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Smart ultra short pulse laser processing with rotating beam – Laser micro drilling, cutting and turning

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Abstract

GFH GmbH has developed a helical drilling optics, which rotates the beam up to 30.000 rpm and allows furthermore to adjust the diameter and the incidence angle. This enables the laser to be used for high precision drilling and cutting and micro turning processes.

Keywords: drilling; cutting; turning; ultrafast laser; trepanning; conicity

1. Introduction

Since several years, ultrafast lasers are ready for industrial use and establish more and more in 24/7 production areas. 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, make them well qualified for high precision micro drilling, cutting and turning.

1.1 Motivation

Current micro drilling, cutting and turning processes are mainly based on EDM, milling, stamping, honing or grinding. All these technologies are using a tool with a predefined geometry that is transferred to the working piece.

On a EDM machine the hole diameter respectively the cutting width are determined by electrode diameter. The same condition is valid for honing. The tool size is also a limiting factor at milling and grinding, because the tool radius defines the minimum flanging radius. For stamping processes even the complete geometry is pictured by the tool.

In contrast the laser is a highly flexible tool, which can adapt its size very fast by changing only a software setting. This allows to create diverse geometries part by part or even within the same part, e.g. different hole shapes in injection parts. With an appropriate optical setup, the tool size is only a few hundredths of a millimeter and can be adapted stepless micron by micron.

Beside precision, robustness and productivity are the most important factors for beeing a real alternative to well established processes. Thanks to the efforts in laser development during the last years, stable ultrafast lasers with sufficiant average power and high repetition rates became industrially available. For using as many pulses as possible, a cost-efficient production demands for innovative processes and machining setups with fast axes movement and special optics for beam manipulation.

1.2 Need for ultra short pulses

The pulse duration of ultrafast lasers is between a few picoseconds down to several hundred femtoseconds. In combination with bundling on a small focal spot, this has the effect, that even a few watts in average power lead to an extremely high intensity and a pulse peak power in a scale of gigawatts. That immense pulse power enables ultrafast lasers to machine any material and process even hardest materials as carbide or diamond.

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For processing with laser, the focused laser beam irradiates the material. When the energy density exceeds a specific limit, the impinge of laser beam results in ablation of material. This limit depends on enthalpy of vaporization ΔH_V, density ρ and absorption coefficient α and is called ablation threshold ϕ_{th}:

$$\phi_{\mathrm{th}} = \frac{\Delta H_V \cdot \rho}{\alpha} \quad (1)$$

Due to the very short interaction time of the single pulses, the heat affected zone is very small and machining with so called “cold ablation” is possible. Of course, as a consequence of the high energy density there is a local heating of material up to several thousand kelvin, but the energy impact is stopped by the end of the short pulse. This effects a vaporization of material in a very limited area and without influencing the area around.

Further increasing of fluency (energy per area) leads to higher ablation rates and improves productivity. But there is a material depending limit, which leads even with ultrashort pulses to a thermal process. Exceeding that limit must be avoided, because the result is generation of melting and negative effects on quality.

Due to the lasers high repetition rates, also single pulses below this limit can lead to a heat accumulation. Each pulse heats up the material and after a certain number of pulses melting limit is exceeded.

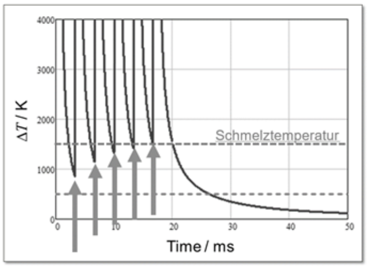

Fig. 1. Heat accumulation of single laser pulses

For keeping the ablation in an athermal regime, either the distance of pulses must be increased (lower repetition rate) or the pulses must be distributed fast enough on the working piece. From the production point of view, the latter is worth striving for.

1.3 Need for tilted laser beam

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

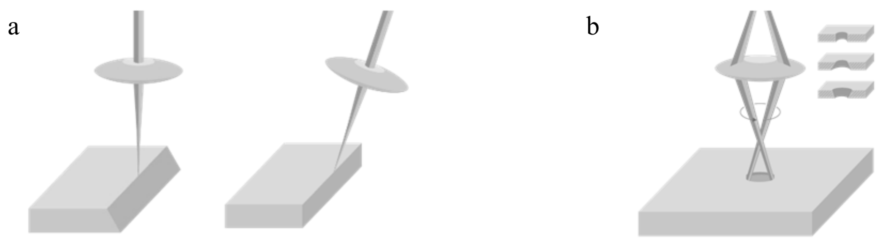

Fig. 2. (a) Influence of inclination angle on wall angle (schematic); (b) Tilted rotating laser beam allows drilling with positive and negative wall angle as well as cylindrical holes (schematic)

Since many precision parts require vertical walls or a well defined 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.

1.4 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:

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

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.

For fine cutting processes, the rotating beam is moved along the cutting line. The maximum cutting speed for this relative movement is inter alia limited by the rotation speed of the beam. A too fast linear moving speed or respectively too slow beam rotation effect a saw tooth design, which influences negatively the geometric fidelity and the roughness of the wall.

Besides the relative linear movement, laser turning demands for a rotation of working piece and the rotating and tilted beam is led sideward to the working piece. This strategy allows a roughing and finishing laser process without limitation on final surface quality.

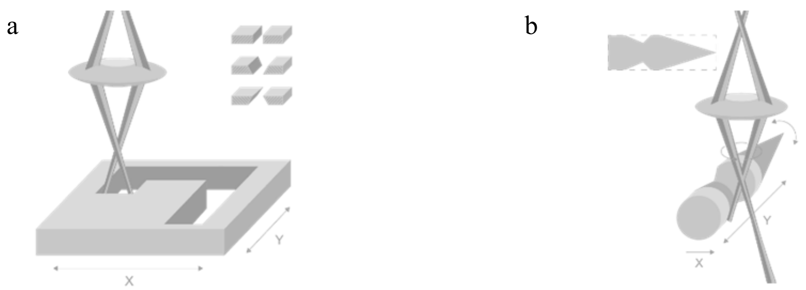

Fig. 3. (a) Precision cutting by turning tilted laser beam and moving workpiece (schematic); (b) Laser turning by rotating and tilting beam as well as linear moving and rotating workpiece (schematic)

2. Experimental

2.1 Laser

All shown samples were produced with a TruMicro 5050 femtosecond laser of Trumpf. It has a pulse duration of 800fs and an average power of 40W. At a repetition rate of 200kHz a single pulse energy of 200µJ is available.

2.2 Helical drilling optics

For rotating and tilting the laser beam, the trepanning head GL.trepan of GFH GmbH was used. The trepanning optics bases on rotating cylindrical lenses, with forces the beam on rotation and allows the setting of hole diameter and wall angle by influence angle and position of entrance beam.

a b

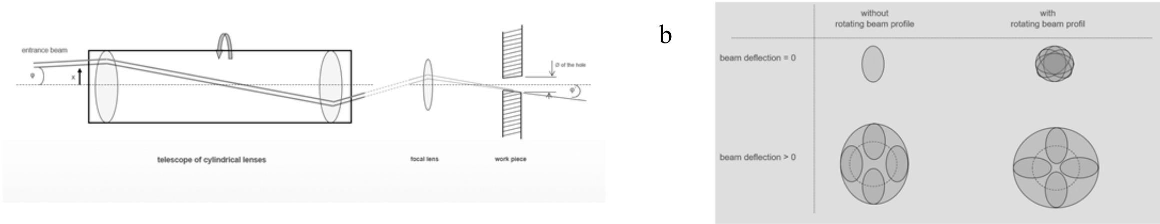

Fig. 4. (a) Optical concept of GL.trepan using a telescope of cylindrical lenses; (b) Rotation of beam profile allows drilling round holes even with elliptical beam profile

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).

2.3 Machining setup

As machining tool a 5 axis GL.evo of GFH GmbH was used. This machine is made for industrial laser micro machining and harmonizes the requirements for precise and dynamic kinematics with the requirements of short pulse laser technology. Linear motors with air bearings ensure positioning of workpieces with an accuracy <1µm and with a speed up to 2 m/s. The rotation axis is also equipped with an air bearing and ensures a very good radial run-out with up to 700 rpm.

Fig. 5. Laser micro machining tool GL.evo of GFH GmbH

3. Results and Discussion

It was demonstrated, that ultrafast lasers can produce micro holes in a diameter range from 20µm to 500µm without melting zones.

Aspect ratios (length/diameter) up to 20 into a work piece thickness up to 2mm are possible. The roundness is better than 95% with a standard deviation of 0,01. The diameters standard deviation $\sigma_{\emptyset}$ depends on hole lengths L and taper angle α and can be calculated as following:

$$\sigma_{\emptyset} \leq 0{,}3\mu m + \frac{0{,}02\mu m * L}{100\mu m} + 0{,}1\mu m \left|\frac{\alpha}{10°}\right| \quad (5)$$

Same quality criteria are valid for the cutting width of precision cutting processes. The maximum linear speed depends on material and decreases with increasing wall thickness. For example, a steel with thickness 0,2mm can be cut with high quality with a feed rate of 250 mm/min.

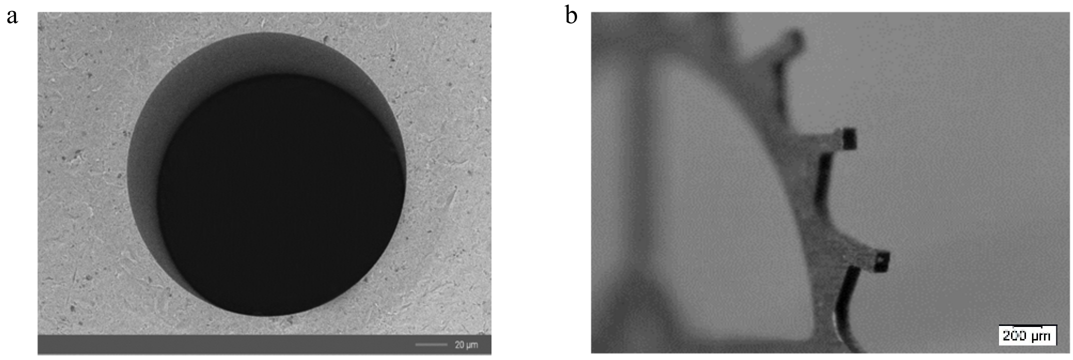

Fig. 6. (a) Micro drilling with diameter 300µm in tooling steel with thickness 200µm; Processing time: 1.7s; (b)Vertical cut of a driving wheel in brass with thickness 0.15mm for mechanical watches industries

The working piece diameter of laser turned parts is in a diameter between 0,03mm to 10mm. The achievable contour accuracy has a standard deviation of < 0,3µm with a roundness smaller than 1 micron. By using different parameter settings for roughing and finishing, an ablation rate up to several mm/min and a surface quality of R_a = 0,1 µm was reached in steel and carbide.

Since the tooling geometry can be adapted software based, a combination of micro drilling, cutting and turning process in one part without additional clamping operations is possible. This avoids loss of accuracy and time consuming measurement operations.

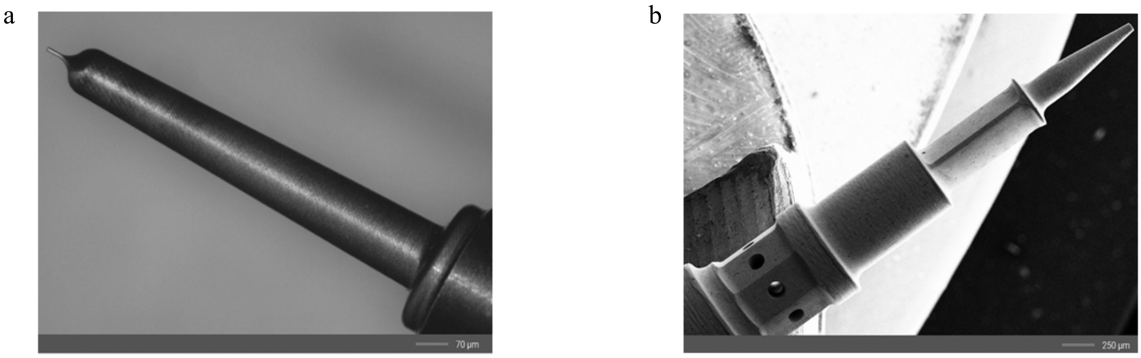

Fig. 7. (a) Laser turned ejector with a length of 9mm and end piece diameter of 40µm made of carbide; (b) Combination of laser turning, drilling and cutting processes with one clamping operation

4. Conclusions

Ultrafast lasers are well suitable for drilling of micro holes, cutting of small parts and fabrication of micro turning parts with highest quality. But next to the laser, a special optics for rotating and tilting the laser beam as well as a machining tool with precise and dynamic axis is a precondition.

Conventional machining technologies can partly be replaced by laser machining. The last years' development effort of industrial lasers down to the femtosecond regime allows a significant increase of efficiency. For metals the production time can be reduced by a factor of at least two compared to picosecond pulses (> 6 ps) and makes the laser technology also economical competitive. Considering the consequential costs, laser have the obvious advantage by processing without tool wear and having always the same sharp tool geometry.

Furthermore, ultrafast lasers open new application fields thanks to their touchless and athermal operation, the extreme small tool size and feasibility to machine any material. The software based fast and flexible adaption of tooling geometry allows moreover a combination of drilling, cutting and turning processes in one part, what leads to an additional increase of accuracy and productivity.

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