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Laser drilling with a top-hat beam of micro-scale high aspect ratio holes in silicon nitride

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Abstract

High aspect ratio micro holes are very important functional features in many products, in particular in electronics industry. Especially, the critical requirements that such holes in electronic devices should satisfy, concern their morphology and quality that can impact directly the products' functional performance. At the same time, ultra-short lasers have shown that they have the capabilities to match such tight requirements due to their unique processing characteristics. The typical beam spatial profile of the laser sources used for drilling is Gaussian and this entails some constraints and limitations. In this study, a beam shaping system for laser micro drilling has been designed and implemented to achieve a top-hat spatial profile. The morphology of the high aspect ratio holes in terms of cylindricity, circularity, tapering angle, heat affected zone (HAZ) and penetration depth was investigated by a high resolution X-Ray Computed Tomography (XCT). The capabilities and limitations of such beam shaping solutions for producing micro-scale high aspect ratio holes has been discussed, i.e. their sensitivity to defocusing, and compared to Gaussian beam spatial distribution. Conclusions were made regarding the effects of top-had beams on morphology of high aspect ratio holes and trade-offs when deploying them for laser micro drilling.

Keywords: Laser micro-drilling; High aspect ratio holes; Flat-top distribution; Hole morphology; beam shaping.

1. Introduction

The continuous advances of electronic devices and microelectromechanical systems, especially their miniaturisation and the integration of more functions in a smaller package, demand new manufacturing methods that could address the increasing requirements regarding their dimensional accuracy, repeatability and cost-effectiveness (Chu et al., 2014). Micro holes are common and often critical features in such devices and also are used as micro vias in PCBs. Vertical probe cards are a notable example that incorporate arrays of micro holes into silicon nitride substrates to support and position micro pins with high accuracy (Choi and Ryu, 2012). In particular, to satisfy the constantly increasing functional requirements for these pins, the holes have to be produced with higher density, i.e. smaller diameters and pitch distances, and geometrical accuracy, i.e. circularity, cylindricity and perpendicularity. So, this translates into stringent technical requirements for the holes' manufacture, e.g. aspect ratios 5:1, diameters and pitches less than 60μm, taper angles less than 10°, minimum deviation from cylindricity and positional accuracy better than 4μm, while increasing the drilling speed in order to produce the holes cost-effectively. In this context, laser micro drilling offer significant advantages compared with alternative machining processes, i.e. high throughput, any material could be processed, a contactless process and small beam diameters in micron level range. However, there are some limitations, too, e.g. achievable aspect ratios, heat affected zone (HAZ), tapered walls and material spatters.

There are different approaches to address such limitations and the most common is to find the optimum processing window, in particular the optimum fluence and pulse durations (Ghoreishi and Nakhjavani, 2008). Other processing solutions have been used successfully, too, such as beam rotation (Zhang et al., 2015), using a background gas (Palya et al., 2019), two side drilling (Nasrollahi et al., 2017) and dynamic focus positioning (Adelmann and Hellmann, 2015). Also, changes in the beam delivery system have been utilized, e.g. employing lenses with different focal distances (Nasrollahi et al., 2018), varying the polarization of the beam either by mechanical rotation of half wave plate (Föhl et al., 2002) or using fast-response liquid-crystal polarization rotator (Allegre et al., 2012).

Predominantly in these investigations to addressing the laser drilling limitations, the spatial beam shape was Gaussian and this entailed a number of intrinsic drawbacks. In particular, only part of the beam energy profile is above the ablation threshold of any given material and as a result the process efficiency is reduced, HAZ is widen and edge definition is worsen (Karnakis et al., 2001). In addition, the non-uniform energy distribution affects cylindricity of the resulting holes (Ruf et al., 2001) and also there are refractive index variations as a function of the local fluence (Ahn et al., 2012) that affect the hole morphology. Thus, converting the spatial beam profile into Bessel or top-hat beam can be considered as another optical solution. For example, He et al. (2017) adopted an axicon and designed a binary phase plate to produce a tailored Bessel beam that facilitated drilling holes with 10µm diameter in 100µm thick Silicon with almost taper-free sidewalls. However, the material transparency to the laser source wavelength and likely ring marks due to high fluence and energy accumulation, limit Bessel beam applications (Duocastella and Arnold, 2012). Other beam shapes were also investigated, e.g. implementing diffracted optical elements (DOE) to attain a doughnut beam shape (Tönshoff et al., 2000) or top-hat beam to produce clean and sharp edges for scribing purposes (Bovatsek and Patel, 2007). Percussion drilling of holes larger than the beam spot size by employing different annular beam shapes (Zeng et al., 2006) is another advantage of beam shaping. The reduction of material spatter around vias by using a Pitchfork beam in the focus produced by comprising three lenses was also investigated (Zhang et al., 2008).

Spatial light modulators (SLM) are another option for beam shaping. Li et al. (2018) achieved a top-hat beam by combining SLM with a deformable mirror while Häfner et al. (2018) reported a SLM use for efficient and accurate micro structuring with a top-hat beam. For drilling, Sanner et al. (2007) implemented a phase-front tailoring system employing SLM to obtain doughnut and top-hat beams. Especially, holes with a diameter of approximately 17μm and depth of 15μm were drilled by using a top-hat beam and they were not only with sharp edges but also unlike those drilled with a Gaussian beam, their diameters were not fluence-dependent. Duc Doan et al. (2013) also investigated top-hat and annular drilling using a fluidic laser beam shaper and compared the resulting holes in regards to their diameters, depths and HAZ.

In most of these investigations the effects of the spatial beam shape on holes' morphology were not thoroughly studied and were limited to shallow holes with low aspect ratios. In addition, the beam shaping techniques used in some cases were sensitive to any defocusing or optical misalignment that limited their flexibility for scale up production or were not applicable for beam diameters less than 100μm.

In this research, a beam delivery system with refractive beam shaping was designed to produce a top-hat beam and the resulting holes were compared with those produced with a Gaussian beam. In particular, the objective was to compare high aspect ratio holes with diameters of approximately 50 μm produced by percussion drilling with both beam intensity profilers. The morphology of the holes in terms of circularity and taper angle together with the penetration depth were investigated by a high-resolution X-ray Computed Tomography (XCT). The capabilities of top-hat drilling together with its limitations were contrasted to the results obtainable with a Gaussian beam and conclusions were made regarding their sensitivity to defocusing and trade-offs in holes' morphologies.

2. Refractive field mapping beam shapers

An optimum beam shaping solution should be selected taking into account application's specific requirements and laser source properties. At the same time, beam shapers should not be considered off-the-shelf products as this could lead to several issues, i.e. divergence shifts, power fluctuations, pointing instabilities and beam spatial profile distortions (Dickey, 2014). Therefore, sufficient understanding of their capabilities and limitations is required before integrating them into beam delivery systems.

The suitability of beam shaping methods for a given application could be assessed based on the following criteria (Bokor and Davidson, 2002):

1- The transformation should result in the desired beam shape with acceptable accuracy for the application;

2- The energy losses should be as low as possible;

3- Minimal sensitivity to minor changes in the process or input beam size;

4- Minimal beam brightness reduction.

Taking into account these criteria, it is necessary to consider the process limitations and laser source characteristics before selecting a beam shaper.

In this research, the focus is on micro drilling of holes smaller than 50µm and therefore the focusing lens should be positioned after the beam shaper into the beam delivery system. A top-hat beam is simply obtainable in planes other than the focal plane by integrating a beam shaper before the lens, as it is shown in **Figure 1**b. Nevertheless, the laser intensity in this case is not sufficient and it is usually below the ablation threshold.

Based on diffraction theory, the resulting beam shape at the focal plane of a lens is proportional to Fourier transform of the input beam (Kanzler, 2001). For instance, the Fourier transform of Gaussian function is still Gaussian function and thus if such beam is used its spatial distribution at the focal plane is the same as the input beam (see **Figure 1**a). Considering Fourier transformation from Eq (1), a Sinc function with an Airy pattern is required before the lens in order to produce a top-hat beam shape in the focal plane, as it is depicted in **Figure 1**c (Kanzler, 2001).

$$\mathcal{F}\big(A.sinc(ar)\big) = \frac{A}{|a|}.rect(\frac{\xi}{a}) \qquad (1)$$

Taking into account that the ultra-short laser sources commonly used for laser micro drilling have Gaussian spatial profiles and also considering the specific application in this research, i.e. laser drilling arrays of micro holes, the following specific requirements should be satisfied in selecting an appropriate beam shaper:

1- Transformation of a Gaussian beam into of a beam with Airy spatial profile before the lens and thus to obtain a top-hat one at the focal plane;
2- Adaptability to the beam diameter of a given laser source;
3- Achieving the required beam diameter in focus;
4- Compatibility with optical X-Y scanners;
5- Beam shape and size consistency within relatively small focus deviations;
6- Damage thresholds compatible with fluence and wavelength achievable with a given laser source.

To select the most appropriate beam shaping method for addressing these requirements, it is necessary to map them against the available methods and consider their limitations. In particular, the beam shaping methods fall into three main classes (Dickey et al., 2005; Dickey et al., 2000):

1- *Attenuators*. These shapers basically use apertures to truncate a desirable portion of the beam. The main shortcomings of this method are the loss of some beam energy and difficulties in finding an optimal position in relation to the aperture and also to decide what portion of beam should be used. In the context of the micro drilling application in this research these are significant shortcomings and therefore this approach is undesirable.

2- *Beam integrators*. These shapers use a lenslet array and break up the beam into beamlets. The main drawback of this beam shaping solution is the beam damage and some deficiency in spatial coherence due to destructive interference phenomena. So, usually a large beam size is required and therefore this approach is impractical in the context of the micro drilling application.

3- *Field mapping*. This method transforms the electromagnetic field by inducing an one-to-one mapping. Generally, refractive, reflective or diffractive optical elements (DOE) are adopted in transforming the beams.

DOEs have been used to produce a top-hat beam in the focal plane and applied successfully in laser micro machining (Bovatsek and Patel, 2007) and drilling (Tönshoff et al., 2000). However, it has some shortcomings, too, e.g. the complexity of the used design algorithms, manufacturing difficulties, the limited diffraction efficiency and the low resistance to the high peak power of ultra-short pulses, that make this method not so attractive for industrial applications (Laskin et al., 2013). At the same time, SLM as a dynamic DOE can modulate the phase of incoming wavefronts by employing tunable liquid crystal molecules (Kuang et al., 2008) but again it has some limitation. E.g., the shaping rate, low damage threshold (Beck et al., 2010) and low resolution (Cheng et al., 2015) are common constrains in particular for shaping the beam at focal plane due to the complexity of the SLM design algorithms (Kuang et al., 2015).

As an alternative, refractive optics can be deployed for beam shaping as it has a simpler structure, offers a higher optical efficiency and also is much easier to manufacture (Duerr and Thienpont, 2014; Laskin et al., 2013). So, after considering the available field mapping methods with their limitations and constraints against the specific requirements in drilling arrays of micro holes, it was judged that Focal-πShapers could address them and therefore was investigated in this research.

Focal-πShapers employ refractive optical elements, i.e. aspheric optical surfaces, and operate as a Galilean type telescope. Thus, any internal focusing associated with high power or ultra-short lasers can be avoided (Laskin and Laskin, 2010). The magnification of about 1× facilitates its integration into beam delivery systems without the need to perform any specific modifications in the beam path. In addition, Focal-πShapers produce a collimated beam as an output and therefore offer sufficient flexibility in selecting where to position them along the beam delivery path and hence this facilitates their integration (Laskin et al., 2016). Therefore, the installation and alignment requirements of these beam shapers are relatively simple but still a good understanding of their main operational principals is required and also to follow as closely as possible their setting up procedures. Such beam shapers have some specific requirements regarding the laser beam, in particular about its diameter and astigmatism. At the same time, the use of beam expanders to obtain the required beam diameter can lead to misalignments and wave aberrations that can cause some profile distortions in output beams and variations of spatial intensity distributions. The astigmatism and ellipticity of input beams can also change the characteristics of resulting beam profiles, in particular the circular symmetry of intensity distributions (Laskin et al., 2014).

Another limitation that should be considered is the necessity to avoid lateral shifts of the beam at the entrance of focal-πShapers. Such shifts are mainly due to the laser source and its angular and lateral positional deviations. This becomes more pronounced when switching between low and full power operation modes or when there is a long beam path between the laser source and the beam shaper (Laskin et al., 2014).

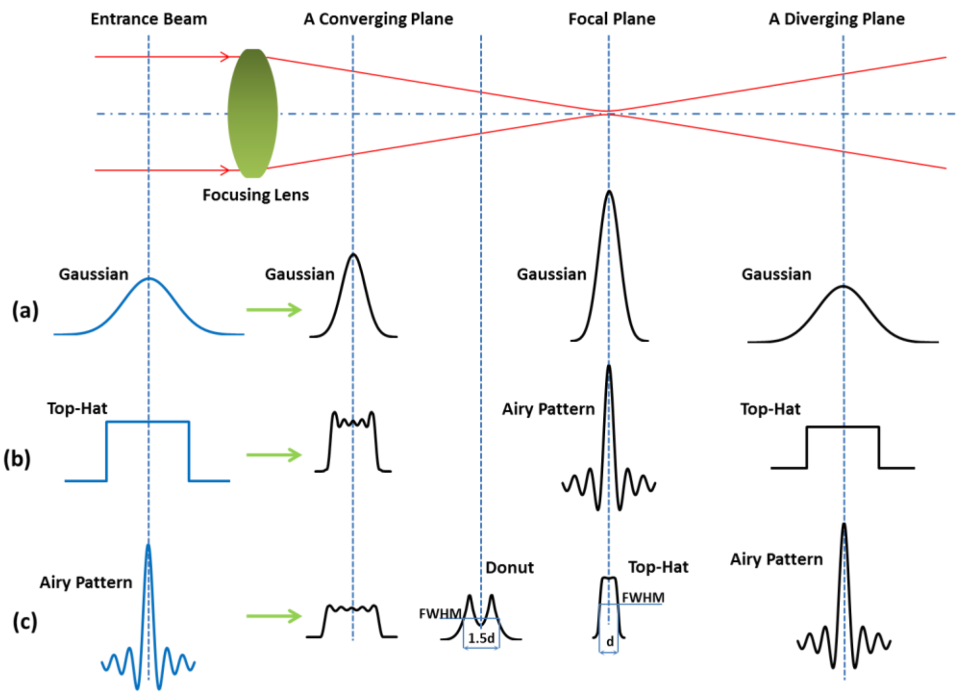

Figure 1.The beam propagation after the focusing lens: (a) Gaussian (b) Top-hat and (c) Sinc entrance beams.

The beam delivery systems should integrate other optical components to achieve the required beam diameter and depth of focus (DOF) in realizing the laser micro drilling operations. Since Focal-πShaper is a 1× magnifier, the FWHM beam diameter of the top-hat beam at focus (d) and DOF can be calculated using the following equations:

$$d = \frac{4\lambda \cdot f \cdot M^2}{\pi \cdot D} \tag{2}$$

$$DOF = \frac{8\lambda}{\pi}\left(\frac{f}{D}\right)^2 \cdot M^2 \quad (3)$$

where: λ is the wavelength of the laser beam; f - the lens focal distance; M^2 - the beam quality factor; and D - the input beam diameter at the beam shaper.

It is shown in **Figure 1**c, how by defocusing, the beam shape can be changed from top-hat to donut (Laskin et al., 2016).

3. Experimental

3.1. Experimental setup and measurement procedure

The micro drilling setup designed to investigate the Focal-πShaper capabilities is shown in **Figure 2**. The technical specifications of the key components integrated in the beam delivery system of a LS5 LASEA machine are provided below:

- **Laser source.** The laser source is an ultra-short pulsed Yb-doped fibre laser with pulse duration of 310fs from Amplitude Systems. Its maximum average power is 5W and 500KHz is its maximum pulse repetition rate. The output is a linearly polarised Gaussian beam with quality factor (M^2) better than 1.3 and wavelength of 1030nm.
- **Polariser.** Elliptical hole shapes and tapered walls are inevitable phenomena in drilling high aspect ratio holes and a way of minimising these effects is to convert the polarisation to circular (Gruner et al., 2016). Therefore, a quarter-wave plate is integrated after the laser source in the beam path.
- **Beam Shaper.** Taking into account the wavelength and max beam intensity of the laser source together with the requirements that the beam shaper should satisfy (see Section 2), Focal-πShaper 9_1064_HP was selected in this research. The $1/e^2$ input beam diameter was set in the range from 4 to 5mm based on the manufacturer

recommendation (Laskin et al., 2016) and thus was similar to the output beam diameter of the laser source. Therefore, it was considered that the beam expander which can be potentially a source of misalignments and beam quality deterioration is not necessary to be implemented in the beam delivery system. The beam shaper installation and alignment was performed following the step by step manufacturer instruction.

- **X Y scanner.** Since the objective of this research is to implement and validate a beam delivery system for producing arrays of holes with high efficiency, beam deflectors was used instead of mechanical stages. The chosen beam shaper allows beam deflectors to be integrated without affecting the beam spatial distribution in the focal plane.
- **Telecentric lens.** A telecentric lens was integrated to insure the orthogonality of the beam across the field of view. The focal length of the lens was 100mm and thus the beam spot diameter at the focal plane was 47 µm based on Eq (2). Thus, the calculated DOF was 2.6 mm based on Eq (3) that was acceptable in the context of this research on laser micro drilling. This lens was mounted on a mechanical Z stage with resolution of 500nm and thus to be able to position the focal plane with sufficient accuracy and repeatability on workpieces.

The beam shape was analysed employing a DataRay Inc WinCamD CMOS scanning beam profiler with a measurement area of 11.3 x 11.3 mm and pixel size of 5.5 µm. Beam measurements were taken at three critical points along the beam propagation axis, in particular before and after the beam shaper and also at the focal plane after the focusing lens. As it is shown in **Figure 2**, the beam spatial profiles were as expected Gaussian, Airy and top-hat at the three measurement points, respectively. The CMOS beam profiler had some resolution limitations and therefore the top-hat distribution was captured by using a 1m focal distance lens.

Silicon Nitride (Si_3N_4) substrates were used to investigate the capabilities of Focal-πShaper for drilling high aspect ratio micro holes because of their wide range of applications in microelectronic and microelectromechanical systems (Dergez et al., 2015). The thickness of the used Si_3N_4 wafers was 250µm while their surface roughness was Sa 220nm, measured with a focus variation microscope (Alicona G5). The drilling strategy applied in the research was percussion drilling without changing the focus position in process. Based on previous investigations on laser drilling of Si_3N_4 substrates (Nasrollahi et al., 2018), pulse energy of 9µJ and pulse frequency of 100kHz was selected as a trade-off between holes' quality, i.e. the edge definition, and the processing speed.

It is extremely difficult and even impossible to analyse properly the morphology of such high aspect ratio micro holes, i.e. diameters and circularity at different depths, employing solely conventional optical measurement methods, especially by making replicas or cutting and grinding of suitable cross-sections. In most of these cases, uncertainty of the measurement procedures would be in order of the measurands. Therefore, a high resolution X-ray tomography was utilised in this research to evaluate the resulted morphology, in particular by analysing a sequence of cross-sections at different depths along the holes' axes. A Zeiss XRADIA Versa XRM-500 system was used with the following scanning settings: acceleration voltage and current were 50 kV and 79 µA, respectively; and the exposure time of each projection was 7 s. As a result, projection images of 1013 by 1013 pixel was captured with pixel binning of 2 reconstructing the volume over a grid of cubic voxels with a side length of 2 µm. This data set was analysed with the Volume Graphics studio 3.0 software and the surface model was defined by VG's advanced surface determination, starting with the ISO 50 surface determination.

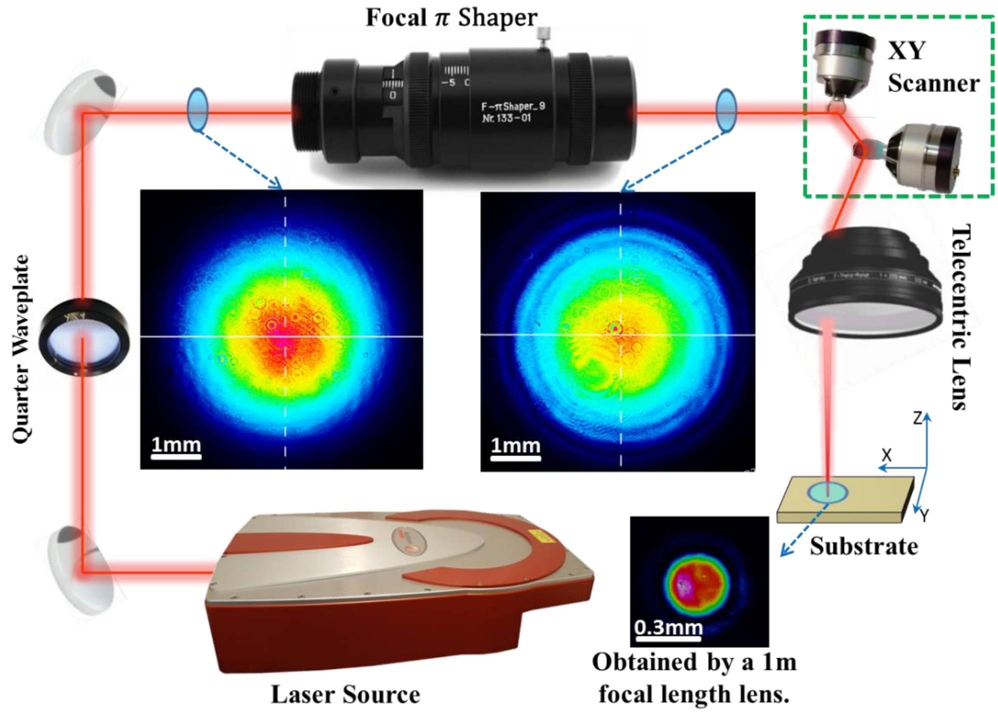

Figure 2. Laser drilling setup with beam profiles at different positions along the beam path

3.2. Design of experiments

A set of experiments was designed to investigate the capabilities of a top-hat beam in drilling high aspect ratio micro holes and compare them with the drilling results achievable with a Gaussian beam. Especially, holes with different number of pulses (NoP) were produced with both spatial beam distributions. The resulting holes' shape and morphology were analysed after pre-set NoPs, i.e. 100, 200, 400, 600, 1000, 2000, 5000 and 7500, and the drilling experiments with each process setting was repeated 7 times. This range was chosen to see clearly the respective continuous increase of penetration depth both before and after the saturation point was reached and then exceeded (Nasrollahi et al., 2017).

As it is depicted in **Figure 1**, the beam diameter and shape can be continuously changed by defocusing. Therefore, laser setups that are highly sensitive to defocusing could not only limit the process flexibility, but also could increase the setup costs due to tighter requirements towards positioning stages and sensors. Therefore, the sensitivity of the investigated laser drilling setup to defocusing in the range from +200 µm to -1000 µm in 200 µm step was analysed, too.

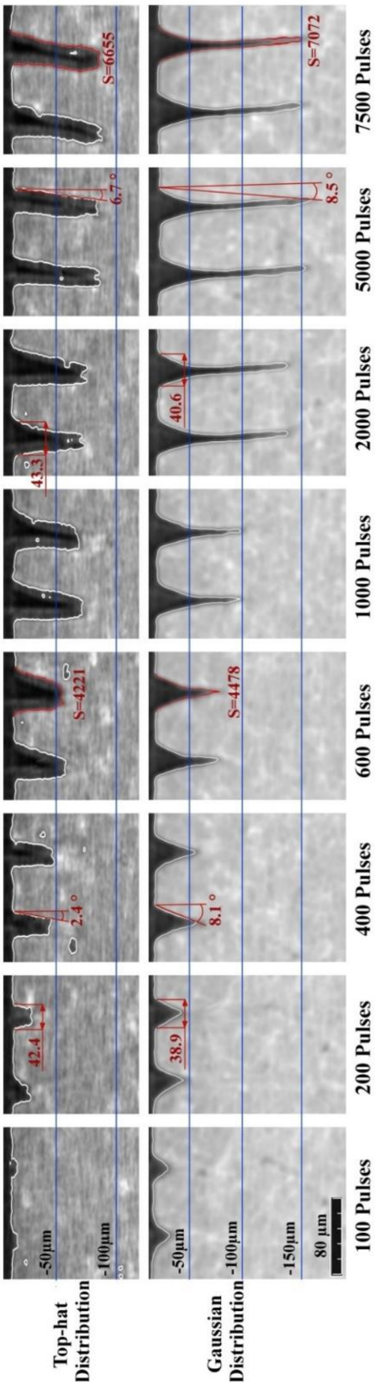

Figure 3. XCT results of Gaussian and Top-hat distribution for different NoP. Note: S is the surface area inside the hole and is in µm^2. All other measurements are in microns.

4. Results and Discussion

4.1. Effects of beam shape on holes' morphology

The effects of the top-hat beam shape on holes' morphology was analysed and compared to the results obtained with a Gaussian beam. Cross sections of XCT results were extracted and the resulting holes' morphology after different NoP is depicted in **Figure 3**. Depth profiles of each two holes produced with the same processing parameters are shown and thus to judge about the repeatability of the drilling process. The morphological evolution of the holes' shape, especially penetrated depth, HAZ, circularity and cylindricity for both top-hat and Gaussian spatial beam profiles are presented.

4.1.1. Penetration depth

The XCT results in **Figure 3** confirm that a higher penetration depth is achievable with a Gaussian beam. The effect of NoP on penetration depth is provided in **Figure 4** and it is evident that at a given NoP the penetration rate drops significantly, indicating that the ablation efficiency has been reduced noticeably. In particular, the efficiency drop was observed at 1000 and 600 NoP for Gaussian and top-hat beam shapes, respectively, while the maximum hole depth was reached at 7500 NoP, i.e. 139 and 74 µm, for the two respective profiles. There are competing factors leading to these differences and thus determining the achievable penetration depth. Specially, plasma shielding and the angular dependence of the laser absorption affect the laser drilling process but the increasing surface area during the drilling process is considered as a dominating factor in decreasing the effective fluence and also in inhibiting the penetration into the material (Ruf et al., 2001).

Therefore, the effect of increasing irradiated surface area inside the holes was analysed and presented in **Figure 5** as a function of NoP. It is apparent that there is only a marginal difference between the surface areas resulting after laser drilling with both profiles. For instance, the area of the holes irradiated with the Gaussian beam was approximately 7000 μm^2 at 7500 NoP and this was only 400 μm^2 higher than the respective areas resulting after top-hat processing. This relatively small difference could be attributed to the Gaussian energy distribution, especially to the changes of the local fluence across the interaction area that led to a high penetration depth in the centre of the holes. At the same time the effective fluence represented as the pulse energy per area was nearly at the same level for both beam profiles, as shown in **Figure 5.** The similar effective fluence achieved with both energy distributions, supports the hypothesis that the increasing surface area is the dominant factor in determining the saturation penetration depth. Unlike the top-hat profile, the holes' deviation from cylindricity was bigger when the Gaussian beam was used, hence the penetration depth was higher while the holes' surface areas were maintained with only a small offset for the two beam shapes.

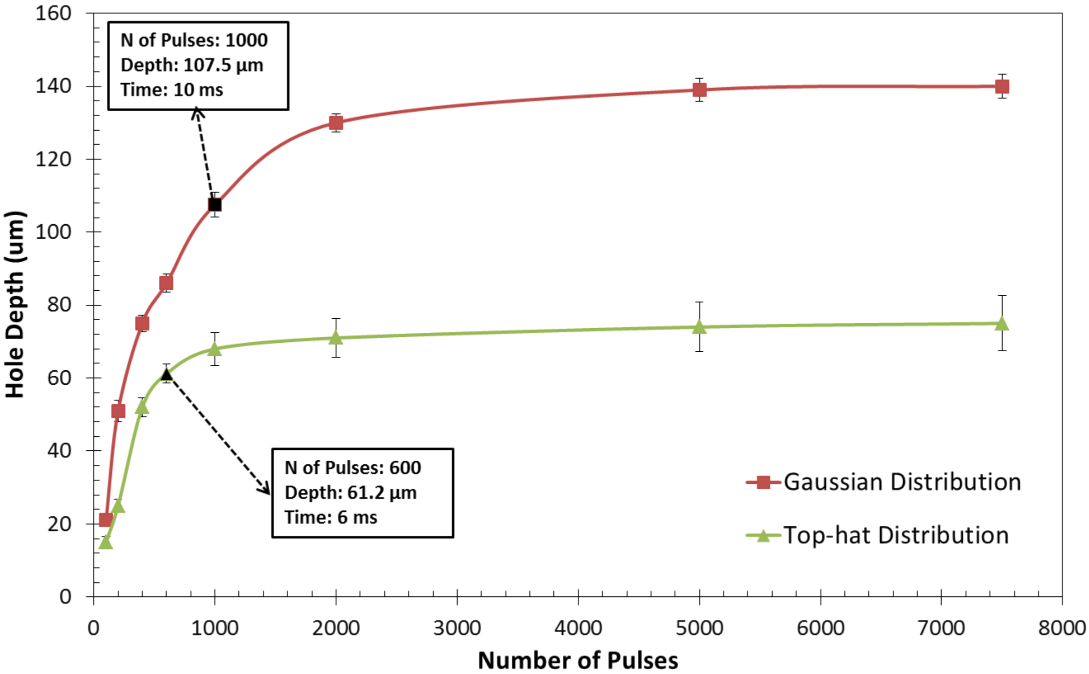

Figure 4. The penetration depths achievable with Gaussian and top-hat beams with an increasing number of pulses

Another difference was the higher spread of holes' depth when the top-hat beam was used as indicated by the standard deviation in Figure 4. The variation of holes' depth was more obvious for the top-hat beam, i.e. the standard deviation for the 7 repeats at 7500 NoP was almost 3 times higher for the top-hat beam.

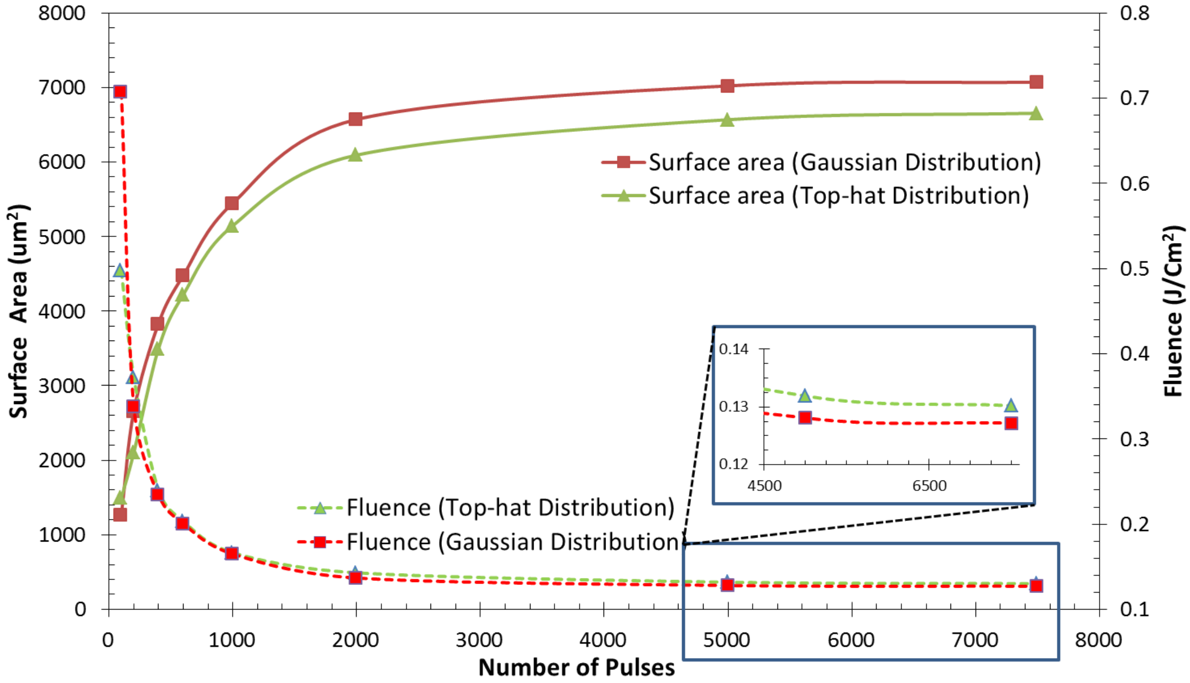

Figure 5. Irradiated surface areas inside the holes together with respective effective fluence for Gaussian and top-hat beams

4.1.2. Heat Affected Zone (HAZ)

HAZ in laser drilling is indicative of the hole quality and can affect the performance of the final product. For instance, it was reported that the resulting HAZ in drilling micro-vias could affect negatively the copper plating operations and thus to impact quality and reliability of produced PCBs (Yung et al., 2002). There is no common approach for quantifying HAZ in laser processing. A number of techniques have been applied in laser drilling, e.g. an analysis of general appearance (Yung et al., 2002) or the grain size changes after processing (Le Harzic et al., 2002). In this research the colour shifting around the holes was analysed by scanning their surrounding areas with Alicona G5. 50× objective was used with a lateral resolution of 0.7 μm and HAZ was measured by using the Alicona software. The uncertainty of this method was assessed by employing the type A statistical method and it was 248 μm^2 with a confidence level of 97%.

The results of HAZ analyse are provided in **Figure 6**. As expected, HAZ extended with the increase of NoP and this was more evident after drilling with the Gaussian beam. Especially, HAZ increased almost 3 (from 139 to 411 μm^2) and 4.5 (from 472 to 2052 μm^2) times for top-hat and Gaussian distributions, respectively, when NoP increased from 200 to 5000. HAZ at 1000 and 7500 NoP were also compared for both beam shapes and it was 4.6 and 5 times bigger after drilling with the Gaussian beam. The main reason for these significant increases is the "tail" of the Gaussian distribution as shown in **Figure 7**a. In particular, fluence of the tails is lower than the ablation threshold and it is sufficient only to heat the surface surrounding the holes without any ablation. In contrast, fluence of top-hat beams can be tailored at the beam spot as shown in **Figure 7**b and thus can be maintained above the ablation threshold to minimise HAZ. This HAZ decrease can enable laser drilling with higher pulse energies as the negative side effects on the surface integrity and material properties can be reduced considerably.

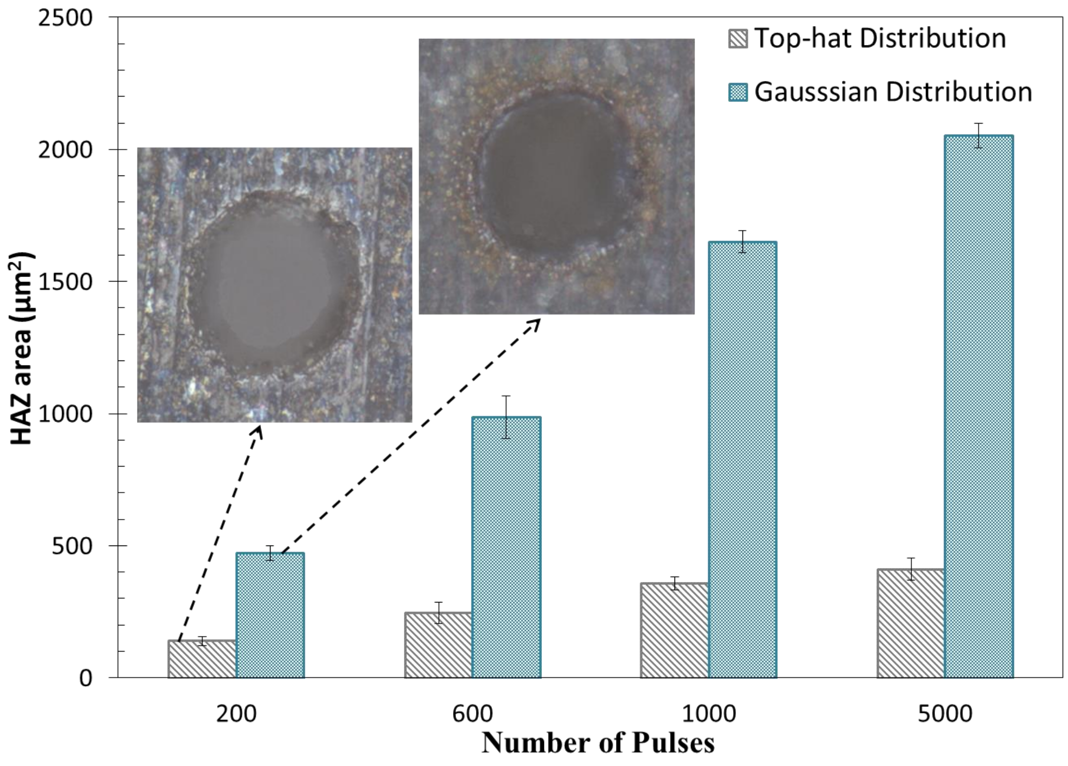

Figure 6. HAZ around the holes produced with Gaussian and top-hat beams

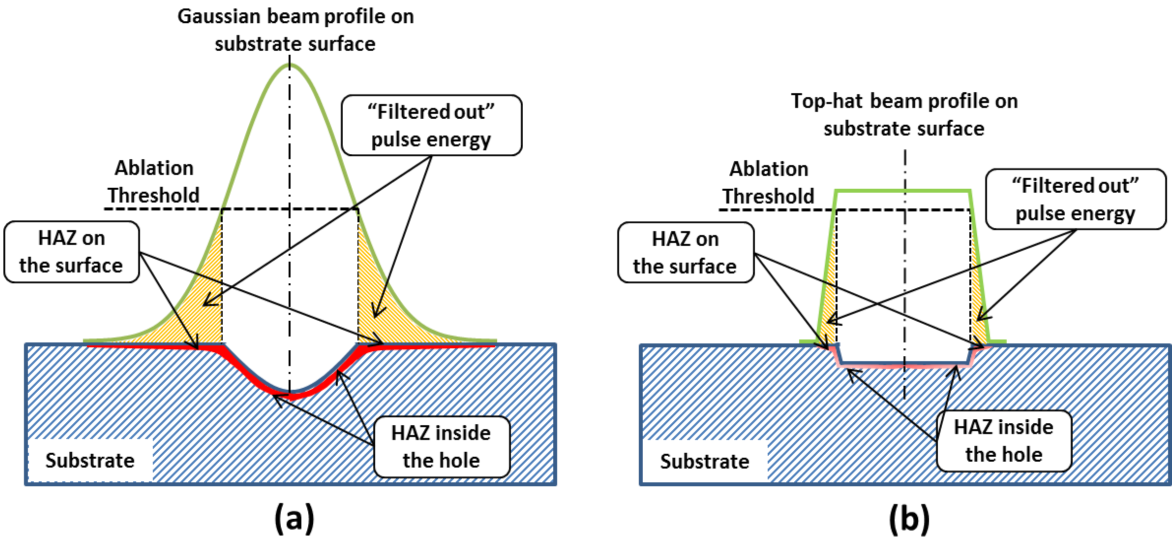

Figure 7. The effects of (a) Gaussian and (b) top-hat beams on HAZ and the holes' shape

4.1.3. Circularity and cylindricity

The cylindricity of the holes can be evaluated by analysing the holes' cross-sections at different depths. Therefore, the cross-sections at every 10 μm along the hole's depth were extracted from the XCT data set and circles were fitted to the holes' profiles employing the least-squares approach. The holes' diameter decrease after 5000 NoP for both beam shapes is depicted in **Figure 8**. For the top-hat distribution, a decrease of dimeters from 43 μm at the hole entrance to 19 μm at depth of 70 μm, the hole bottom, was measured. At the same time, the hole diameter at this depth achieved with the Gaussian beam was 9μm and stayed nearly unchanged onward. This can be explained with the non-uniform fluence distribution. Based on the Beer-Lambert law, the ablated depth after one pulse is a function of local fluence (Inam et al., 1987), in particular:

$$Depth = \frac{1}{\alpha}.\ln\frac{F}{F_{th}} \tag{4}$$

where: α is the absorption coefficient; F - fluence and F_{th} - the ablation threshold of material. When a Gaussian beam is used, the beam irradiation is higher at the centre and respectively the holes are at the centre, too, and ultimately the pulse trains lead to holes with non-uniform shape in terms of cylindricity. At the same time, the homogeneous energy distribution of the top-hat beam improves uniformity of the holes. This is depicted schematically in Figure 7.

Beam shapers can potentially affect the beam circularity and lead to elliptical or irregular hole shapes. Therefore, the holes' circularity at different depths was assessed but there were no irregularities, e.g. the deviations for circularity at depth of 10 µm for both beams were in the same range of 5 µm as shown in Figure 8.

Another important morphological parameter of laser-drilled holes is the average taper angle. As shown in **Figure 3**, the taper angle was 2.4° and 8.1° after 400 NoP for the top-hat and Gaussian beams, respectively. However, the taper angle increased only marginally to 8.5° with the increase of NoP in case of the Gaussian beam while the increase was substantial, i.e. to 6.7°, for the top-hat one.

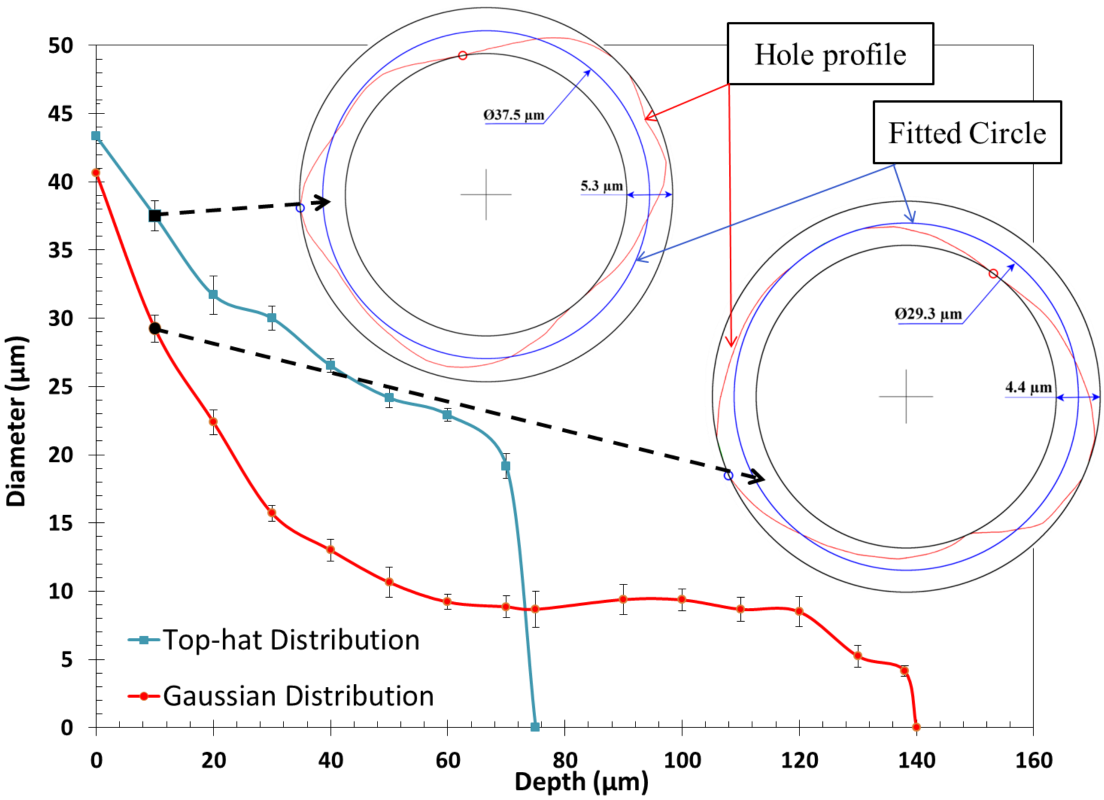

Figure 8. The changes of holes' diameters at different depths for the Gaussian and top-hat beams after 5000 NoP

4.2. Sensitivity of beam shaper to defocusing

The use a top-hat beam can be advantageous in terms of holes' morphology and HAZ as it was discussed in Section 4.1. Nevertheless, the use of beam shapers can make the setting up of the drilling process sensitive to defocusing and so limit their wider application. The effects of beam defocusing on the hole depth after 5000 NoP are depicted in **Figure 9**. While defocussing of ±200 µm for both beams did not affect the penetration depth, a defocusing of -1000 µm led to a depth reduction of 81% (from 74 to 13 µm) and 64% (from 139 to 49 µm) for the top-hat and the Gaussian beams, respectively. This sharp decrease in the top-hat case reflects the beam profile shifting as shown in the **Figure 1**, e.g. the resulting donut hole shape at Z of -1000 µm shown in **Figure 9** is in line with the beam shape at this position that might be useful in other applications.

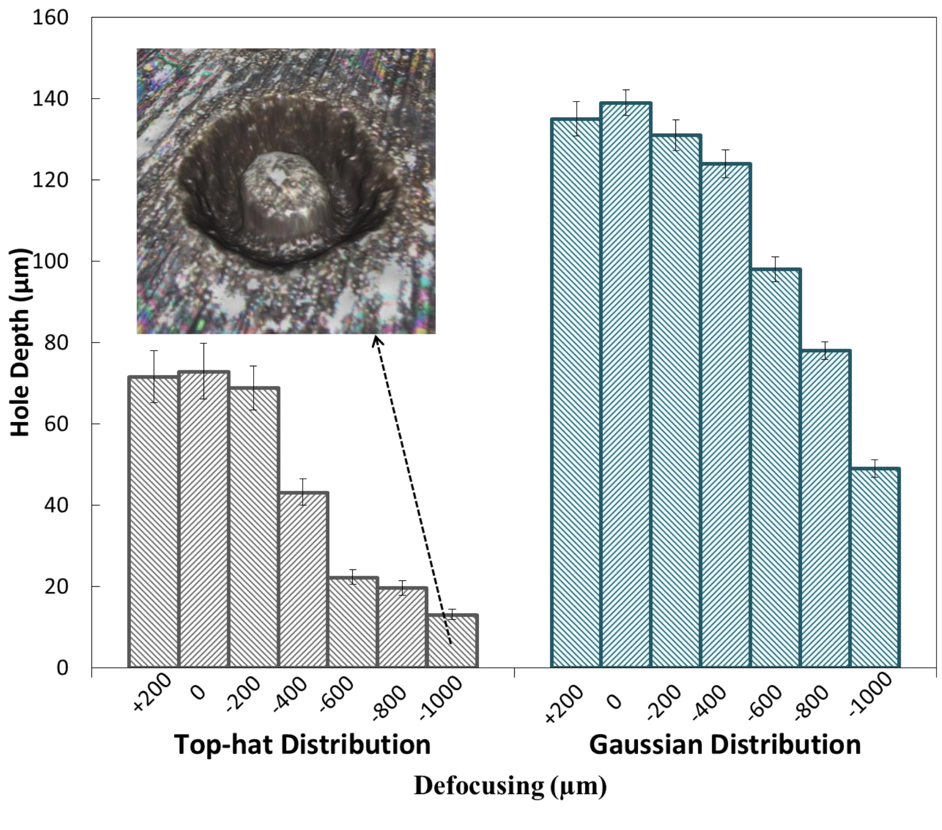

Figure 9. Sensitivity of holes' depth after 5000 NoP to defocusing of top-hat and Gaussian beams

5. Conclusion

A beam delivery system that integrates Focal-πShaper was designed and implemented to achieve a top-hat spatial profile and its capabilities for laser micro drilling was investigated and compared with the machining results achievable with a Gaussian beam. The morphology of high aspect ratio holes was investigated employing a high resolution XCT system and the following conclusions were made:

- The penetration depth and aspect ratios achievable with a Gaussian beam are higher but the use of a top-hat beam improves the holes geometrical accuracy, especially the deviations of the holes from cylindricity are less and also the holes are with a lower tapering angle.
- The achievable penetration depth and the respective saturating points for both beam spatial distributions can be explained with the increase of surface area inside the holes during the laser drilling operations that leads to a drop of effective fluence. In particular, due to the lower cylindricity of the holes produced with a Gaussian beam, the equivalent surface area of the holes produced with a top-hat beam can be achieved only at a higher penetration depth.
- The top-hat spatial distribution minimises not only HAZ but also fluence at the beam spot area can be tailored accurately in respect to the ablation threshold. Especially, the negative effect associated with the "tails" of the Gaussian spatial distributions can be minimised. The HAZ decrease offered by the top-hat beams can enable laser drilling with higher pulse energies without impacting the surface integrity and material properties.
- It was shown that the field mapping approach based on refractive optics, i.e. Focal-πShaper, did not affect the holes' circularity. At the same time, the analysis of the top-hat beam sensitivity to off-focus drilling had shown that the penetration depth would be affected when defocusing exceeded 400 μm.

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