High precision drilling with aspect rations of 1:40: From laser source to application

Florian Lendner*[1], Roswitha Giedl-Wagner [1], Steffen Rübling[2], Marc Sailer[2], Axel Fehrenbacher[2]
[1)] GFH GmbH, Deggendorf, Germany
[2)] TRUMPF Laser GmbH, Schramberg, Germany

Abstract

In laser drilling, one challenge is to achieve a high drilling quality in high aspect ratio drilling. Ultra-short pulsed lasers use different concepts like thin disks, fibers and rods. The slab technology is implemented because of their flexibility and characteristics. They bring together both advantages and deliver high pulse energies at high repetition rates. Materials with a thickness > 1.5 mm demand specialized optics handling the high power and pulse energies with adapted processing strategies, integrated in a machine setup. In this contribution, we focus on all the necessary components and strategies for drilling high precision holes with aspect ratios up to 1:40.

Keywords: Ultrafast, micro drilling, industrial lasers, temporal energy deposition, burst optimization

1. Motivation

During the last decade, ultrafast micromachining found its way into industrial use in many applications and industries like aerospace, automotive, photovoltaics, medical or electronics. The fact, that these lasers work with extremely small focal spots, without any mechanical force effects and no relevant thermal impact on the working piece, makes them also well qualified for high precision micro drilling applications.

Due to their ultrashort interaction time, ultrafast lasers apply their energy in a time regime of several picoseconds down to several hundred femtoseconds and convert the material into plasma almost instantaneously. The result are two beneficial effects: On the one hand ultrafast lasers can machine any kind of material and on the other hand the heat impact on the residual part is marginal what results in outstanding surface quality.

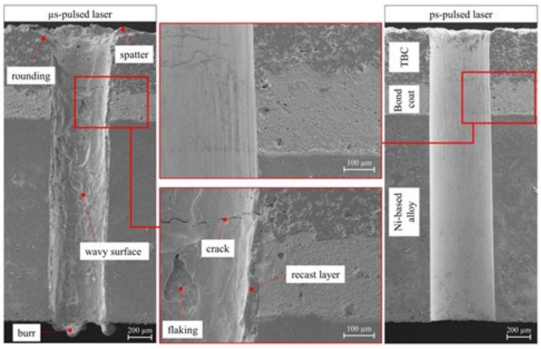

Fig. 1. Ultrashort laser pulses (right) produce much better surfaces than short laser pulses (left). [1]

Depending on the requirements of the hole there exist different techniques to create holes with lasers (see figure 2). The fastest and simplest way is shooting holes with single or several pulses of a focused beam. For this method, the hole diameter is pregiven by the optics setup and due to physical properties of the laser beam and material interaction it results in positive tapered holes. The trepanning technique starts with a percussion drilled hole following by a cutting process tracing the contour of the hole. This adds the degree of freedom for adjusting the hole diameter larger than the focal spot, but still does not allow to influence the taper of the hole.

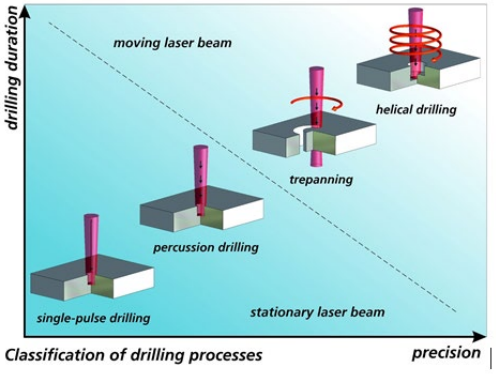

Fig. 2. Overview of different laser drilling strategies [2]

The helical drilling is performed by a special optical system to rotate and incline the laser beam during the drilling sequence. Next to the possibility to change the diameter and taper of the hole this guarantees the best distribution of the pulses and allows therefore the best drilling quality. During the last years this method has been established to create high precision bore holes by laser for different industrial applications like injection parts, spinnerets or medical devices.

Today the high precision drilling reaches its limits with increasing wall thickness of the part and is typically used up to a bore length <1,5mm. The cause lies on the one hand in the maximum available energy of the industrial ultrafast lasers (pulse energy x repetition rate) and on the other hand the availability of optical systems, that can deal with higher pulse energies.

This paper demonstrates, that the combination of Trumpf's new laser concept TruMicro series 6000 and GFH's helical drilling tool GL.trepan allow to overcome the known limits and create high precision micro holes in the several mm range and with aspect ratio up to 1:40.

2. Laser Source

2.1. Ultra-short pulse portfolio of TRUMPF

A wide variety of market and application requirements for ultra-short pulse lasers were supplied by a board portfolio of different amplification technologies and corresponding products. For power levels below 100 W, the fiber amplification offers a flexible parameter space with variable pulse duration and numerous parameter combinations. The linear fiber amplification enables advanced Pulse on Demand and burst mode with up to 16 pulses. For higher power levels up to 200 W the regenerative disk amplification was used, although with some limitations concerning the flexibility. With the development of slab technology, flexible linear amplification can be combined with higher power levels up to 200 W, high pulse energies with up to 2 mJ and sub-pico second pulse durations.

2.2. High-energy slab amplification for high-aspect ratio drilling

TRUMPF TruMicro Series 6000 offers slab amplification architecture to combine high process dynamics with high pulse energy and power. Advantages of heat management of the amplification crystal with the benefits of linear amplification supplies high pulse energies in combination with dynamic pulse output. For example, burst patterns in high numbers (up to 16 pulses with equal pulse energy) and high accumulated burst energy (up to 8 mJ) and pulses on demand with low jitter (< 20 ns) are possible. New control electronics regulate the pulse energy level output for a constant energy input into the workpiece independent of dynamic change of repetition rate or burst patterns.

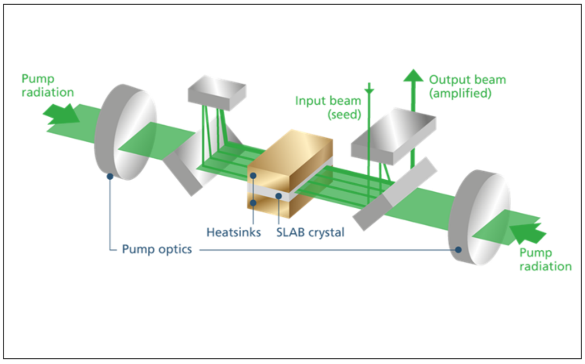

Fig. 3. Beam path inside the amplification module. [1]

Both features, *Advanced Pulse on Demand* and *Burst Mode*, can be realized because of the linear amplification principle. Multiple pulses can be amplified to an equal energy level at the same time inside the slab crystal. (figure 3). That is a main step forward, compared to the regenerative disk amplification, where every pulse needs to be amplified by several cycles through the disk.

The variable burst mode of TRUMPF opens many possibilities. Within a timeframe of up to 320 ns, up to 16 pulses can be emitted with a temporal distance of 20 ns between each pulse (50 MHz seed repetition rate). The maximum accumulated pulse energy inside one burst train can be up to 8 mJ, while the maximum single pulse energy is 2 mJ. These high energy levels often exceed the necessary energy levels for processing of thin materials. However, drilling applications and especially high-aspect ratio drilling application tremendously benefit from higher energy levels since scaling of processing speed via repetition rate is also often constrained due to heat accumulation effects.

As an example of different operation points of the laser which can be beneficial for high-aspect laser drilling, a four-pulse burst is able to provide a total burst energy of 8 mJ at 25 kHz. For non-burst processing, the laser can provide 2 mJ pulses at up to 100 kHz, both operation points resulting in a maximum power level of 200W.

3. Applications and Results

3.1. Need for tilted laser beam

Due to physical characteristics of a Gaussian beam, an orthogonal irradiation of laser beam on the material surface effects a positive taper in wall angle.

Fig. 4. (a) Influence of inclination angle on wall angle (schematic); (b) Tilted rotating laser beam allows drilling with positive and negative wall angle as well as cylindrical holes (schematic). [4]

Since many precision parts require vertical walls or a configurable wall angle, a compensation by tilted beam must be realized. The angle of attack depends mainly on the optical setup and the material and therefore it has to be configurable for the individual application.

3.2. Need for fast and precise beam rotation

For using the laser as a drilling tool, the beam must be rotated on a circular movement. Depending on lasers repetition rate f, spot radius r and the required drilling diameter $\emptyset_h$, the pulse overlap PO is determined by the number of beam rotations n:

$$PO = \frac{r^2 4 * \arcsin \sqrt{\frac{\left(r - \frac{\emptyset_h \pi n}{2f}\right)}{2r}} - \sin\left(4 * \arcsin \sqrt{\frac{\left(r - \frac{\emptyset_h \pi n}{2f}\right)}{2r}}\right)}{(2r)^2 * \frac{\pi}{4}}$$

Typically, lasers with high energy per pulse are used for precision drilling and cutting. These lasers provide a frequency in a range of several hundred kilohertz. For achieving a high quality, process must be kept in cold regime and therefore the pulses overlap should be kept in a range between 80-95%. To fulfill this requirement and to use as many provided laser pulses as possible, the drilling of typical hole sizes between 100µm to 500µm demands for a beam rotation speed up to 30.000 rpm.

Furthermore, the circularity of beam rotation a very important factor, because it is displayed on the working piece. Therefore the rotations' roundness and stability is a significant quality criteria for drillings'roundness and diameter consistency.

3.3. Helical drilling optics

For rotating and tilting the laser beam, the helical drilling head GL.trepan of GFH was used. The optics bases on rotating cylindrical lenses, which forces the beam on rotation and allows the setting of hole diameter and wall angle by influencing angle and position of the incoming beam. Since the concept uses transmitting optics in combination with a beam diameter of 5mm, it is able to handle serval mJ single pulse energy even of ultrafast pulses.

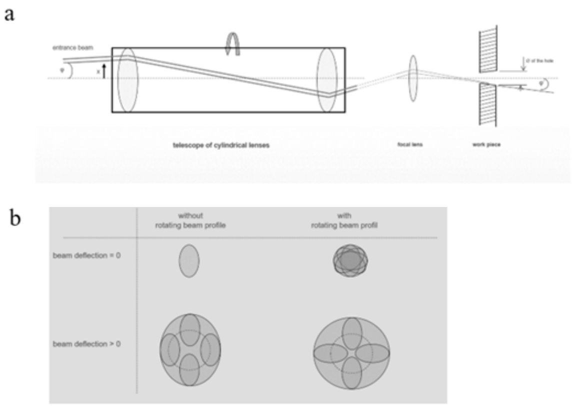

Fig. 5. a) Optical concept of GL.trepan using a telescope of cylindrical lenses; b) Rotation of beam profile allows drilling round holes even with elliptical beam profile [4]

These cylindrical lenses are set into a precision balanced spindle, ensuring absolute precision of the path roundness even at high rotational speeds. In order to take advantage of the high repetition rates of the laser, a beam rotation up to 30.000 rpm is possible. Therefore, it does not contain any adjustable components inside, which could change the center of gravity and affect the drilling results. The optical concept effects also a co-rotating intensity profile of the beam. This makes the production process more robust since it allows the production of round precision holes even if the focus spot itself is not perfectly round. (see Figure 4).

A beam manipulation unit located before the spindle allows in-situ-control of the beam position and angle entering the rotating telescope and thus enables a flexible tool diameter and inclination angle during laser processing. This allows to apply different drilling strategies and to realize cylindrical holes as well as positive and negative tapered holes (see figure 5).

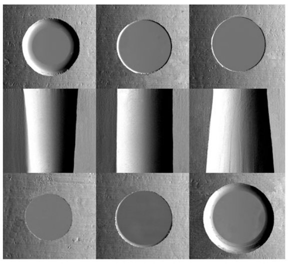

Fig. 6 Stainless steel, t=0,25mm, drilling diameter = 150µm (cylindrical hole)

3.4. Processing strategy

For industrial precision drilling typically, a laser fluence well above ablation threshold is used. It varies with the type of material, but is typically in a range of about 20-25 J/cm² and a good drilling result is archived within the Rayleigh length of the beam caustic. Therefore, the available pulse energy is a limiting factor for the choice of the focal lengths of the optics and the maximum length of the drilling. Using a 1030nm laser with 200µJ pulse energy and 5mm raw beam diameter with 25J/cm² allows a maximum focal length of 100mm. The resulting Rayleigh length is about 600µm, what limits the material thickness to drill at a maximum to 1,2mm.

The drillable maximum can be further increased by using different z positions during the drilling sequence till the caustic of the diverging defocused beam impacts the material at the hole entry side. Using a f100 lens for drilling a hole with diameter 200µm, this will occur at a z position of -1.6 mm and limits the maximum thickness to 2mm and a maximum aspect ratio of 1:10 for processing a cylindrical hole (see figure 7).

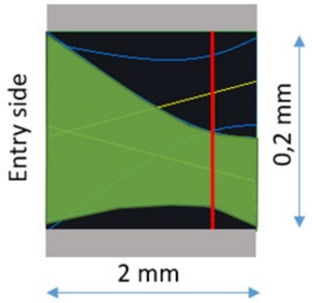

Fig. 7. Limit of beam caustic for f100 mm in 2mm bore hole length, hole diameter 200µm (green line); hole diameter not to scale; red line shows focal position

With the Trumpf series 6000 laser there is a maximum single pulse energy of 2mJ available. This has two beneficial effects. On the one hand it allows the use of a focal length up to 250mm by keeping the fluence of 25J/cm² and gaining an increasing Rayleigh length up to 3,9mm. On the other hand, the beam caustic of the larger focal lens exhibits less divergence and therefore, it allows a larger range of defocusing without damaging the entry of the hole.

For drilling a hole with diameter of 200µm it increases the limit of maximum thickness to 8 mm at a focal position of -5mm and a maximum aspect ratio of 1:40 can be achieved.

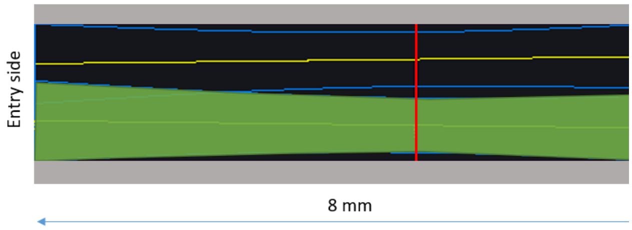

Fig. 8. Beam caustic for f250 mm in 8 mm bore hole length, hole diameter 200µm (green line), focal position at hole exit; hole diameter not to scale

3.5. Processing head

Process gas plays an important role in laser drilling applications. Depending on the material to be drilled, the type of gas is chosen. The nozzle geometry, standoff distance and flow rate define the gas dynamics and its influence on the resulting bore. The paper deals with high aspect ratio holes with hole lengths exceeding the Rayleigh length of the used setup. As discussed before, adaptation of the laser focus during drilling is helpful for the progress of the hole formation.

Conventional drilling heads have a fixed assist gas nozzle for drilling in one dedicated z position. For good results, the typical distance of the gas nozzle to the part is in a range of 0.2 mm – 1mm. For drilling high aspect ratio holes and varying the z-position during the drilling sequence over several millimeters, the standoff distance must accommodate the full travel. This results in an increased distance to the part and therefore lead to a negative effect on quality and efficiency of the drilling.

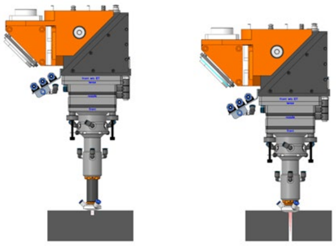

Fig. 9. The new processing head includes optics up to f250 and allows to change the z-position relative to part in a range of 0mm (left) to 50mm (right)

Therefore, a new design of processing head was developed (see figure 9). It has a movable part, which is connected with the gas nozzle and ensures, that the distance of gas nozzle to part is kept in the same range over the full drilling sequence.

3.6. Results and Discussion

All shown results were produced with a TruMicro 6020 (see figure 10) in combination with GL.trepan and a focal lens f250 on machining tools of GFH.

Type	TruMicro 6020
Wavelength	1030nm
Beam quality M²	<1,3
Average power	up to 200W
pulse duration	3ps
Max. pulse energy	2mJ
Frequency	100 kHz

Fig. 10. Specification of used laser type Trumpf TruMicro 6020

It was demonstrated, that it is possible to drill different hole configurations in a diameter range from 100µm to 300µm on various materials and different bore lengths resulting in different aspect ratios up to 1:38 without any melting zone.

The parameter set was different depending on the material type and hole configuration. While the frequency was reduced with metals to prevent the melting point, the full laser power could be implemented with hard metals and ceramics. The available single pulse power of the laser was used up to its maximum of 1,9mJ at focal point.

The processing time per hole differs with material type, hole configuration and bore length and does not increase linearly with the wall thickness. The aim of the paper was to show the feasibility and achievable quality. Therefore, the shown samples were not fully optimized for shortest processing times. Nonetheless the drilling rate achieved was in an acceptable range of 8s to 15s per millimeter.

The surface quality reflects the same quality, which can be achieved for ultrafast drilled precision holes of smaller aspect ratios and was in a range of Ra = 0,1 µm and below.

The measured roundness of the shown samples differs slightly and was measured in a range of 93-99% (short axis versus long axis of the hole).

Overall the diameters at entry and exit of the drillings showed a good repeatability hole to hole with a standard deviation of less than 1,5% of the diameter.

3.7. Al2O3

Material	Entry diameter	Exit diameter	Bore length	Aspect ratio	Drill rate	Drilling time
Al2O3	108µm	98µm	2mm	1:20	15s/mm	30s

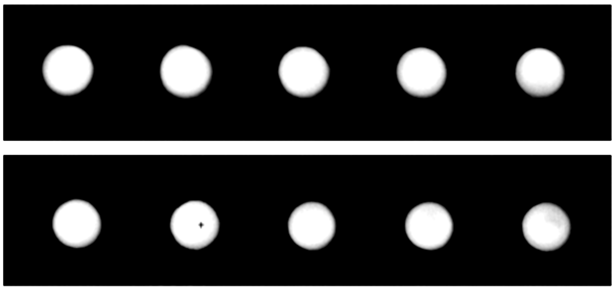

Fig. 11. Stainless steel, t=2mm; entry: 108µm (top), exit 98µm (bottom)

3.8. Stainless steel

Material	Entry diameter	Exit diameter	Bore length	Aspect ratio	Drill rate	Drilling time
Stainless steel	200µm	200µm	4mm	1:20	10s/mm	40

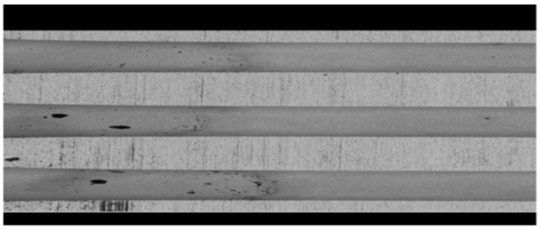

Fig. 12. SEM picture of surface of holes in 4mm steel

3.9. Carbide

Material	Entry diameter	Exit diameter	Bore length	Aspect ratio	Drill rate	Drilling time
Carbide	140µm	126µm	5 mm	1:38	8s/mm	40s

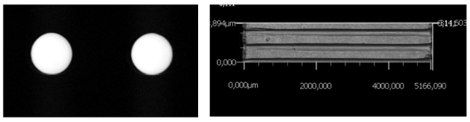

Fig. 13. Carbide, t=5 mm; Entry diameter 146µm (left); LSM scan of cross section (right)

3.10. Nickel

Material	Entry diameter	Exit diameter	Bore length	Aspect ratio	Drill rate	Drilling time
Nickel	278µm	278µm	6 mm	1:21	10s/m	60s
Nickel	168µm	148µm	6mm	1:38	9s/m	54s

Fig. 14. Nickel, t=6 mm; Entry diameter 278µm (left); Exit diameter 278µm (right)

Fig. 15. Nickel, t=6 mm; Entry diameter 168µm (left); Exit diameter 148µm (right)

4. Conclusion

Ultrafast lasers are well suitable for drilling of micro holes with highest demands on quality. Thanks to their touchless and athermal operation, the extreme small tool size and feasibility to machine any material, they are already industrially used for different applications and industries. Considering the consequential costs, laser have the obvious advantage of processing without tool wear and having always the same sharp tool geometry. The material thickness was still a limiting factor and today this technology is typically used up to bore lengths of < 1,5mm.

The new Trumpf 6000 series provides ultra-short pulses with a single pulse energy of up to 2mJ and GFH's helical drilling tool GL.trepan has an optical concept able to handle its full energy and apply it for micro drilling applications. In combination with an adapted processing head including optics up to f250 new drilling strategies with a z shift of several mm were realized. The result is the possibility to drill high precision holes in a material thickness up to 6mm millimeter and aspect ratio up to 1:48 in a acceptable time frame.

Since the optical concept allows to handle even higher pulse energies, there are further investigations running if the burst mode (up to 4 times 2mJ = 8mJ) can be beneficially used to decrease drilling time or to allow to drill thicker materials. This investigation will also help to estimate, if higher pulse power of future laser concept can also be applied for micro drilling and push the boundaries of the results shown in this paper even further.

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