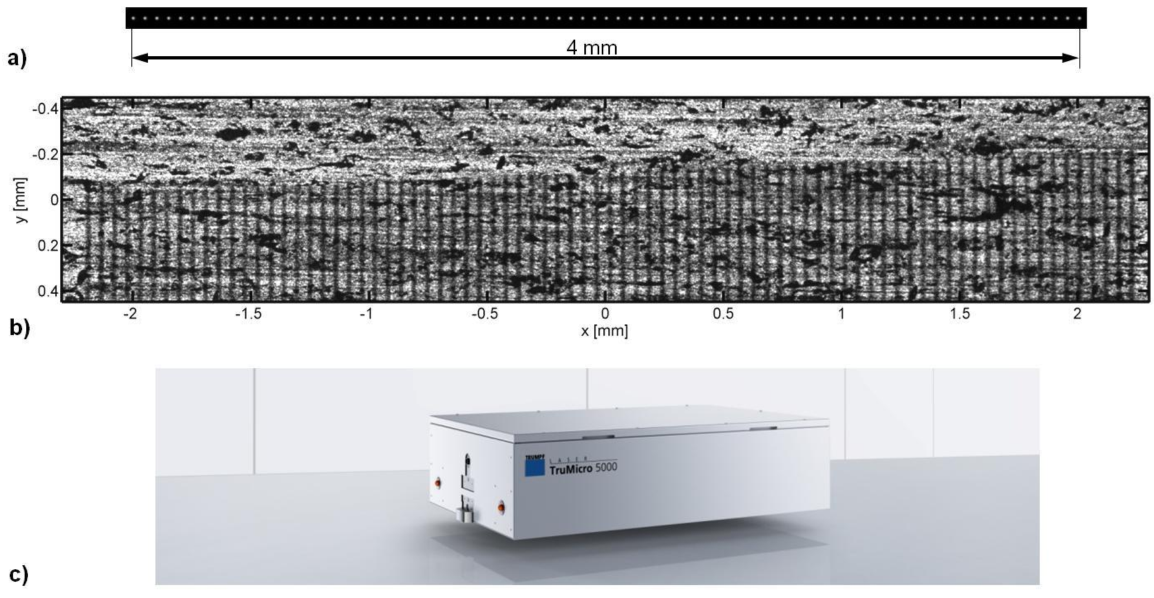

Figure 8: Design and demonstration multi-spot arrangement. a): Intensity image of the simulated 81 x 1 multi-spot profile with a spot diameter of 15 µm at a 50 µm interval leading to a total length of 4 mm. b): Image of single pass ablation with multi-spot array arranged about nearly perpendicular to the feed direction by using a slightly modified optical setup. c): Laser system of the TruMicro series 5000 as used for Multispot engraving and single pass full thickness glass processing.

In order to achieve the desired groove in a single pass, a multi-spot approach according to figure 2c was chosen. The optical system is based on a diffractive optical element (DOE) and was designed for 81 spots of diameter 15 µm in a line of length 4 mm (Fig. 8a). The first tests of the multi-spot DOE were done in a slightly different optical setup, an example image of a single pass engraving with DOE aligned about perpendicular to the direction of feed is shown in figure 8b, showing engraving tracks for each of the 81 spots.

Results from engraving by using a laser of the TruMicro series 5000 under precision alignment of the DOE axis with respect to the feed direction are shown in figure 9. With the DOE aligned parallel to the feed direction, a burr free single pass engraving with depth of 11 µm and width of 12 µm was achieved a feed rate of 2.2 m/s, as illustrated in the laser scanning microscope image in figure 9a and the corresponding cross section (Fig. 9b). As indicated in figure 9c, a minor deviation of the DOE axis with respect to the feed direction results in reduced depth and increased width of the groove.

This example clearly demonstrates the suitability of such a multi spot approach for processing along straight paths with high speed. The benefit from using shaped beam is not solely given by the increased processing speed. Even at moderate feed rate no detrimental effects due to heat accumulation are visible at an average power of about 80 W. Furthermore in a roll to roll processing environment, it would be challenging to hit the groove precisely within all passes for multipath approaches. In a multi-spot approach instead, the precision is achieved by proper alignment of the multi-spot axis with respect to the effective feed direction, i.e. the superimposed feed direction of workpiece and beam translation.

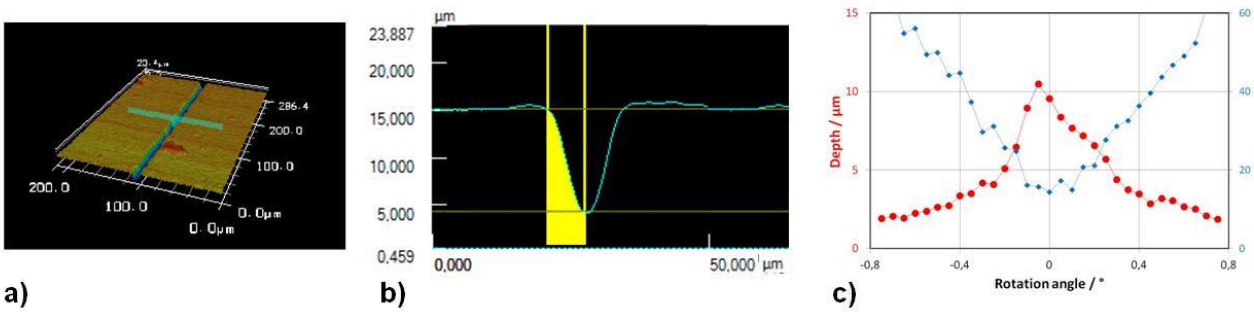

Figure 9: Measurement of grooves engraved by laser scanning microscope. a): Image of groove achieved with axis of multi-spot-array parallel to feed direction. b): cross section of groove corresponding to a). c): Measured width and central depth of grooves as a function of the angle between feed direction and axis of multi-spot-array.

3.2 Single pass full thickness processing of sheet glass

The development of beam shaping for processing by tailored absorption inside the volume of transparent materials can be supported by in-situ diagnostics [13]. Increasing the length of elongated beam profiles with small lateral extend allows thickness scaling in single pass modification for cutting applications. Figure 10 shows examples for modification of glass with normal incidence corresponding to figure 6a and inclined incidence (Fig. 6b), followed by mechanical separation. Whereby inner contours with an aspect ratio as in figure 10a cannot be separated mechanically by normal incidence modification, an inclined modification as in figure 10b allows separation even in this zero gap condition, if the direction of inclination is adapted to the contour.

By longer beam profiles at accordingly scaled pulse energy the thickness of the material processed can be scaled. Depending on the material and the complexity of the contour, the modifications are inscribed at a distance between 1 µm and 10 µm at repetition rates of up to several 100 kHz. By using pulse on demand technique, processing under acceleration up to speeds exceeding1 m/s can be achieved at average power above 100 W, without disturbing effects due to incubation and heat accumulation. Inclined beam profiles already increase the applicability of the process. 3D beam shaping will allow both, combining of processing steps so far done successively and new processing concepts, e.g. supported by tailored shock or pressure waves. DOE based beam shaping offers high flexibility and excellent power handling capability for processing with elongated beam profiles, applied in the TOP Cleave optics (Fig. 10c).

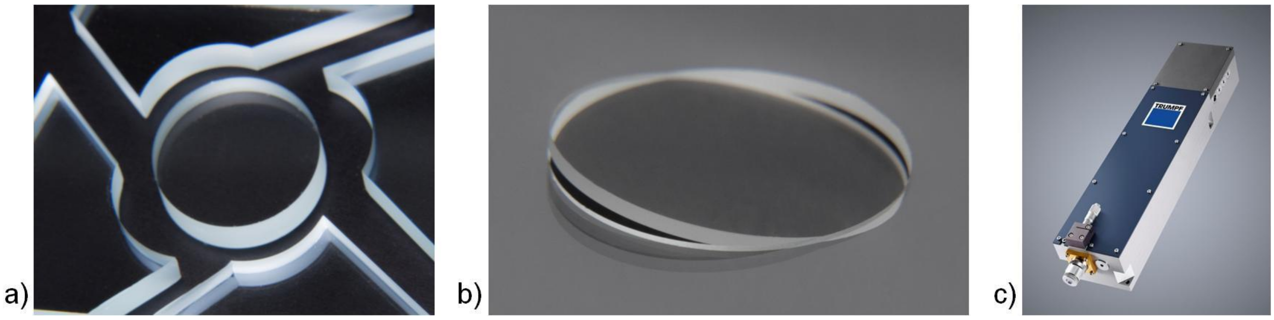

Figure 10: Single pass cutting of glass by elongated modification. a): Disc of diameter 16 mm from soda-lime glass of thickness 4 mm, separated along modification inscribed in a single pass in normal incidence. b): Disc with diameter 12 mm from non strengthened Corning Gorilla® glass of thickness 500 µm, separated along modification inscribed in a single pass with an angle of incidence of about 14 ° in air, resulting in a taper angle of about 10 °. c): TOP Cleave Optics

3.3 Tailored heat generation inside of transparent materials

In contrast to the examples presented in section 3.1 and 3.2 other applications, like welding of transparent materials, rely on controlled heat generation. Welding of fused silica by heat accumulation of laser pulses absorbed in the interface region, as illustrated in figures 4a and 4b, are already established. The gap bridging feature (Fig. 11a) [16] allows robust welding of protective windows through the antireflective coating onto a tube by several parallel weld tracks. This results in a high mechanical and thermal stability, is gas proof and shows low optical absorption, making it suitable for use as a protective cap for high power laser light cables used for industrial laser processing [17].

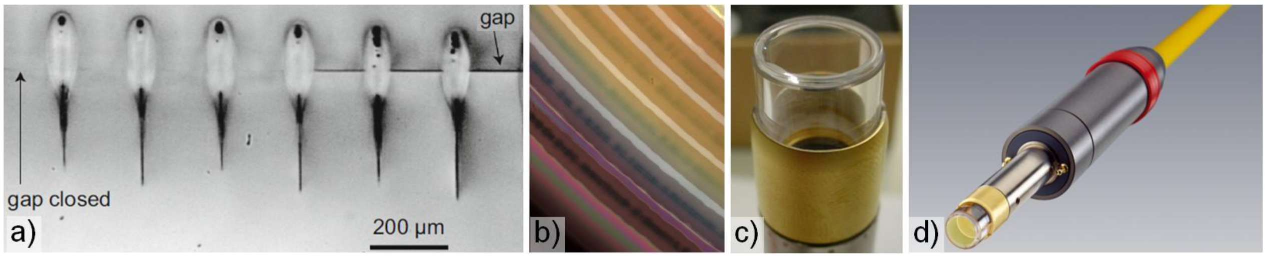

Figure 11: Ultra short pulse laser welding of fused silica. a): Gap bridging by tailored energy deposition [16]. b): Image of seven parallel weld tracks of protection cap as seen through the AR-coated protective window welded onto a tube of fused silica. c) Welded protection cap with mount. d): Laser light cable with mounted protective cap.

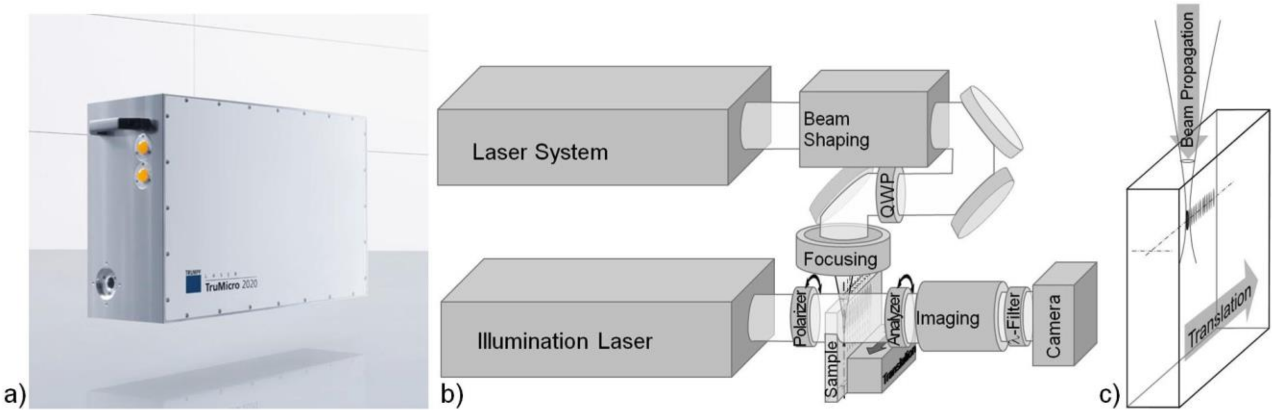

Figure 12: a): Laser of TruMicro series 2000, used for welding and applied as laser system for in-situ stress birefringence microscopy b): Setup for in-situ stress birefringence microscopy. c): focusing and translation directions with respect to the sample

Throughput scaling of thermal processing inside of brittle materials requires careful management of the spatial and temporal temperature distribution. In-situ stress birefringence microscopy turned out to support identifying levers for the development of processing of transparent materials in the heat accumulation regime [13] and results already presented will be shown here again for discussion of effects relevant for scaling. In the experimental setup, the stress birefringence was imaged perpendicular to the beam propagation of the processing beam of wavelength 1030 nm during machining (Fig. 12). The processing beam was focused by a microscope objective (f = 10 mm, NA 0.4) through a polished edge into the sample (Corning Gorilla® glass, non-strengthened) mounted on a translation stage. A liquid crystal spatial light modulator was applied for beam shaping. A randomly polarized laser with 300 ns pulse duration and 500 W peak power at wavelength 810 nm was used to illuminate the sample after passing through a polarizer, mounted in a rotation mount and adjusted in 0°, 30°and 60° with respect to the propagation direction of the processing beam. We imaged the focal region through an analyzer, orientated in 90° with respect to the polarizer, onto a high speed camera. Stress birefringence images were calculated by taking three images for a polarization of 0°, 30° and 60°during separate passes and adding the signal pixel by pixel.

Figure 13 shows the development of stress birefringence for focusing pulses of 10.6 µJ at a repetition rate of 200 kHz about 600 µm into the sample. The laser was switched on at 0 ms for 13 ms, corresponding to the time given in the individual images. Some process light could be seen in the focal region during laser emission, indicating some dynamical structures within the absorption region, growing towards the beam entrance side [18]. Without translation (Fig. 13a), stress was building up surrounding this absorption region and showing a maximum on the beam axis. The stress during this phase was generated in a region adjacent to a melt zone. This melt zone was growing during laser emission, finally exceeding the width of the absorption region by far. After switching off the laser, the stress resulting from temperature gradients decreased while some permanent stress was built up mainly in the solidifying material. The intensity scale of the stress induced signal for the images after stop of laser emission was stretched, indicating a by far higher transient stress compared to the permanent stress induced.

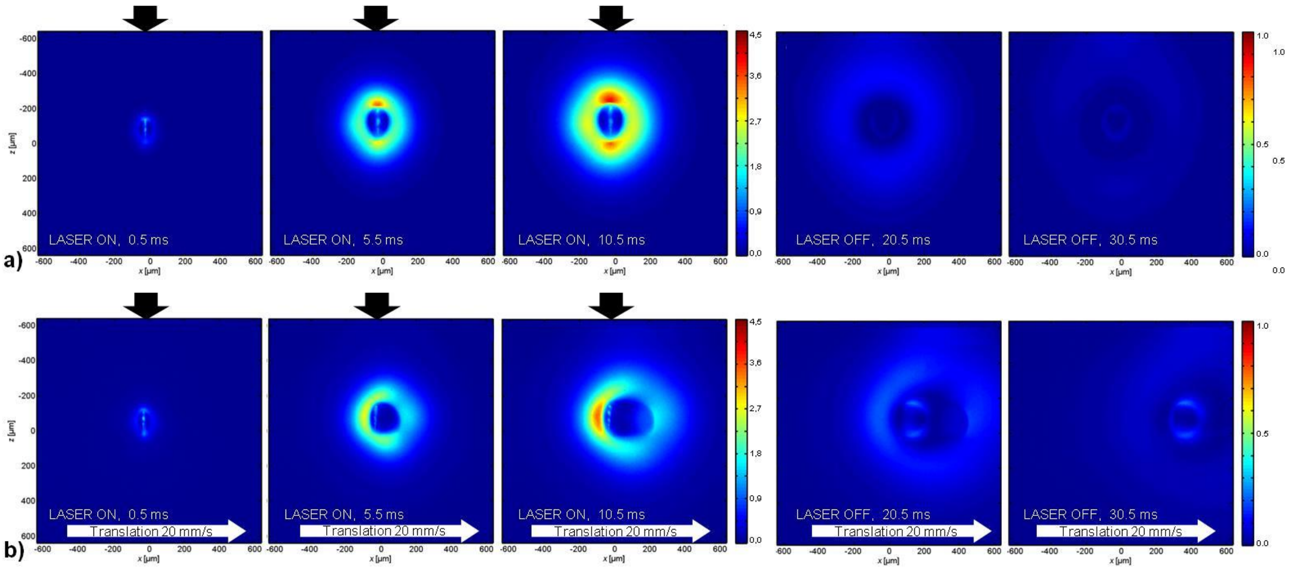

Figure 13: Evolution of stress birefringence for single spot focusing. At 0 ms corresponding to the time scale given in the images, the laser was switched on for 13.5 ms with a repetition rate of 200 kHz, pulse duration of 300 fs and pulse energy of 10.9 µJ. The color scale was expanded for the images at 20.5 and 30.5 ms by a factor of 4.5 with respect to the images taken during laser emission. The direction of beam propagation is indicated by the black arrows. a): no translation. b): translation 20 mm/s perpendicular to the directions of beam propagation and observation.

Under the same conditions but with a translation speed of the sample of 20 mm/s, the maximum transient stress developed in front of the beam axis, adjacent to a small melt zone (Fig. 13b). Behind the beam axis, the melt zone expanded. Slight stress was observed rearward at 10.5 ms, indicating solidification during laser exposition. Again the scale was stretched for the images taken after the end of emission, indicating dominant transient stress. Nevertheless, since the intensity scales correspond to figure 13a, one detects increased permanent stress due to translation, compared to the stationary case. Scaling the feed rate, keeping the same energy per length by adaption of the repetition rate would result in further increased transient and permanent stress.

Therefore we investigated the influence of multi-spot arrangements on the stress evolution under laser emission for duration of 3 ms with repetition rate of 200 kHz and overall pulse energy of 21 µJ at a feed rate of 200 mm/s (Fig. 14). Figure 14a displays results achieved for locating two spots with a distance of 165 µm in direction of beam propagation. A connected stress region with a substructure developed during the laser emission of 3 ms from two separate stress regions of the individual spots.

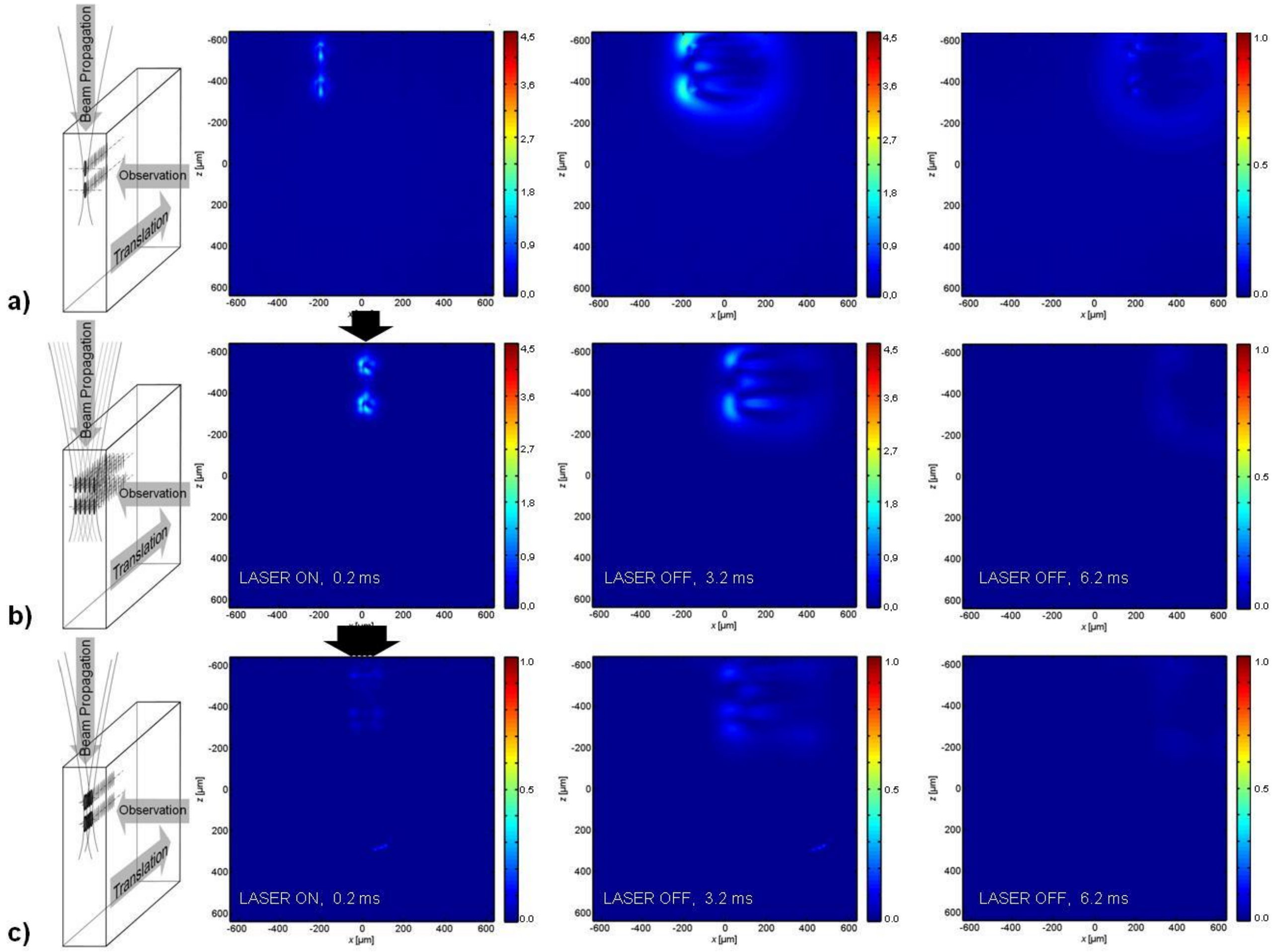

Figure 14: Evolution of stress birefringence for multi-spot focusing into the sample under translation with a feed rate of 200 mm/s. Laser emission with 200 kHz with 21 µJ overall pulse energy was switched on at 0 ms for 3 ms, corresponding to the time given in the images. Signal scale corresponds for all images in this figure but differs from figure 12. Color scale stretched by a factor of 4.5 for some images, as can be seen from the corresponding scale. a): Images for dual spot focusing. The two spots with energy of 10.5 µJ were separated 165 µm in direction of beam propagation, as sketched on the left. b) Images for multi-spot focusing, spots arranged in a plane perpendicular to the feed direction. The ten spots of 2.1 µJ pulse energy were arranged in two lines separated by 165 µm in direction of beam propagation, the lines with a spot separation of 20 µm were orientated perpendicular to the direction of translation, as sketched on the left. c): Images for multi-spot focusing, spots arranged in the plane of beam propagation and feed direction. The ten spots with pulse energy 2.1 µm spots were arranged in two lines separated by 165 µm in direction of beam propagation, the lines with spot separation of 20 µm were orientated in direction of translation.

By further splitting each of the two spots into five spots orientated perpendicular to both, the direction of beam propagation and of translation (Fig. 14b), a comparable, insignificantly reduced transient stress birefringence signal for ten spots was achieved as for two spots. Nevertheless the permanent stress seemed to be reduced by this split of energy into five separate spots. For an orientation of the five spots per line in direction of translation (Fig. 14c), the color scale is stretched for both the images under and after laser emission. This is due to remarkably reduced signal from transient stress. Compared to the ten-spot arrangement with orientation of the spot perpendicular to the feed direction, a further reduced permanent stress signal is observed additionally.

The results presented on transient stress birefringence microscopy clearly demonstrate that under heat accumulation regime, throughput scaling requires careful attention on the spatiotemporal evolution of the temperature profiles. Thereby, both the transient and the permanent stress have to be addressed. From the observations of start and stop of processing it is obvious that feed rate scaling in such processing schemes will necessitate adapting the parameters to individual processing phases, e.g. by variation of feed rate and laser parameters. The observations from multi-spot processing furthermore depict the possibility to control the evolution of the temperature profiles for throughput scaling, e.g. by spatially tailored energy deposition regime. Beside the geometry of the absorption region, the shape of the sample and the processing path, the material parameters, the rate of repetition and feed have to be considered in the process development. Tailored heat generation will not just enable improved welding applications. For example, stress buildup can be used for controlled crack propagation, tailoring temperature distribution in space and time for local annealing or dopant diffusion.

4. CONCLUSION AND OUTLOOK

Ultra short pulse lasers with average powers exceeding 100W allow throughput scaling for ultrafast laser processing, attractive for industrial applications. We illustrate that, besides parallel processing by energy sharing or scaling via repetition rate at correspondingly increasing feed rates, beam shaping facilitates throughput scaling by processing of larger volumes per pulse. We furthermore demonstrate the concept of simultaneity to be beneficially applicable by beam shaping. As shown by the examples, this holds for both, raster and vector based processing strategies. Dynamic focusing is of major importance for scaling of machining by ultrafast lasers. Applying beam shaping, especially in vector based processing, other aspects than just feed rate and synchronization gain relevance with respect to dynamic focusing. Applying beam shaping typically results in a more pronounced impact of individual pulses. Therefore it is important to control this impact by adapting its shape and the processing parameters. For fast high quality processing this means typically advanced pulse on demand concepts, supported by the laser, the applied system technology and the machine. Furthermore the beam shape often shows preferred direction to be adapted to feed direction, as long as shape of the beam itself will not be changed dynamically.

We do not expect to identify one common concept suitable for throughput scaling, not one sole shaping and dynamical focusing solution. Especially under heat accumulation conditions process, development requires paying attention to effects on multiple scales in space and time. We already applied different setups for in-situ diagnostics [13]. The extension towards improved pump probe capabilities is in progress, will allow a sup-ps temporal resolution within a delay range spanning from sub-ps to ms at frame rates of more than 200 kHz under applying spatial and temporal beam shaping and highly dynamic focusing. The experimental systems will be equipped with lasers offering pulse energies exceeding 1 mJ, repetition rates of 2 MHz and flexible multi-pulse options, extended timing capabilities and with different beam and pulse shaping techniques. This will support process development and implementation of new and throughput scaled industrial ultrafast laser applications.

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