Advanced Laser Micro Machining Using a Novel Trepanning System

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The LMTB has designed and implemented a novel optical concept for the development of a versatile trepanning system, enabling the adjustment of the displacement **and** the inclination angle during circular rotation at up to 20000 r.p.m. The presented trepanning systems are able to laser machine through-holes diameters of 100 µm with a negative taper of up to 5°. Starting from an early stage of implementation, the novel trepanning system has been customized for different applications and industrial partners. The conference paper outlines the development steps and advanced performance, accenting laser micro machining results utilizing the novel LMTB trepanning system in operation at different laser parameters.

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1. Introduction

Laser material processing, e. g. fast and precise production of holes, is competing with several other sophisticated conventional methodes, for example diamond tooling, sand blasting, water jet and ultrasonic processing, chemical etching and plasma eroding. While each conventional method is optimized for a certain class of materials, laser induced material ablation using short or ultra-short pulsed light can be utilized for practically every metal, ceramic, dielectric and semi-conductive work piece [1,2]. Diode pumped solid state laser (DPSSL) systems can generate short and ultra-short pulses with a very good beam quality, i.e. excellent focus ability. DPSSL systems are very versatile tools and provide important precondition for precise material machining. These laser devices are usually compact and processing can be conducted under ambient conditions. Hence, DPSSL systems are easily integrated in production lines, provided the laser processing technique has been developed to a stage, that it meets the necessary requirements in quality and speed.

The drawbacks in laser machining are the effort to be invested to develop the appropriate processing technique. Laser parameters, i.e. combination of wavelength and pulse width for providing the required optical and thermal penetration depths, laser beam alignment, energy distribution, relative movement of the work piece and optics, temperature, pressure, and many other factors have to be optimized for the development of a laser processing method. Even a "simple" problem such as drilling small through-holes in different samples such as tungsten, silicon, and ceramic AlN or Al_2O_3 can mark a challenging job. For the microfabrication of through-holes, laser percussion drilling may be considered [3], however, this method is subject to critical boundaries. For the realization of precise and reproducible through holes, laser trepanning, also known as core-drilling, is more appropriate [4]. Laser trepanning with an advanced laser trepanning system has another important advantage over percussion drilling: the possibility of engineering the taper structure.

This paper represents a "snap-shot" report on the development in laser trepanning systems followed at the laser application laboratory of the LMTB GmbH. The novel trepanning systems are implemented in CNC processing stations, integrating diode-pumped solid-state laser systems generating energetic nanosecond or even picosecond pulses. Our investigation in the laser-induced material ablation concentrate on industrial–near application goals, for example, the completion of high-quality micro-holes at predefined diameter and taper angle.

2. The Optical Concept

The optical concept of the LMTB trepanning system was guided by the following priority constraints:

1) Free choice of focusing optics: Provided the effective focusing length *f* remains large enough for an adequate working distance, e.g. $f > 50$ mm, the laser beam can be focused practically by any sampling optics available. An optimal intensity distribution on the work piece is a stringent requirement for precise laser machining. The trepanning systems developed at the LMTB try to meet this requirement as good as possible.

2) Straightforward circular displacement: By introducing a slanted optical plate (e.g. window material with polished, highly parallel surfaces) below the focusing optics, the laser beam receives a parallel displacement. If the optical plate is rotated and the slanting position remains fixed, the laser beam will simply follow a perfect circular path on the work piece.

3) Straightforward introduction of an inclination angle: Important requirement of the trepanning system is a fairly simple and reliable optical arrangement (after the displacement) that accounts for the inclination.

4) Variation of displacement and/or inclination during processing: The optics can be positioned while in rotation to readdress the displacement and inclination on the work-piece during laser machining, if necessary.

This can be conducted without jeopardizing the other priority constraints mentioned above.

5) Symmetric mass distribution: In a trepanning system, the optics responsible for varying the laser beam displacement and inclination has to be rotated. To ensure high rotation speeds and minimize a deteriorating vibration, the moving optical elements are chosen and aligned specifically for an optimal symmetric mass distribution around the rotation axis.

6) Compact size and low weight: One constrain, that drives the implementation step details, such as the choice of the hollow shaft motor and external drivers, the construction of the mechanical parts, choice of optical material, etc., is minimization of weight and size (and costs). This point is very important for a widespread implementation of any trepanning system in laser micro machining.

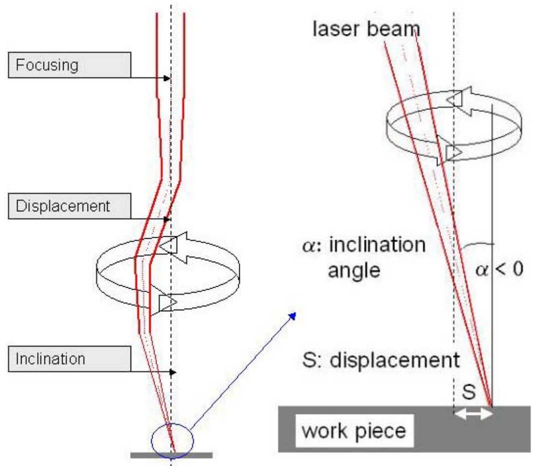

Fig. 1 Illustration of the beam path along the LMTB trepanning system: The beam propagates through (stationary) focusing optics and the rotating displacement & inclination optic set-up. The right picture depicts a magnified view near focal point with definition of inclination angle and beam displacement at the work piece

Fig. 1 illustrates the optical concept of the novel trepanning system, separating the laser guiding path in three steps: 1. focusing, 2. (rotating) displacement and 3. (rotating) inclination optics. An example of the laser beam propagation along the optical axis inside the trepanning system is illustrated in Fig. 1 (left). After passing the focusing optics, the converging laser beam is displaced parallel from the original path, i.e. from the optical axis. In a third step an inclination is introduced. The laser beam is then guided back towards the optical axis.

The magnification in Fig. 1 (right) illustrates this in more detail: the converging laser beam crosses the optical axis before the focus hits the surface of the work piece at an chosen displacement S. The inclination angle α is negative in the example of Fig. 1. Note that for illustrative purpose, the inclination angle is exaggerated from typical applications (α = 3..0..–5°). If the outer laser beam is perpendicular to the surface, i.e. α = 0°, one will expect in rotation a cylindrical drilling mode with a circular diameter of 2 S.

Based on the optical software tool ZEMAX, the laser beam propagation through the trepanning system is simulated and analyzed implementing the three optical elements described above: focusing, displacement and inclination. The protective glass substrates are also included in the simulation. One result of a specific optical concept is depicted in Fig. 2, using a optical focusing element with an effective focal length equal 150 mm. Note that in this case the laser airy disk at focal point is expected to be 19 µm, much larger than the focus diameter of only 0.6 µm determined in the ray tracing program. Important for the application is not only the intensity distribution directly at the focus spot. Fig. 2 also presents the simulated intensity distribution at a distance of ±300 µm from the expected focal point, which is surprisingly symmetric considering the potential optical aberrations that are introduced if the optical alignment is not designed with great care.

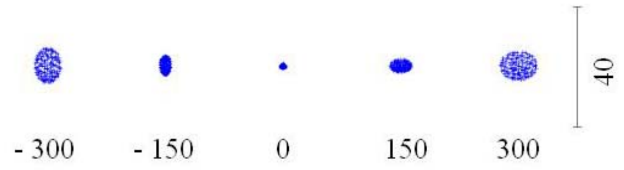

Fig. 2 Simulated beam intensity distribution (ZEMAX) for a defined optical trepanning system design, given for different positions (-300, 150, 0, +150, and +300 µm) relative to focal point. Note: the airy disk for a laser beam at focus (not shown) is ca. 20 µm.

Hence, table 1 compiles the optical simulation results for a specific trepanning system [5] developed for a zero taper through hole, i.e. realizing cylindrical laser drilling. The working distance is equal the gap between protective glass and laser focal point on the work piece. The data is presented for three different focusing optics, including the case presented in Fig. 2, without changing or replacing the other optics responsible for varying the displacement and inclination. Only the alignment of the optics has been adjusted to confirm the 0° inclination angle in all three cases outlined in Tab. 1.

The following priority constrain, the free choice of focusing optics, is feasible within a certain range even for an already completed and implemented trepanning system, which demonstrates the great flexibility of the laser processing tool.

Table 1: Optical specifications for a LMTB trepanning system designed for cylindrical drilling: three different focusing optics

Focal length	**75 mm**	**100 mm**	**150 mm**
Working distance	35 mm	50 mm	50 mm
Ray tracing: focus diameter	2.5 µm	2.0 µm	0.6 µm
Gaussian optics: airy disk (M^2 = 1.3)	10 µm	13 µm	19 µm
Raleigh length	140 µm	240 µm	550 µm
Inclination angle	0°	0°	0°
Drilling diameter	50 to 1500 µm	50 to 1400 µm	50 to 1000 µm

3. Trepanning Systems for Glass Machining

Investigations on laser machining of transparent materials, such as technical glass or quartz, are an on-going topic at the LMTB laser application lab. Several different laser diode-pumped solid-state laser systems generating short “green” 532 nm pulses in a pulse width range of 3 to 50 ns are implemented for the application near studies. These parameters allow for laser machining from the rear side of the transparent sample, i.e. the laser propagates through the work piece and the focal point is at the rear surface. This method can yield a highly efficient average ablation rate of over 100 µm per pulse. In addition, since the drilling is conducted upward, it yields perpendicular walls in e.g. through-hole drilling quite straightforwardly. Rear side processing makes any compensation strategy by introduction of an inclination angle for the laser beam unnecessary. Hence, for glass machining, the simpler trepanning system of only focusing and the displacement optics are implemented.

Fig. 3 (left) depicts the glass trepanning system while completing a 10 mm diameter hole in a 3 mm thick glass plate in only a few seconds. The typical rotation speed of the glass trepanning system is set to 18000 r.p.m. at laser pulse repetition rates of 20 kHz. For many applications in laser glass processing, the displacement can be fixed to 150 or 250 µm, yielding cutting diameters of 300 and 500 µm, respectively. Fig. 3 (right) illustrates the laser pulse distribution on the rear side of the transparent work piece at the starting point of processing (the first “dot” on the right end). The circular arrangement of ablation points is shifted after every rotation due to the additional motion of the work piece on a CNC programmable XY table.

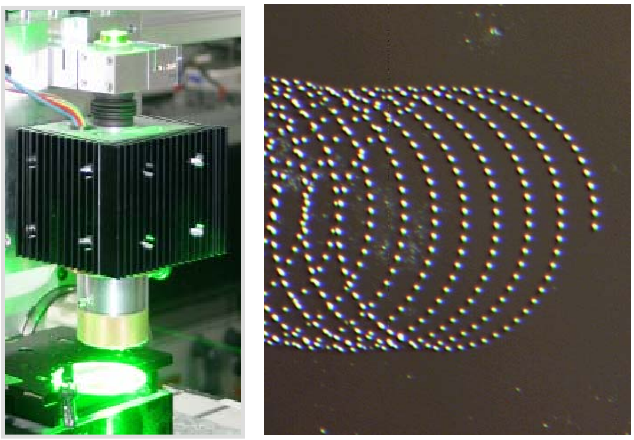

Fig. 3 Laser trepanning and cutting of glass. Right: microscope picture of glass substrate marking the very beginning of the trepanning cycles

As mentioned, taper-less through-hole drilling is easily accessible in laser trepanning of glass. Fig. 4 (top) depicts an example of a 1 mm diameter hole through a K8 glass cube of 48 mm size. In the center part the drilling diameter was continuously broadened and then placed back to the original state in a single step to additionally yield the tapered structure inside the cube, note the insert in Fig. 4 (top). The lower picture in Fig. 4 represents the capability of laser contour cutting using the glass trepanning system. The star-like structure can be cut out of the 3 mm thick glass substrate in only a few seconds.

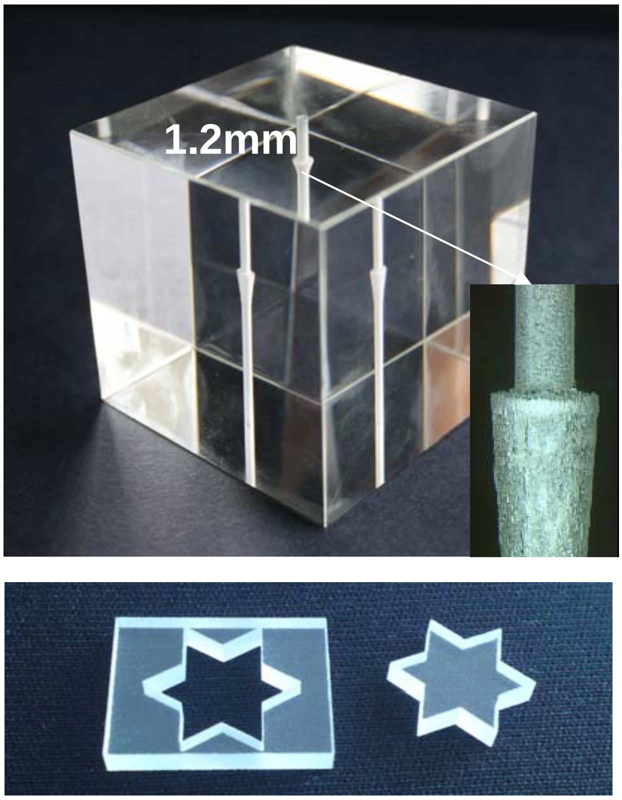

Fig. 4 Examples of laser glass trepanning. Top: 1.2 mm through-hole in 48 mm thick glass cube (with a special taper in the middle). Below: star shape cut out of a 3 mm thick soda-lime glass.

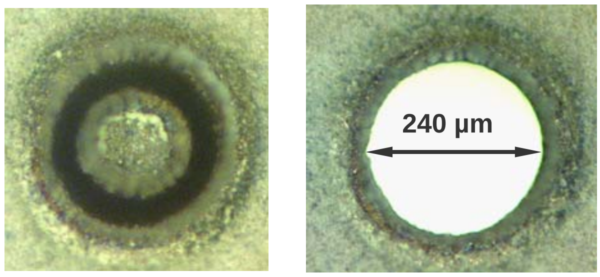

Fig. 5 Microscope pictures of two different stages after laser trepanning of a 500 µm thick tungsten sample at a circular displacement of 200 µm: Processing time from left to right: 5s and 10 s.

Fig. 5 depicts the development of an individual through-hole into a 500 µm thick tungsten foil using a lamp-pumped Nd:YAG laser system generating 10W of short laser pulses at a wavelength of 1064 nm, a pulse width of 200 ns and a repetition rate of 5 kHz [6,7]. The holes were drilled with the glass trepanning system at a displacement of 100 µm, yielding a circular trepanning diameter of 200 µm. Naturally, the rear side processing method utilized for glass can not be transferred to metal substrates at 1064 nm, therefore one can expect positive tapered through holes. The opening hole of 250 µm is completed after 10s. The exit hole remains smaller and yields 130 µm after 10s and reaches a maximum of 185 µm after over 60 s trepanning. Hence, this very versatile trepanning system designed for glass machining proved to accomplish well-defined circular through holes for non-transparent materials. However, the fabricated structures demonstrate a positive taper with an angle between 3 and 7°, depending on trepanning diameter and type of material.

4. Trepanning Systems for Non-Transparent Materials

To compensate for the observed narrowing in conventional laser trepanning, the optical design was improved, as depicted in Fig. 1, pending patent. The recently completed novel trepanning systems, see Fig. 6, allows for a continuing variation - in operation / during rotation - of the trepanning optics. In Fig. 6 (left) the alteration of the displacement is motorized, the inclination angle has to be set and fixed manually. In the set-up shown in Fig. 6 right, the trepanning system allows for motor-control variation of both, displacement and inclination. The driving units, such as the hollow shaft motor, dominating the central part of the device, mostly govern size and weight.

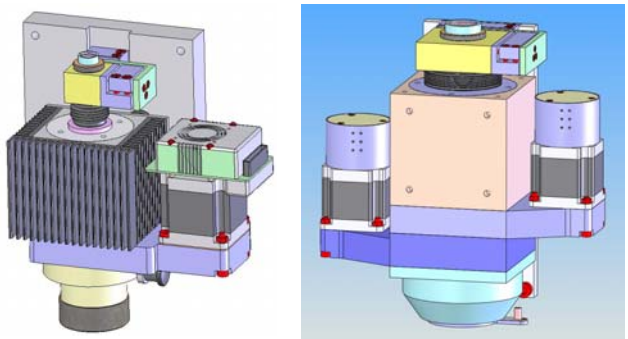

Fig. 6 CAD illustrations of completed laser trepanning systems for solving universal drilling problems, i.e. control of drilling diameter and taper.

Micro drilling applications utilizing the implemented LMTB trepanning systems are currently being actively perused with different ns and ps laser systems. The tasks involve free choose of hole diameter and taper. One emphasis of the work conducted at the LMTB laser application laboratory is the fabrication of cylindrical (zero tapered) through holes in ceramic substrates.

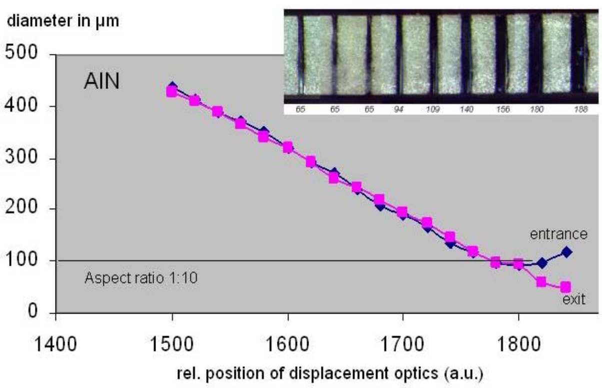

Fig. 7 AlN ceramic through-hole diameter of entrance and exit hole versus relative position of the displacement optics. The insert above right depicts a microscope image after the cross-section polish of the AlN sample.

Preliminary results comparing the size of the entrance and exit through hole after laser machining of a 1 mm thick AlN ceramic plate is illustrated in Fig. 7. The drilled through holes remain cylindrical until reaching an aspect ratio of 1:10, hence, hole diameter of 100 µm. Above a certain relative position of the displacement optics (inclination is held constant), the shape of the hole yields a positive taper, i.e. entrance hole is smaller than exit hole diameter.

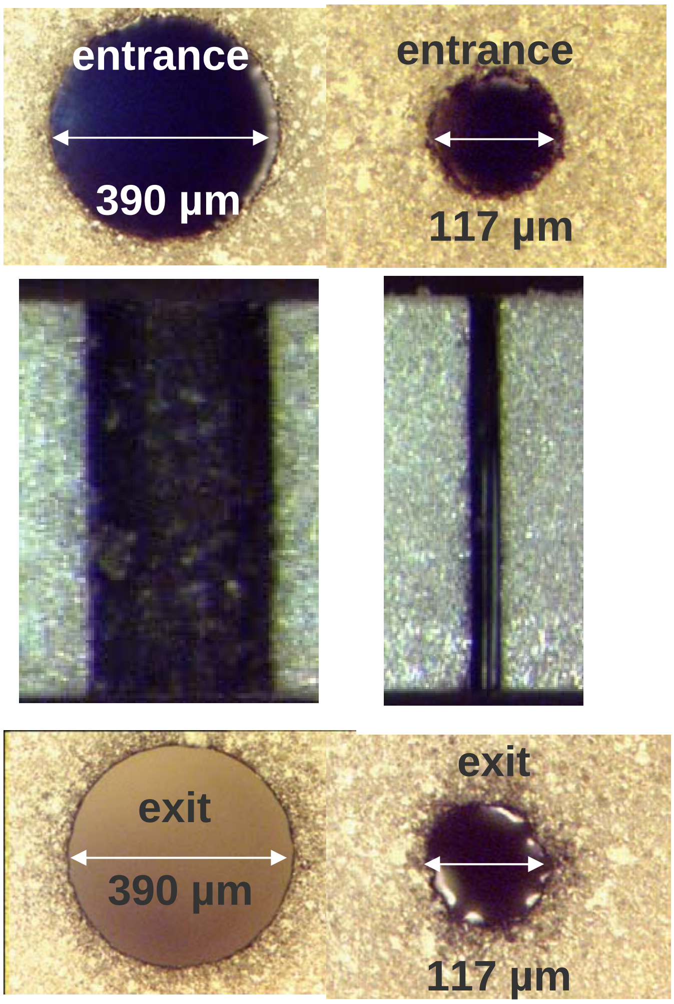

Fig. 8 Microscope images of two cylindrical through holes, 390 and 117 mm, in an 1 mm thick AlN sample: entrance hole (top), cross-section (middle) and exit hole (bottom). Note: the scale for the cross-section differs from the entrance and exit hole.

Fig. 8 presents two examples of zero tapered through holes in 1 mm thick AlN ceramic plates with a hole diameter of 390 and 117 µm. Note, that the exit holes resemble the entrance hole fairly exactly in size and shape.

In addition to cylindrical holes, the precise laser fabrication of reversed tapered micro holes, i.e. exit hole > hole entrance diameter, is a important challenge to be met. The inclination angle is here set to values below zero, for example: –3 to –5°.

Fig. 9 depicts results on reversed tapered holes in Aluminum foils of ca. 600 and 800 µm thickness. At the present state of development and applications, the first example depicted in the Fig. 9 (left) with an entrance and exit hole of 60 and 120 µm, respectively, characterizes a more elaborate achievement. However, reversed tapered through-holes with entrance holes of >90 µm in 0.5 to 1 mm thick samples can be processed with the novel LMTB trepanning system rather straightforwardly.

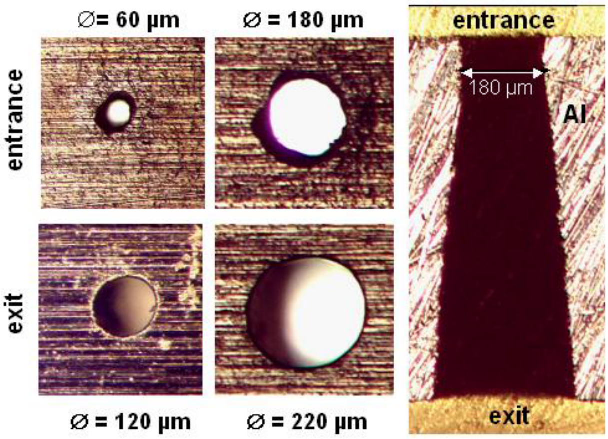

Fig. 9 Microscope images of reversed tapered through holes in Al-metal sample, 600 (left and middle) and 800µm (right cross section) thick.

5. Conclusion

Driven by industrial application and innovative fabrication tasks, the non-profit research company LMTB GmbH is developing optical components for laser monitoring and processing. The novel trepanning system is closely guided by the following constrains: optimal focusing, straightforward online variation of displacement (drilling diameter) and inclination angle (taper structure), symmetric mass distribution (for low-vibration high rotation speeds) and limited size, weight and costs. Several customized trepanning systems are implemented or are presently completed for near-time utilization at industrial partners. Standard specification of a LMTB trepanning system is the following:

- Drilling diameter: 50 to 1500 µm
- Inclination angle: -5 to +3°
- Rotation speed: up to 20000 r.p.m
- Weight and size: 5 to < 10 kg, 200 x 250 x 120 mm^3

The first processing results with the novel LMTB trepanning system utilizing ns and ps laser pulses are very encouraging. Further studies with different materials are conducted at the LMTB laser application laboratory to optimize the laser trepanning system for even more precise and reliable micro drilling. Presently, the LMTB is developing a module allowing for an online measurement of the position for displacement and inclination, which will simplify calibration and CNC work station integration of the novel trepanning system. A realization and implementation of this new development is expected to be completed end of 2010.

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