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High precision drilling with ultra-short laser pulses

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Abstract

Micro processing with ultrafast lasers has become a well-established technology during the last few years due to the availability of reliable and affordable industrial lasers and variety of processes for which they can be applied.
Drilling of injection nozzles is of great interest for the automotive industry. Laser drilling of fuel injection nozzles has already been established in production lines.
Injectors for diesel engines are more complex and have to withstand higher pressures than injectors for petrol. For the drilling process this means increasing requirements concerning the wall thickness and the hole diameter, which in turn leads to a more challenging processing. Taper free or even negative conical holes are of interest whereby the diameter should be smaller than 100 µm. To meet these needs the laser beam has to be moved and inclined during the drilling process. This can be reached by using a 5-axis system together with an USP laser.
In this paper we report on high precision drilling with a TRUMPF TruMicro5070 (Femto Edtion) femto-second laser together with the SCANLAB precSYS 5-axis micro-machining sub system.
In a first step, different drilling strategies were investigated regarding their advantages and disadvantages for the process. To reach holes with a high aspect ratio and high quality different drilling strategies were combined. During the research, two different challenging bore geometries were studied: cylindrical and negative conical holes. Additionally to the geometry of the holes the material thickness was varied from 0.5 mm to 1 mm. Furthermore, the processing limits regarding the smallest possible diameter were investigated.

Keywords: high precision drilling, femto-second laser, 5-axis micro-machining, high aspect ratio, cylindrical and negative conical holes

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1. Introduction

In recent years laser drilling already has been established in different fields of industrial applications as it delivers some advantages compared to conventional processes. The contactless and thus wear-free machining is an important reason why lasers are used for drilling processes more frequently. Furthermore, a higher flexibility concerning drilling geometry and material can be reached by using a laser. The laser can exploit its strength especially for high precision applications. In this subject the advantages of material processing with ultrashort pulsed lasers (USP) partly in combination with special optical systems can be implemented in a effectively.

Drilling of gas injection nozzles with USP lasers for example is an application which is already realized in the industry (Mielke 2013) (Litzlfelder 2014). By a conversion from conventional methods e.g. EDM or stamping towards to USP drilling processes it was possible to increase the performance of the motors as the hole geometry can be adapted more flexibly (Mielke 2013). In times of diesel exhaust affairs, manufacturers of diesel injection nozzles also have to deal with the big challenge of increasing the performance of these kinds of motors (Föhl 2011). This can be reached for example by reducing the nozzle diameter, which causes a better fuel vaporization and thus a more efficient combustion (Reif 2010). The actual target figures are around 80 µm with a tolerance of ±1 µm for a material thickness of 1 mm and a drilling time below 20 s (Langmack 2010). The exit of the bore hole additionally should be greater than the entrance and both sides are intended to be sharped-edged (Reif 2010). The nozzle is the connection between combustion chamber and fuel system and thus it has to withstand very high mechanical stress. Therefore stainless steel which has good mechanical properties is used for diesel injection nozzles (Reif 2010). In conclusion it can be said, that these high requirements cannot longer be attained by EDM (Honer 2004) due to a limitation in miniaturization which affects negatively the process stability at the same time.

Laser technology seems to be a suitable approach for these challenges wherefore this paper focus on this investigation. In comparison to already realized gas injection nozzle laser drilling the demands for diesel injection nozzle drilling are quite higher (miniaturization, higher aspect ratio). This requires not only stable laser parameters but also a highly dynamic external unit for deflection and focusing of the laser beam. In this work we focused on the appropriate experimental setup and the process investigation for different drilling geometries which were produced by a Trumpf USP Laser (TruMicro5070 Femto Editon) together with the SCANLAB 5-axis micromachining sub system precSYS.

2. Laser - Matter - Interaction and Drilling Methods

The advantage of material processing with USP lasers is that a cold process takes place. However, this expression cannot be understood literally. The direct transition from solid to gaseous condition is significant for this kind of processes. Very short pulse durations and specific material interaction times are the reason for this behavior. During a material process with ultra short laser pulses different mechanisms expire within very short time scales. The energy is absorbed by the electron system as the atoms cannot absorb it directly. This in turn leads to a very fast increase of the electron temperature. Thereby the energy is deposited in the electron system (Nolte, et al. 1997) (Mannion, et al. 2003). The lattice meanwhile remains cold. The temperature of the electrons is independent from the lattice, what can be described by the two-temperature model (Breitling, Ruf and Dausinger 2004) (Bliedtner, Müller and Barz 2013, 136).

Subsequently, the energy is transferred to the lattice by electron-phonon-interaction. This in turn leads to a temperature rise in the lattice. This process takes place after a material specific electron-phonon-relaxation time (τ_{ep}) which is in a range of a few picoseconds for metals (Dausinger, Helmut and Konov 2003). The temperature rise within the lattice finally leads to a material transfer into a gaseous state and thus to material ablation. Just a very small amount of energy remains within the material, which means that the ablation is not completely cold. However, the thermal load of the material can be reduced compared to longer pulse durations (Föhl 2011) (Bliedtner, Müller and Barz 2013). This in turn can be seen by a very good ablation quality within USP processes. Especially the development of melt, burr and other thermal influences can be reduced by the use of lasers with pulse durations in the pico- or even femtosecond regime.

Therefore high precision processes can be machined by USP lasers without the need of post-processing steps. Because of this reason fs-lasers are suitable for high precision drilling but not only the short pulses help for the preciseness but also a special laser beam guidance is needed if bore hole entrance and wall propagation should not be influenced by the laser beam caustic. Fig. 1 shows schematically the five known methods for laser drilling.

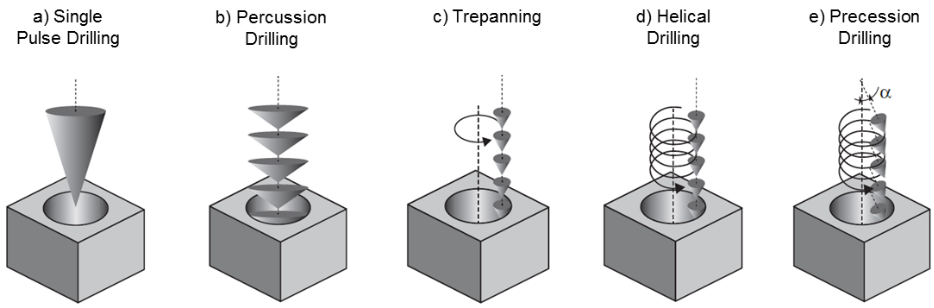

Fig. 1**.** Different laser drilling methods. Resulting precision increases from a) to e)

Using the method of **single pulse drilling** (Fig. 1a) the material is drilled by one single pulse. Typically, the pulse duration for this kind of process is in the range of milli- or nanoseconds. For a **percussion drilling** process (Fig. 1b) several pulses are necessary to ablate the material. This application is typically done with pulses in the range of few hundred femtoseconds to several nanoseconds. During the process the laser beam is static positioned. Single pulse drilling commonly generates a high amount of molten material which limits the precision that can be achieved. Percussion drilling presents a higher precision because a small amount of material is ablated with each pulse and therefore, the process can be better controlled.

Trepanning processes (Fig. 1c) require several laser pulses distributed in a circular trajectory which can be achieved for instance with scanner systems. Within one low rotational movement the through-hole can be completely drilled.

Similarly, **helical drilling** (Fig. 1d) is based on a circular motion of the laser beam with the addition of a perpendicular movement of the focus position improving the accuracy of the process by creating a defined 3-axis xyz movement (Dausinger, Friedrich; 2004). For this method laser pulses with relatively low pulse energy are required to achieve a defined ablation with low melt generation. However, **3-axis machining** of high aspect ratio results always leads to a positive tapered hole due to the influence of the laser beam caustic on the bore hole entrance and wall during perpendicular laser incidence (Fig. 2a).

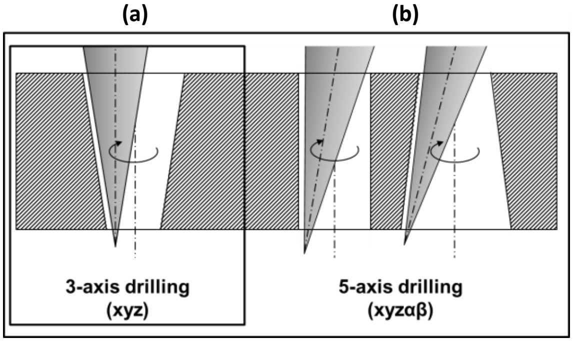

Fig. 2. (a) Scheme of focused laser caustic movement during 3-axis drilling of high aspect ratios (resulting in positive tapered wall propagation) vs. (b) 5-axis drilling (resulting in positive, negative and zero tapered wall propagation)

5-axis machining (Figure 2b) provides a solution for high aspect ratios and zero or even negative tapered wall propagation results. **Precession drilling** (Fig. 1e, α ≠ 0°) allows processing with a laser beam which is moved helically (xyz) and whose angle of incidence AOI (αβ) can be precisely defined at the same time. The precision of the five compared drilling strategies (Fig. 1) increases from method a) to method e).

3. Experimental setup

For process development an open laboratory setup was used. Fig. 3 contains an overview scheme of the used experimental setup and a picture of the working area. To reach the high accuracy requirements, a TRUMPF femto second laser (**TruMicro5070 Femto Edtion**) was selected for the trials. In order to achieve a flexible movement of the laser beam focus in five axes with defined variable angles of incidence, the 5-axis micromachining sub system (**precSYS**) from SCANLAB was chosen to investigate the drilling processes.

The TruMicro5070 Femto Edtion provides an average output power of up to 80 W, a wavelength of 1030 nm and a pulse duration of 870 fs. The base frequency of the used laser can be set to 400 kHz or 800 kHz which in turn delivers different pulse energies at the same average power. Laser and scan unit are water cooled and gas-purged for highest process stability in micro machining applications. The laser beam is guided by static mirrors (Fig. 3, ①) towards a beam-conditioning unit to adjust the beam diameter, divergence and polarization before entering the precSYS.

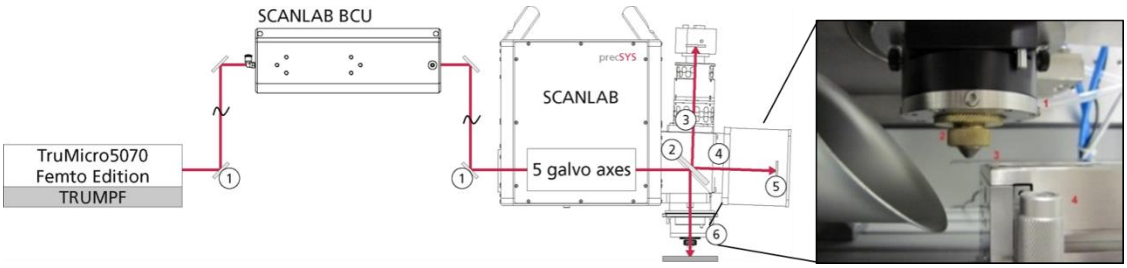

Fig. 3**.** Overview scheme of the experimental setup: TRUMPF laser TruMicro 5070 Femto Edition, **B**eam **C**onditioning **U**nit, SCANLAB 5-axis galvano scanner based system precSYS with its software DrillControl

With precSYS, SCANLAB provides a factory calibrated and highly integrated solution. Advanced digital encoders, control algorithms and application-optimized servo control on embedded PC enable contour-true, speed-independent processing in 5 axes (x, y, z, α, β) with rotation frequencies up to 30 000 rpm on diameters ≤1 mm. Specially conceived for USP precision processing, the optical path is polarization-maintaining and accommodates pulse energies up to 300 µJ. Circular polarization in the working field is adjusted with the help of the beam conditioning unit.

precSYS comes with a product specific **software DrillControl** which provides an intuitive graphical user interface (GUI) with 3D job visualization of the laser focal motion for easily creation and simulation of processing jobs. Moreover **factory calibration** enables the description of laser motion directly in metric units within the precSYS's cartesian image field coordinate system. Variable process parameters are laser power and repetition rate, number of revolutions, rotation frequency/velocity, beam path diameter, ellipticity and its rotation, focus z-movement and laser beam angle of incidence AOI.

Furthermore, precSYS offers two observation ports in the back of its beam splitter optic (Fig. 3, ②): one for process-monitoring (Fig. 3, ③) and one for beam-monitoring (Fig. 3, ④) add-ons. For coaxial process control, a camera with an objective has been adapted on the process monitoring port ③. By means of an integrated beam position measurement unit (Fig. 3, ⑤) SCANLAB provides an **automatic fine adjustment** solution for beam position monitoring and control near the working field (Fig. 3, ⑥). After manual adjustment, the fine adjustment can be done using this option via software commands to enhance machining results. Similarly, the software can be used to readjust the beam back to its original zero position by setting the precSYS's internal galvo axes. Therefore, variations throughout the whole beam path, from the laser to the working field, can be minimized. The processing gas nozzle (Fig. 3, ⑥) is adjustable in xyz. The workpiece fixture was positioned in x, y and z directions with help of a high precision table. Stainless steel was used as workpiece material since this material is of particular interest for drilling applications in the automotive industry.

3.1. Tool characterization

In the first step, the focused laser beam was measured in the working field with a PRIMES MicroSpotMonitor MSM beam measurement unit. The analysis by using the second moment method, results in a focused laser beam diameter of 14 µm and a Rayleigh length of 130 µm for a beam quality factor M^2 of 1.12. In the second step, the set angle of incidence was verified. For this purpose, a circular path with an angle of incidence AOI = +7.5° was marked at a defined distance above (Figure 4, ①) and below (Figure 4, ③) the surface of the workpiece by using the precSYS's z-axis. Thereby the workpiece was not moved. Fig. 4 shows a scheme of the behavior of the circular path at different z-positions and the marking results to verify the AOI. Based on the size of the two ablated circles shown in Fig. 4 (right) the set angle of incidence can be calculated backwards. The validation shows that the pre-calibrated angle of incidence is reached within an accuracy of 0.1°.

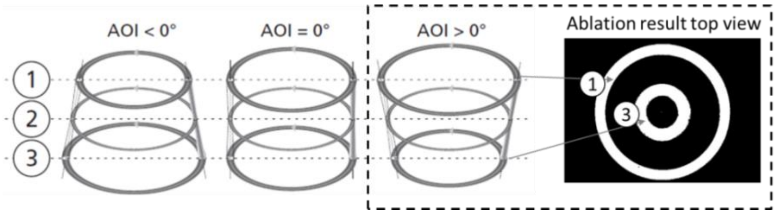

Fig. 4. Ablation test for visualization of angle of incidence at various workpiece positions: ① focus above workpiece, ② focus on workpiece and ③ focus below workpiece (left). Ablated result for defocused processing (right)

In a third step for tool characterization, a matrix with different parameter settings was processed and evaluated. In every matrix field the parameters rotation frequency, angle of incidence AOI and position of the internal z-axis were varied. Fig. 5 (left) shows an extract of the ablated matrix for a rotational speed of 30 000 rpm (frequency 500 Hz) and AOI = -7.5°, 0°, +7.5°. The workpiece was displaced together with the precSYS's z-axis so that ablation always occurred in focus. Thanks to the factory calibration of the precSYS the angle of incidence is precisely controlled within the whole trajectory. Ablated circles with diameters from 90 µm up to 300 µm resulted in a maximum deviation of ±1 µm from target radius over the varied parameter settings (Fig. 5, right): frequency 50 Hz to 500 Hz (rotation speed 30 000 rpm), AOI = -7.5°, 0°, +7.5° and z = -1 mm, 0 mm, +1 mm.

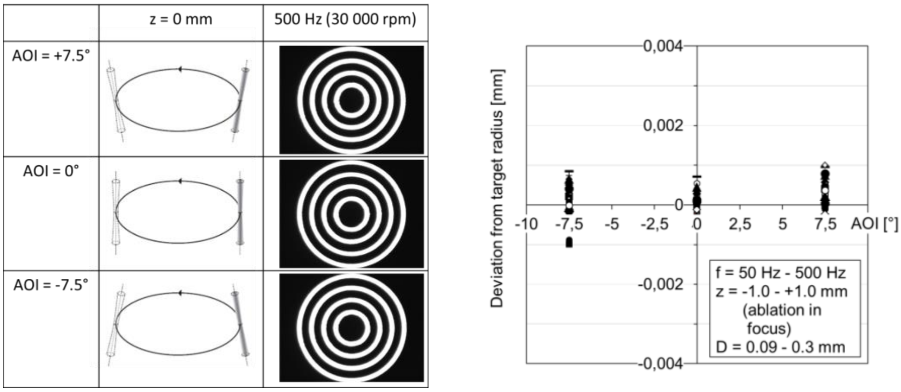

Fig. 5. Tool characterization, parameters: rotation speed 30 000 rpm (frequency 500 Hz), AOI = -7.5°, 0°, +7.5° and z-axis-Position z=-1 mm, 0 mm, +1 mm (left). Measured deviation from target radius, parameters: frequency 50 - 500 Hz for different diameters (right)

3.2. Experimental trials

To test the fundamental functions of the precSYS together with the TruMicro5070 FE drillings in 0.5 mm stainless steel were done. The target was to obtain drillings with 100 µm diameter at entrance and exit of the bore hole. In a second step, drilling at stainless steel samples with a thickness of 1 mm was investigated. In this case the target was to achieve negative conical holes with an entrance diameter of 100 µm and an exit diameter of 130 µm. Finally, a 1 mm stainless steel sample was used to drill cylindrical holes. These trials were specifically aimed to achieve the smallest possible diameters to approve the limit of the laser and optical system.

4. Results

As mentioned above, it is possible to machine different materials without generating significant heat effects by using laser pulses in the range of pico- or even femtoseconds. Besides the pulse duration, it is necessary to choose the appropriate strategy to drill highly precise holes. An important aspect is a flexible and well-defined motion of the laser beam on the workpiece during the process which can be achieved with the precSYS. Furthermore, only an optimized interaction between laser parameters and optical setup leads to an accurate drilling process. The current chapter presents the results of drilling stainless steel with thicknesses of 0.5 mm and 1 mm.

4.1. Cylindrical drillings in 0.5 mm stainless steel (zero taper)

First of all three different modes were tested independently to get an understanding of their impact on the results. The three used strategies are depicted in Fig. 6. With help of a 3D helix (Fig. 6a) the inclined laser beam was moved spindle-shaped within 5-axis movement into the workpiece (precession drilling mode). Fig. 6b shows a 2D circular movement which was also tested. Finally a 2D spiral was used whereby the laser beam was moved outwards (Fig. 6c).

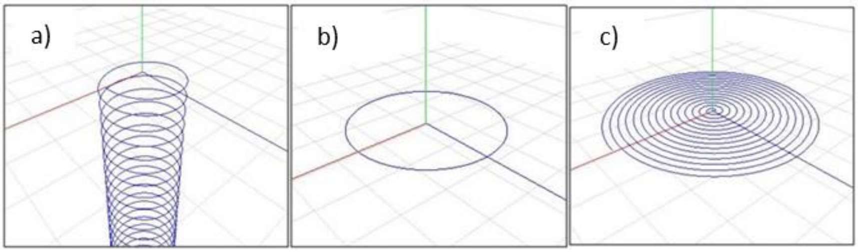

Fig. 6. Different drilling strategies: a) helix, b) circle, c) spiral with simultaneously tilted laser beam

Besides the drilling strategies mentioned above the micro machining sub system allows the precise adjustment of several further parameters. In a first parameter study for every drilling strategy a start parameter was defined with help of a characterization matrix. Subsequently the results were optimized by a fine tuning of particular parameters. Finally, the results of all three strategies were compared with each other in an improved characterization matrix. For the evaluation, different properties were rated proportionally to their importance. Drilling time and contour accuracy of the hole were rated to 25% each since they are crucial to determine if the process can be used in a production line. Additionally, thermal influences such as burr, debris and discoloration as well as the development of a radius at the entrance were considered. The evaluation showed that the best result is achievable with a 2D spiral with superimposed angle of incidence (AOI) during laser focal motion.

A SEM picture of a bore hole drilled by using the spiral trajectory is depicted in Fig. 7a. A laser scanning microscope (LSM) was used to measure the profile of the bore wall which is shown in Fig. 7b. The profile shows up a constant progress. The noise above and below the profile shows the range beyond the measurement.

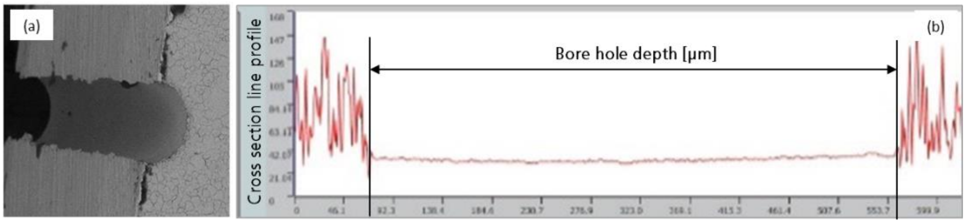

Fig. 7. a) Cross section SEM-picture of a cylindrical 100-µm bore hole in 500-µm-thick steel. b) Line profile of the cylindrical hole

The laser parameters for this process were adapted based on quality and throughput. The frequency of the laser was set to 100 kHz by using a pulse divider producing a pulse energy of 34 µJ. The measured drilling time was approximately 3 sec for the complete process.

4.2. Negative conical holes in stainless steel with 1 mm thickness

A four-step drilling strategy was necessary to achieve these drillings since a single strategy didn't lead to the required results with regard to the quality.

The four-step strategy is schematically illustrated in Fig. 8. First of all a 2D spiral with a small negative inclination angle was used to drill a pilot hole (Fig. 8a). In a second step the spiral diameter was reduced whereas the negative inclination angle was highly increased (Fig. 8b). With this setting it was possible to shape the inner hole. The exit was formed in step (Fig. 8c) by using a circular movement with a reduced negative inclination angle. The last step (Fig. 8d) was done to form the holes entrance by using a circular movement and an inclination angle with a positive value.

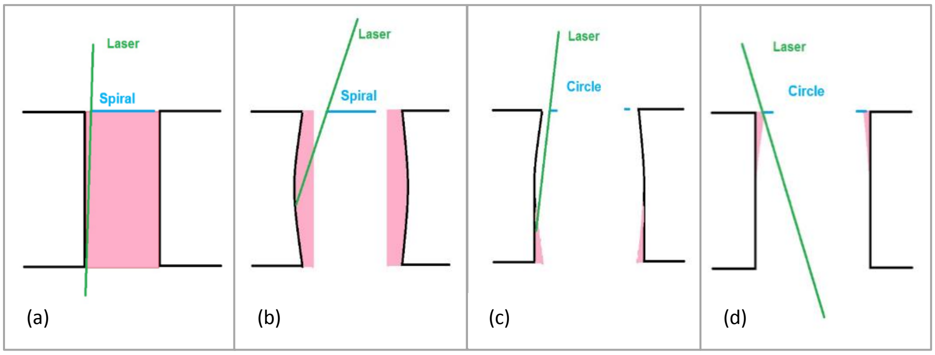

Fig. 8. Four-step drilling strategy. (a) hole preparation, (b) hole forming, (c) exit forming, (d) entrance forming

The used parameters for this four-step drilling strategy are summarized in Table 1. For this process the laser repetition rate was also set to 100 kHz and the pulse energy was enhanced up to 135 µJ. The drilling time for the complete process was approximately 9 sec. In Fig. **9** an entrance and an outlet of a hole drilled with that drilling strategy is depicted.

Table 1. Parameter setting for negative conical hole (100 µm/130 µm) in 1 mm stainless steel

Parameter	Step 1	Step 2	Step 3	Step 4
Rotation Diameter [µm]	10 to 50	48	65	8
Inclination Angle (AOI) [°]	-0.05	-3.45	-1.7	2

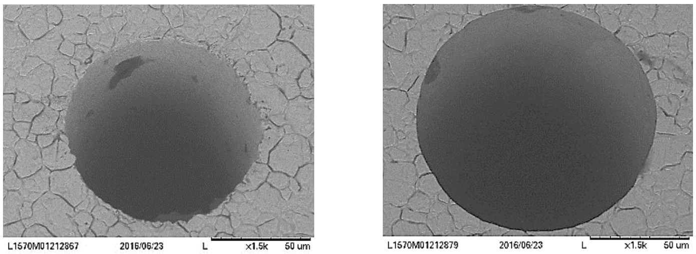

Fig. 9. Hole entrance (left side) and hole outlet (right side) of a negative conical hole drilled in 1 mm stainless steel

4.3. Smallest possible drillings

Similar to the previous tests for these drillings a multi-step strategy was also necessary whereas in this case the second step (Fig. 8b - increase the hole inside) was not realized. Due to the high aspect ratio of the hole diameter, the inclination angle had to be adapted (Table 2). While the repetition rate for all three steps was set to 100 kHz the pulse energy was just increased to 90 µJ.

Table 2. Parameter setting for a cylindrical hole (50 µm/50 µm) in 1 mm stainless steel

Parameter	Step 1	Step 2	Step 3	Step 4
Rotation Diameter [µm]	5 to 23	-	15	31
Inclination Angle (AOI) [°]	-2.1	-	-1	0.5

Fig. **10**a shows the entrance of a 50 µm hole with an aspect ratio of 20. As visualized via SEM-picture the entrance is sharp edged but in the lower part of the hole entrance some cracks along the grain boundaries are visible. The bore hole outlet is illustrated in Fig. **10**b next to a human hair. The picture's magnification was reduced compared to the picture Fig. **10**a to achieve a better impression about the proportion between hair diameter and the half as wide hole diameter size in this result.

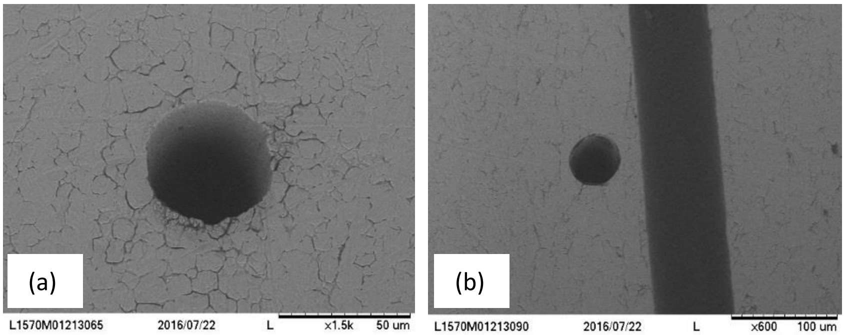

Fig. 10. a) Entrance of a 50 µm hole; b) exit of a 50 µm hole with a human hair right to the hole

5. Summary and Outlook

In this investigation the SCANLAB 5-axis micromachining sub system precSYS was combined with a TRUMPF TruMicro5070 FE to create high precision holes in stainless steel. Different geometries have been developed in 0.5 mm and 1 mm stainless steel samples. A multi-step drilling strategy was more advantageous for processing samples with a thickness of 1 mm achieving holes with a diameter of 50 µm (aspect ratios up to 20). Theoretical estimations indicate that even smaller bore holes diameters as 50 µm should be achievable via USP 5-axis drilling. The research showed that it is possible to meet the requirements for diesel injection nozzle drilling by using the combination of a TRUMPF TruMicro 5070 FE and the SCANLAB precSYS.

References

Bliedtner, Jens, Hartmut Müller und Andrea Barz. Lasermaterialbearbeitung. München: Carl Hanser Verlag, 2013.

Breitling, Detlef, Andreas Ruf, und Friedrich Dausinger. „Fundamental aspect in machining of metals with short and ultrashort laser pulses.“ SPIE. 3, Nr. 1 (2004): 49-63.

Dausinger, Friedrich, Hügel Helmut, und Vitali Konov. „Micro-machining with ultrashort laser pulses: From basic understanding to technical applications.“ SPIE. 2, Nr. 1 (2003): 1-10.

Dausinger, Friedrich;. „Präzisionsbohren mit kurzen und ultrakurzen Pulsen.“ Laser Technik Journal 1, Nr. April/Mai (2004): 40-44.

Föhl, Christian. Einsatz ultrakurz gepulster Laserstrahlung zum Präzisionsbohren von Metallen. München: Herbert Utz Verlag GmbH, 2011.

Heckl, O.H., et al. „Industry-grade High Average Power Femtosecond Light Source.“ Proc. Of SPIE Vol. 8972, March 2014.

Honer, Michael. Prozesssicherheitsmaßnahmen beim Bohren metallischer Werkstoffe mittels Laserstrahlung. München: Herbert Utz Verlag GmbH, 2004.

Langmack, Malte. „Laserbohren und Mikrofunkenerosion zur Herstellung komplexer Bohrungen.“ Futur 12, Nr. 3 (2010): 4-5.

Litzlfelder, Matthias. „inFranken.de.“ 11. Oktober 2014. http://www.infranken.de/regional/bamberg/Bosch-setzt-Lasertechnik-bei-Duesen-ein;art212,543802 (Zugriff am 26. Juli 2016).

Mannion, Paul, Jonathan Magee, Edward Coyne, und Gerard M. O´Conner. „Ablation thresholds in ultrafast laser micro-machining of common metals in air.“ SPIE. 4876 (2003): 470-478.

Mielke, M. „The hole story: Femtosecond manufacturing improves automobile fuel efficiency.“ Laser Focus World, 2013.

Nolte, S., Momma C., H. Jacobs, A. Tünnermann, B.N. Chichkov, und B. Wellegehausen. „Ablation of metals by ultrashort laser pulses.“ Optical Society of America 10, Nr. 14 (1997): 2716-2722.

Reif, Konrad. Dieselmotormanagement im Überblick. Wiesbaden: Vieweg+Teubner Verlag, 2010.

Strickland, D., und G. Mourou. „Compression of amplified chirped optical pulses.“ Opt. Commun. 56, 1985: 219.