Research Article

Alexander Kroschel*, Andreas Michalowski and Thomas Graf

# Model of the final borehole geometry for helical laser drilling

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**Abstract:** A model for predicting the borehole geometry for laser drilling is presented based on the calculation of a surface of constant absorbed fluence. It is applicable to helical drilling of through-holes with ultrashort laser pulses. The threshold fluence describing the borehole surface is fitted for best agreement with experimental data in the form of cross-sections of through-holes of different shapes and sizes in stainless steel samples. The fitted value is similar to ablation threshold fluence values reported for laser ablation models.

**Keywords:** ablation threshold; helical drilling; laser materials processing; simulation; ultrafast lasers.

## 1 Introduction

Laser drilling is applicable for creating holes in various materials in a wide range of industrial products. Over time, several process strategies evolved, differing in productivity and hole quality. Besides single-pulse drilling, percussion drilling, and trepanning, helical drilling is a widely applied strategy. When ultrashort laser pulses are used, the ablation of the material is dominated by vaporization, offering a high hole quality, as the material is completely removed from the hole, and the holes are formed with sharp edges without burr. Commercially available helical drilling optics [1–5] offer the possibility to influence the borehole geometry by a rotary movement of the laser beam with three degrees of freedom: a rotation frequency, a helical radius, and an inclination toward or away from the rotation axis.

The possibility of drilling wear-free, force-free, and with a high precision and reproducibility in a wide range of materials offers the potential to complement or replace mechanical or electro-erosive drilling steps by laser micro drilling, for example, the processing of spray holes in injector nozzles [2]. The increasing number of applications poses the need of efficient and reliable drilling processes, which is aided by a process simulation. The aim is to generate the resulting borehole geometry for a given laser, process, and material parameter set. Simulation models have been presented for laser drilling in the nanosecond [6] and picosecond [1] pulse regime.

This paper presents a modeling approach for the resulting hole geometry when helical drilling with ultrashort laser pulses is used. The cross-section of the borehole geometry in a steady end state is assumed to equal a line of constant absorbed fluence when the expansion is limited by an ablation threshold. A numerical algorithm is presented, suitable to calculate a line of constant absorbed fluence, given a fluence distribution and material properties. The model is validated by comparing simulated and real boreholes.

## 2 Isophote model

Kraus et al. [1] proposed a model to predict the shape of boreholes based on isophotes calculated for pulsed laser beams propagating in free space with Gaussian intensity (and fluence) distribution and caustic. In contrast to the definition of isophotes (lines of constant brightness), the local fluence is used as the constant parameter in the calculation. In modeling the borehole shape, this constant fluence was fitted for best agreement with the experimental results of the hole shapes.

The model in Ref. [1] is not based on the absorbed fluence at the hole walls because neither the angle between the direction of the light propagation and the local surface nor the Fresnel absorptivity are considered. Therefore, the

***Corresponding author: Alexander Kroschel,** Robert Bosch GmbH, Zentrum für Forschung und Vorausentwicklung, Renningen, Germany; and Universität Stuttgart, Graduate School of Excellence advanced Manufacturing Engineering (GSaME), Stuttgart, Germany, e-mail: alexander.kroschel@de.bosch.com
**Andreas Michalowski:** Robert Bosch GmbH, Zentrum für Forschung und Vorausentwicklung, Renningen, Germany
**Thomas Graf:** Universität Stuttgart, Institut für Strahlwerkzeuge, Stuttgart, Germany

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physical meaning of the fitted constant fluence and the predictive capability of the model is questionable.

Here, we present an extended model for predicting the hole shape by calculating a surface of constant absorbed threshold fluence. For that, the light propagation is described by ray optics. The angle of incidence to the local surface normal as well as the Fresnel absorptivity are taken into account. However, reflected beams impinging upon the hole wall elsewhere inside the borehole are neglected. This is a valid assumption for modeling through-holes and especially boreholes with a significantly larger diameter than the laser beam diameter, as in these, the vast majority of reflected light is propagated outside the borehole without further absorption.

In the laser drilling process, the borehole evolves and expands as long as the absorbed laser fluence is higher than the ablation threshold. The expansion stops in the points where the absorbed fluence falls below the threshold value. Therefore, the isophote (surface of constant absorbed fluence) defined by the ablation threshold fluence can be assumed to equal the steady end state of a borehole produced by an infinitesimally long laser drilling process where all beam, material, and process parameters are constant.

While in the actual drilling process an evolution of the borehole geometry takes place until the final hole shape is reached, in the static model, only the steady end state of the hole geometry is considered. Hence, it is assumed that there is no influence of the temporal borehole evolution on the final shape (e.g. bifurcations, reported in Ref. [7]).

The threshold fluence describing the borehole surface is fitted for best agreement with the experimental data and has the meaning of a material specific ablation threshold. These ablation thresholds are well known from laser ablation models [8–10].

## 2.1 Calculation of an isophote

For all points on the surface of constant absorbed fluence, it holds

$$A \cdot F_{in} = F_{th} = \text{const.}, \tag{1}$$

where $A$ denotes the local absorptivity, $F_{in}$ the incident laser fluence, and $F_{th}$ the constant ablation threshold fluence.

By assuming an ideal Gaussian fluence distribution, the laser drilled borehole is rotationally symmetric, meaning that for calculation, only the cross-section has to be considered, resulting in a two-dimensional problem. The coordinate system is defined with the $z$-axis as the central axis of the borehole and the $r$-axis as its radius (Figure 1).

Consider one arbitrary point $P(r, z)$ in this cross-sectional plane where a ray of a laser beam with a given

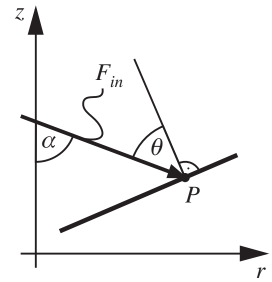


**Figure 1:** Absorption of a ray of light at a surface element.

fluence $F_{in}(r, z)$ and a given direction of propagation (angle $\alpha$ to the central axis $z$) is absorbed at a surface element with a relative angle $\theta$ between the ray and the surface normal (Figure 1). At this point $P$, Eq. (1) must be fulfilled to be part of the surface of constant absorbed fluence.

The local absorptivity $A$ is dependent on the relative angle $\theta$, described by the Fresnel equations incorporating the complex refractive index of the material $\bar{n} = n + ik$, where $n$ is the refractive index, and $k$ is the extinction coefficient. By these assumptions, Eq. (1) can be refined to

$$A(r, z, \alpha, \theta) \cdot F_{in}(r, z) - F_{th} = 0\ . \tag{2}$$

To calculate the direction of the local surface element, Eq. (2) can be solved for $\theta$ by a suitable root-finding algorithm (e.g. bisection method or Newton's method) resulting in

$$\theta = f(r, z, \alpha, F_{in}, F_{th})\ . \tag{3}$$

In other words, Eq. (3) describes a way to calculate the direction of a surface element relative to a given ray, such that the fluence absorbed there equals a constant threshold $F_{th}$. At an isophote line as the cross-section of an isophote surface (modeling the borehole surface), the absorbed fluence must be equal to this threshold at all points.

Considering not only one ray, but a laser beam as a bundle of rays with a given fluence distribution (Figure 2), a line of constant absorbed fluence can be calculated numerically by repeating the procedure, which is illustrated above for one element:

1. Calculate $\theta_1$ by Eq. (3) for a ray absorbed at point $P_1$ with $F_{in_1}$ and $\alpha_1$.
2. Generate a next point $P_2$ in an infinitesimally small distance $\Delta l$ to $P_1$. The direction of the line segment $\overline{P_1P_2}$ is given by $\theta_1$.
3. Repeat steps (1) and (2) for all succeeding points $P_i$ with $F_{in_i}$ and $\alpha_i$.

The start condition of this numerical algorithm is a point $P_0$ on a given initial, unprocessed surface where

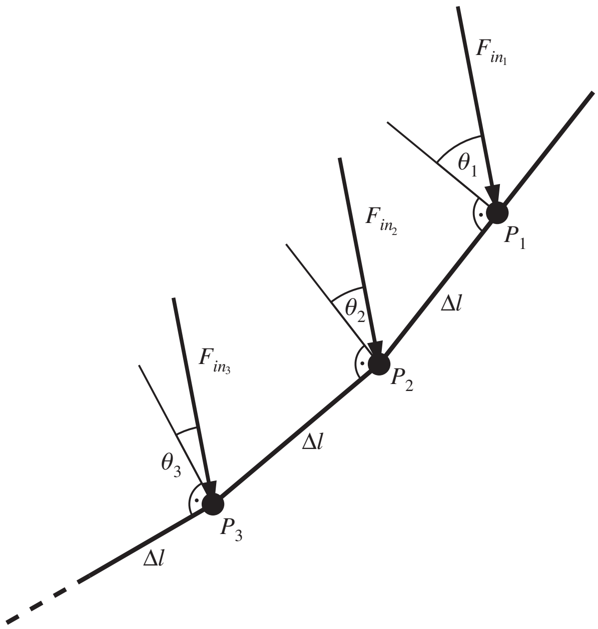


**Figure 2:** Calculation of an isophote line consisting of several line elements.

the absorbed fluence is equal to the ablation threshold (Figure 3). For the initial surface to be appropriate for the two-dimensional algorithm, it must be a line, which is the cross-section of a surface that is rotationally symmetric to the central borehole axis $z$. From $P_0$ on, the algorithm [steps (1) to (3)] from above is used to follow the isophote.

There are two possible end conditions for the algorithm (both shown in Figure 3):
1. The bottom surface of the given workpiece is reached ($z=z_{\text{bottom}}$). This generally leads to a through-hole as $r \geq 0$ at the bottom surface.
2. The borehole central axis $z$ is reached ($r=0$) leading to a blind hole. Note that in this case, the assumption of negligible absorption of multiply reflected rays does not hold, and the geometry prediction, especially of the bottom part of the borehole, is not accurate.

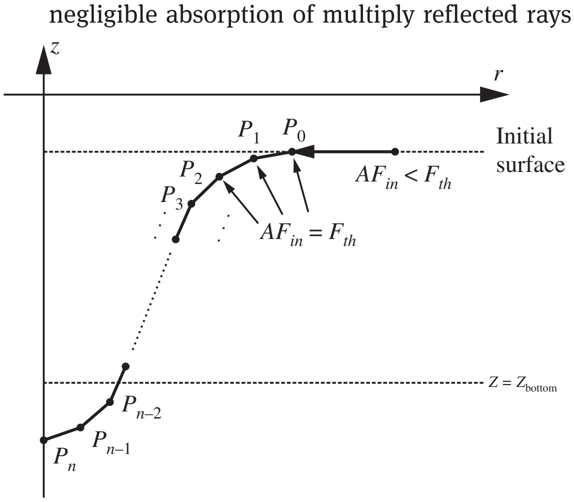


**Figure 3:** Algorithm for isophote calculation with start condition and both possible end conditions.

## 2.2 Calculation of laser beam characteristics

In the algorithm described above, the local incident fluence $F_{in}$ and angle $\alpha$ of the incident ray have to be calculated for any point in the cross-sectional plane where a ray is absorbed. In these laser beam characteristics, the helical drilling process parameters (e.g. helical radius $r_{\text{helical}}$ and angle of inclination $\beta$) are contained. As stated earlier, a Gaussian fluence distribution is assumed, which is given by

$$F_{in}(r^{(CR)}, z^{(CR)}) = \frac{2Q}{\pi w^2(z^{(CR)})} \cdot \exp\left(-\frac{2(r^{(CR)})^2}{w^2(z^{(CR)})}\right), \tag{4}$$

where $Q$ is the total energy contained in one laser pulse, $(r^{(CR)}, z^{(CR)})$ is the coordinate system of the central ray (CR), and $w(z^{(CR)})$ is the radius where the fluence values fall to $1/e^2$ of their axial values,

$$w(z^{(CR)}) = w_0 \sqrt{1+\left(\frac{z^{(CR)}}{l_R}\right)^2}, \tag{5}$$

with the waist radius $w_0$ and the Rayleigh length $l_R$.

The laser beam characteristics are defined in a second coordinate system to incorporate parameters suitable to describe helical laser drilling. As already mentioned in Eqs. (4) and (5), the coordinate system is centered at the focus point $P_0^{(CR)}$ of the laser beam with the $z^{(CR)}$-axis pointing in the direction of the central ray and the $r^{(CR)}$-axis perpendicular to it (Figure 4).

According to the possible beam propagation characteristics for helical drilling, the central ray coordinate system $(r^{(CR)}, z^{(CR)})$ is displaced relatively to the borehole coordinate system $(r, z)$, whose $z$-axis is simultaneously the axis of rotation of the helical drilling process. Three degrees of freedom are used in this model.
1. The laser beam is rotated about the central borehole axis $z$ in a circular motion with radius $r_{\text{helical}}$.
2. The focus point can be shifted in the $z$-direction by a (defocusing) length $s$.
3. Additionally, the central laser beam axis can be inclined by an angle denoted by $\beta$ toward or away from the $z$-axis.

Mathematically, the transformations (1) and (2) can be described by a translation of the focus point $P_0^{(CR)}$ (and, thus, the coordinate system of the central ray), while (3)

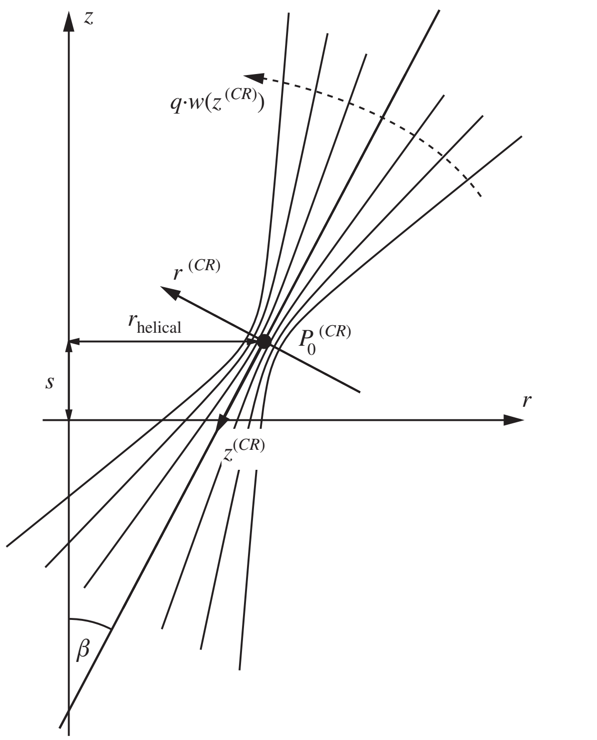


**Figure 4:** Relationship between borehole and laser beam coordinate system with a laser beam described as a bundle of rays.

leads to a rotation of the coordinate system in the cross-sectional plane. Both transformations are combined by

$$\begin{pmatrix} r^{(CR)} \\ z^{(CR)} \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} r - r_{\text{helical}} \\ z - s \end{pmatrix}. \tag{6}$$

With Eqs. (4)–(6), $F_{in}(r, z)$ can be calculated for any point in the cross-sectional plane with respect to the helical drilling process. The remaining laser beam property, needed for the calculation of the hole shape, is the local angle $\alpha$ of the direction of the incident ray at the coordinate $(r, z)$. This is derived from a ray optical description of the laser beam.

In our approach, the laser beam is approximated by a bundle of rays (Figure 4) whose local Poynting vectors are perpendicular to the wave fronts. The radius coordinate $r^{(CR)}$ of a bent ray is a function of the coordinate along the central ray $z^{(CR)}$ [see Eq. (5)] and is scaled by a factor $q$

$$r^{(CR)}(z^{(CR)}) = q \cdot w(z^{(CR)})\,. \tag{7}$$

The local angle $\alpha$ of the direction of the incident ray is the sum of the angle $\gamma$ between the local Poynting vector (tangential to the scaled caustic) and the central ray axis $z^{(CR)}$ as well as the angle of inclination $\beta$ of the central ray (Figure 5)

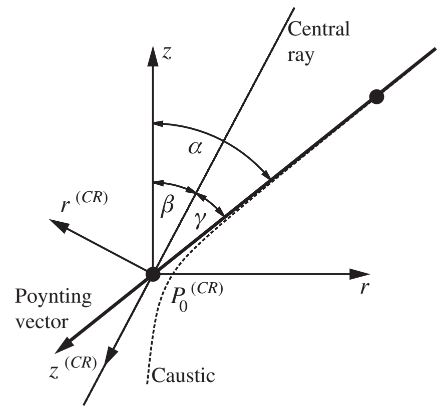


**Figure 5:** Calculation of the angle $\alpha$ of the direction of the incident ray.

$$\alpha = \beta + \gamma. \tag{8}$$

The angle of inclination $\beta$ is constant, and $\gamma$ is the directional derivative of Eq. (7) with respect to the central ray coordinate

$$\tan\gamma = \frac{dr^{(CR)}}{dz^{(CR)}} = q \cdot \frac{dw}{dz^{(CR)}} = q \cdot \frac{w_0 z^{(CR)}}{l_R^2 \sqrt{1 + \frac{(z^{(CR)})^2}{l_R^2}}} \tag{9}$$

with

$$q = \frac{r^{(CR)}}{w(z^{(CR)})}, \tag{10}$$

following from solving Eq. (7) for $q$.

With these equations, the angle $\alpha$ of the incident ray can be calculated for any point in the cross-sectional plane.

In summary, in this section, an algorithm has been presented for calculating an isophote line of constant absorbed fluence for a given laser beam, material, and helical drilling process parameter set. The isophote related to the ablation threshold fluence can be assumed to describe the steady end state of a laser-drilled borehole for an infinitesimally long, pulsed laser drilling process, where all beam, material, and process parameters are held constant.

# 3 Validation experiments

## 3.1 Experimental setup

For validation of the model given in Section 2, drilling experiments have been conducted using an Amplitude Tangerine laser system at its fundamental wavelength and a five-axis scan system (Precise Laser Drilling Scan System MA-1000iR) from Canon Inc., Japan, as helical drilling optics. The processing parameters used can be found in Table 1.

**Table 1:** Processing parameters.

| Parameter | Value |
|---|---|
| Wavelength | 1030 nm |
| Pulse duration | 0.5 ps |
| Repetition rate | 50 kHz |
| Focal length | 60 mm |
| Focal diameter $d_f$ | 22 µm |
| Defocusing length $s$ | 0 µm |
| Helical diameter $d_{\text{helical}}$ | 200; 500 µm |
| Angle of inclination $\beta$ | −10°, 0°, 7.5° |
| Pulse energy $Q$ | 1.76 … 58 µJ |
| Tangential feed rate | 0.05 mm/s |
| Polarization state | Circular |

In the experiments, several holes have been drilled varying the helical diameter $d_{\text{helical}}$ and the angle of inclination $\beta$, as those parameters lead to boreholes of very different shapes. Therefore, the model can be validated on a large parameter space. Both helical diameter and angle of inclination have been calibrated before the experiments.

By definition, for a negative angle of inclination, the diameter of the laser beam path increases after passing the focal plane. For a large angle, this leads to a negatively conical borehole, i.e. the outlet in the direction of propagation of the laser beam has a larger diameter than the inlet. The experiments were carried out on 0.5-mm-thick stainless steel samples, which were ground and polished to the central cross-sectional plane of the respective holes. Those were recorded in a scanning electron microscope (SEM).

### 3.2 Experimental results

As the model is capable of predicting a steady end state geometry of a borehole, the drilling program has been designed for a very long drilling process with a constant parameter set for $d_{\text{helical}}$ and $\beta$. With these two parameters held constant, the pulse energy has been ramped in six discrete steps in the range given in Table 1 such that the last step with maximum pulse energy lasted for 5000 revolutions. The drilling program has been designed for the purpose of validation of the model, not for achieving the best possible hole quality, which is accountable for a rough inner borehole surface in the bottom half. A smaller roughness is achievable with different drilling parameters.

In Figure 6, SEM images of cross-sections of several boreholes are displayed with the corresponding isophote lines as modeling results at the right borehole edges. The borehole contour is assumed to be symmetrical.

For the simulation, the complex refractive index of stainless steel was taken to be $\bar{n}=2.59+i\cdot 4.87$ [11]. For all other parameters, the values from the experiment have been used, except for the ablation threshold fluence. This parameter was used as a free parameter to find the best agreement between model and experiments. This value was fitted for the largest borehole (Figure 6A) and kept constant for the prediction of the other hole shapes (Figure 6B–D). The calculated hole shapes are in good agreement with the cross-sections of the laser-drilled through-holes. The constant radial deviation observed in Figure 6B is most likely caused by an inaccurate execution of the preparation of the cross-section.

The value found for the ablation threshold fluence is $F_{th}=0.02$ J/cm². This is, by definition in Eq. (1), the value of the absorbed fluence at the ablation threshold. It can be used to estimate an appropriate ablation threshold, related to the incident fluence and normal illumination. It follows from Eq. (1), for the refractive index used for stainless steel

$$F_{th,in}=\frac{F_{th}}{A(0°)}=\frac{0.02\ \text{J/cm}^2}{0.283}=0.071\ \text{J/cm}^2. \tag{11}$$

This value is similar to the ablation threshold fluence of stainless steel for $\tau_p=0.5$ ps, $F_{th,in}=0.06$ J/cm², measured by Neuenschwander et al. [9].

In the model, ideally smooth hole walls are assumed. In Figure 6, inhomogeneities in the bottom half of the borehole walls indicate an increased surface roughness. Interestingly, this does not have a negative effect on the agreement with the model.

## 4 Conclusions

The presented model seems to be capable of accurately predicting the geometry of laser-drilled through-holes with different shapes and sizes. It is applicable to the steady end state geometry of boreholes produced by an ultrashort pulsed helical laser drilling process. Furthermore, it is based completely on physically meaningful values. The only fitted parameter for the ablation threshold fluence is in good agreement to the literature values.

Nevertheless, the model is subject to some limitations. Multiple reflections inside the borehole are neglected. This means that an incident ray is absorbed at the borehole surface, but the generated reflected ray is not considered in the energy balance. Therefore, the best agreement between model and experiments is expected for through-holes with large borehole diameters and long drilling times. In contrast, the predictive capability of the model is expected to be weaker for small boreholes. These limits of the model will be examined in future work.

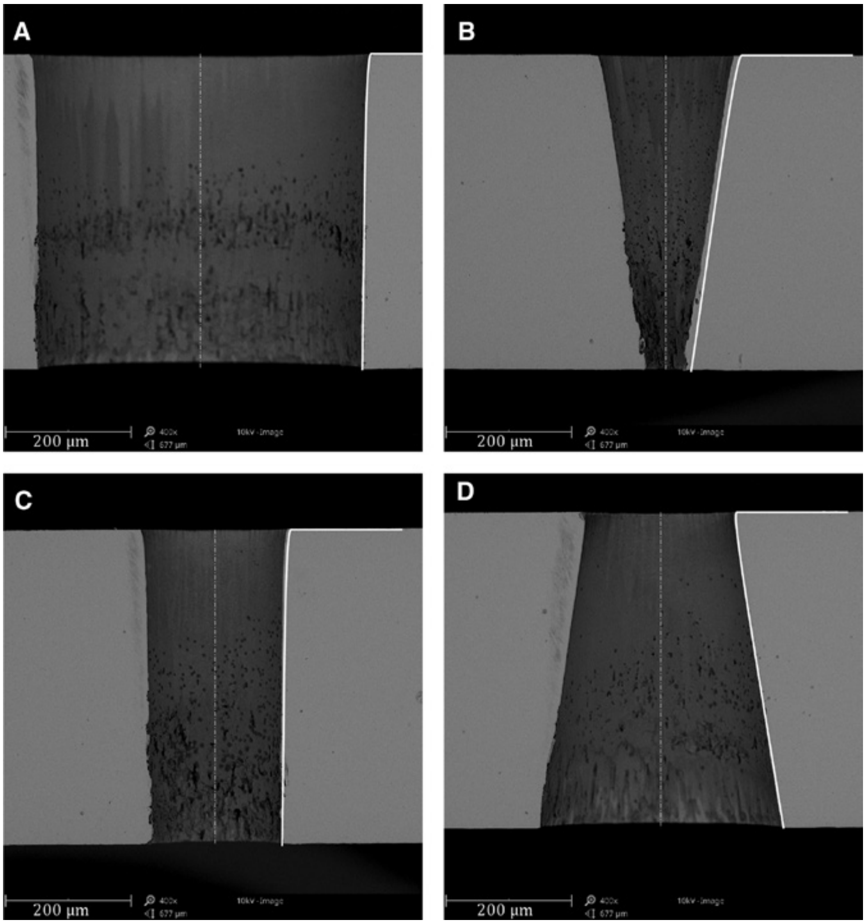


**Figure 6:** SEM images of boreholes with modeled isophote lines (white lines at right borehole edges), (A) $d_{helical}=500$ µm, $\beta=0°$, (B) $d_{helical}=200$ µm, $\beta=7.5°$, (C) $d_{helical}=200$ µm, $\beta=0°$, (D) $d_{helical}=200$ µm, $\beta=-10°$. The purpose of the presented holes was a validation of the model, not the best possible hole quality. A smoother inner borehole surface could have been achieved with different drilling parameters.

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**Alexander Kroschel**
Robert Bosch GmbH, Zentrum für Forschung und Vorausentwicklung Renningen, Germany; and Universität Stuttgart, Graduate School of Excellence advanced Manufacturing Engineering (GSaME), Stuttgart, Germany
**alexander.kroschel@de.bosch.com**

Alexander Kroschel studied Mechanical Engineering at the Ilmenau University of Technology, Germany. Since 2016, he is a doctoral student at the University of Stuttgart, Germany, and Robert Bosch GmbH. His research topic is on laser drilling with ultrashort laser pulses.