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Depth and quality limit for percussion-drilled microholes with depth > 1 mm using ultrashort pulsed laser radiation

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Abstract

Based on the assumption that laser-drilled microholes can be approximated by a cone the maximum depth as a function of the laser fluence can be predicted by a simple analytical model. In this contribution, it will be shown, that the calculated maximum depth agrees well to microholes in stainless steel with drilling depth > 1mm. A Ti: sapphire laser at a wavelength of 800 nm and a pulse duration of 1 ps was used to percussion drill microholes with pulse energies up to 5 mJ and the corresponding maximum drilling depth was determined. Due to the low repetition rate of 1 kHz heat accumulation effects could be excluded. Furthermore, the quality of the microhole exit was investigated as a function of the peak fluence in 1 mm stainless steel, including the formation of side channels and the development of the shape of the microhole exit.

Keywords: Laser micro processing; Drilling; Percussion-drilled microholes; Final drilling depth; Sidechannels

1. Introduction

In recent years, high-performance ultra-fast laser systems with significantly increased pulse energies and repetition rates of several hundred kilohertz have been developed (Negel et al., 2016), opening up new fields of application in micro materials processing. During the laser drilling process, the irradiated laser fluence is distributed over the entire surface of the inner wall of the microhole so that the drilling progress stops at a certain drilling depth, where the transferred energy hardly exceeds the ablation threshold (Ruf et al., 2001). If a fixed focusing setting is considered, higher drilling depths can therefore be achieved with higher pulse

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energies. Depending on the laser fluence, the maximum achievable drilling depth can be estimated with a simplified analytical model (Foerster et al., 2018). Its validity could be shown in stainless steel for different focusing settings up to a drilling depth of 2 mm (Foerster et al., 2018). In the present contribution, the maximum achievable drilling depth was studied up to 5 mm. In addition, the quality of the microhole exit was investigated in the region, where the drilling process comes to a halt. At the end of the drilling process, the tip of the microhole splits into several narrow side channels. If a fixed sample thickness is considered, a definite main microhole exit is only formed with increasing laser fluence. With a sample thickness of 1 mm, it could be shown that a high-quality microhole can be produced if the laser fluence exceeds a factor 35 of the minimum laser fluence required for drilling through.

2. Theoretical limit of the drilling depth

When the microhole geometry is approximated by a conical shape, the depth or aspect ratio of the microhole can be estimated with a simplified analytical model given by Foerster et al., 2018

$$\frac{z_{\mathrm{Drill}}}{w_0} = \sqrt{\frac{\Phi_0^2 - \Phi_{\mathrm{th}}^2 \cdot ln\left(\frac{\Phi_0}{\Phi_{\mathrm{th}}}\right)^2}{2 \cdot \Phi_{\mathrm{th}}^2 \cdot ln\left(\frac{\Phi_0}{\Phi_{\mathrm{th}}}\right)}}, \tag{1}$$

where z_{Drill} is the hole depth achievable with a given beam radius w_0. The aspect ratio only depends on the ablation threshold Φ_{th} of the given material and on the peak fluence Φ_0 of the incident Gaussian beam. It is assumed that the drilling progress comes to a halt, when the incident local fluence drops below the ablation threshold Φ_{th} throughout the inner wall of the microhole.

3. Experimental Set-up

The percussion drilling experiments were performed with a Ti: sapphire laser system operating at a wavelength of 800 nm. The beam quality factor was measured to be $M^2 < 1.2$. In order to minimize heat accumulation effects and melt formation, the repetition rate and pulse duration of the laser pulses was set to 1 kHz and 1 ps, respectively. The circularly polarized laser beam was focused onto the surface of the sample. The focal radius was measured to be 39 µm and the Rayleigh length was measured to be 5.0 mm.

In order to ascertain the minimum peak fluence $\Phi_{0,\mathrm{min}} = 2E_{\mathrm{P,min}}/(\pi w_0^2)$ of the laser beam for drilling through a stainless steel sample (1.4301), the pulse energy E_{P} was gradually reduced with each hole. After drilling, the samples were examined with a light microscope. It was determined for each sample thickness at which minimum peak fluence it is still possible to drill through the sample. The average between the minimum peak fluence that was needed to drill through and the maximum peak fluence at which the sample was not drilled through was used as the experimentally determined value of $\Phi_{0,\mathrm{min}}$. The difference of the two values was used as the measure of the uncertainty. The drilling process was additionally recorded with a camera in order to measure the drilling time.

4. Results and discussion

Fig. 1 shows the aspect ratio z_{Drill}/w_0 of the percussion-drilled holes and the experimentally determined values of the minimum peak fluence $\Phi_{0,\mathrm{min}}$ of the beam for drilling through stainless steel samples with thicknesses from 1 mm to 5 mm in steps of 1 mm. The blue line is given by Eq. (1) assuming an ablation threshold of 0.061 J/cm². The ablation threshold was determined experimentally by Vetter, 2019 according to Liu et al., 1982 in stainless steel 1.4301 for 10 pulses at a wavelength of 800 nm and a pulse duration of 1 ps.

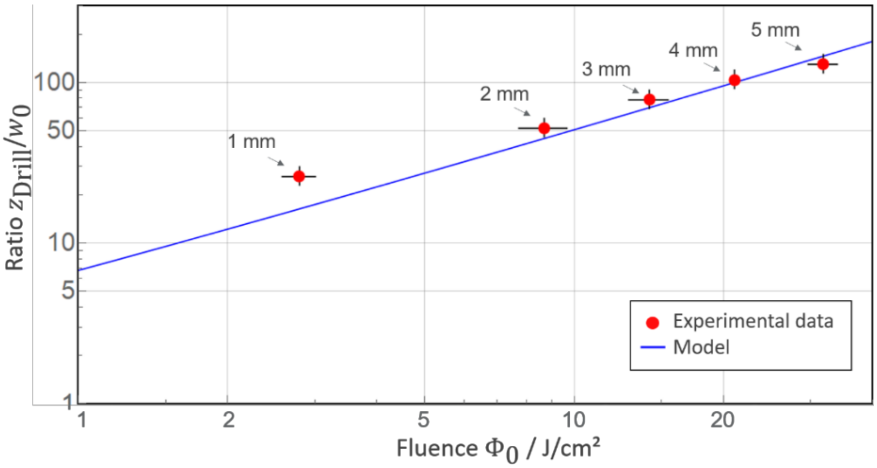

Fig. 1. Experimentally determined values of the minimum peak fluence $\Phi_{0,\mathrm{min}}$ for drilling through stainless steel (1.4301) samples with thicknesses from 1 mm to 5 mm in steps of 1 mm (red dots with error bars). The blue line shows the calculated aspect ratio z_{Drill}/w_0 of the percussion-drilled hole as a function of the peak fluence Φ_0 irradiated given by Eq. (1) assuming an ablation threshold of 0.061 J/cm².

It can be seen that the experimental data points can be well represented by the assumed model. Only at a drilling depth of 1 mm does the model underestimate the experimentally determined value.

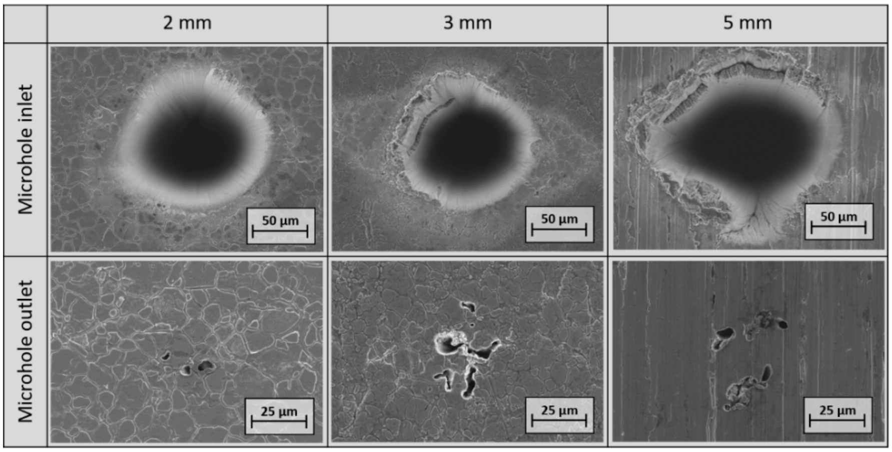

Fig. 2. Entrance and exit of percussion-drilled holes for stainless steel samples with thicknesses of 2 mm, 3 mm and 5 mm drilled with the minimum peak fluence $\Phi_{0,\mathrm{min}}$. In the last phase of the drilling progress side channels are formed.

The SEM pictures in Fig. 2 show the entrance and exit of percussion-drilled holes for stainless steel samples with thicknesses of 2 mm, 3 mm and 5 mm drilled with the minimum peak fluence $\Phi_{0,\mathrm{min}}$. Over all depths, it was shown that at the minimum peak fluence for drilling through, the microhole exit is split into many minor side holes. During transmission measurements in PMMA published by Ruf et al., 2001, it was observed that ablation stops in the last phase of drilling progress when the local fluence at the tip falls below the ablation threshold, but then suddenly resumes after several further pulses. In most cases, the ablation continues at a location next to the tip, resulting in the formation of side channels. It can be assumed that the drilling progress and the formation of the side channels in stainless steel are similar to those observed in PMMA.

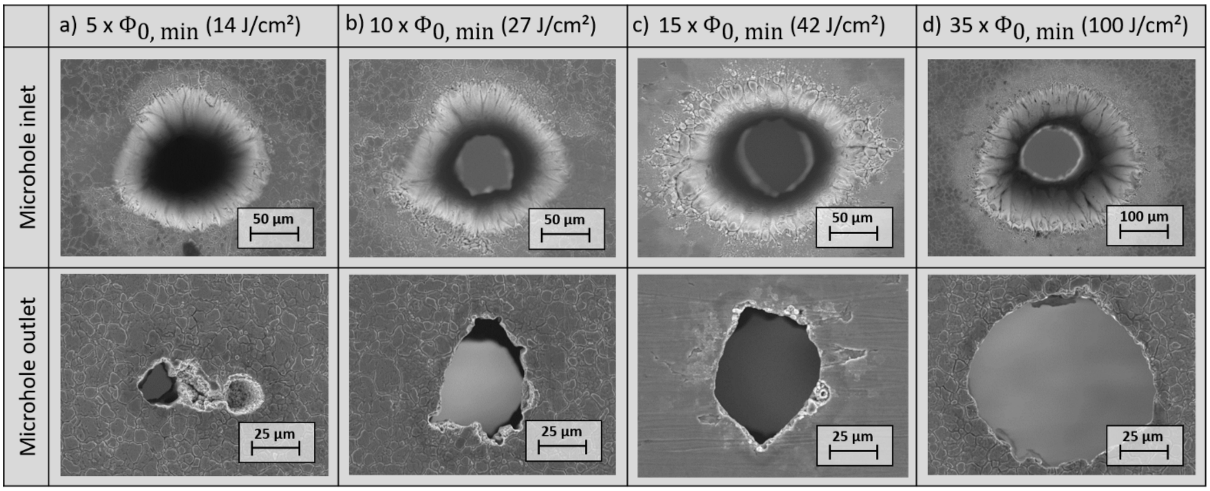

Fig. 3. Entrance and exit of percussion-drilled holes in 1 mm thick stainless steel samples drilled with different multiples of the minimum peak fluence $\Phi_{0,\mathrm{min}}$. During the drilling process, the pulse energy was ramped to the corresponding value.

Only with increasing fluence, a definite microhole exit is formed. The assumption is that the quality of the hole increases as long as the hole is formed in a stable phase of the drilling process. Fig. 3 shows the exit of percussion-drilled microholes in 1 mm stainless steel for increasing multiples of the minimum peak fluence $\Phi_{0,\mathrm{min}}$ for drilling through 1 mm. During the drilling process, the pulse energy was ramped to the corresponding value. When the laser fluence exceeds $\Phi_{0,\mathrm{min}}$ by a factor of 10, no side channels can be observed any more, but grooves appear at the microhole exit. With a factor of 15 of $\Phi_{0,\mathrm{min}}$, the grooves are reduced, but the shape remains irregular. Only with a significant increase in fluence a round microhole exit with a roundness deviation of < 15 % is formed, see Fig. 3 (d). It should be noted that at high intensities above $2 \cdot 10^{13}\ \mathrm{W/cm^2}$ (Breitling et al., 2004) the ablation process changes due to the formation of laser-induced plasma in air (optical breakdown). Optical breakdown is associated with a number of nonlinear phenomena ranging from wavelength conversion to widening and distortion of the beam profile in the far field behind the breakdown spark (Breitling et al., 2004). In the experiment presented, a significant beam widening could be observed from a fluence of 41 J/cm², which significantly widened the capillary and thus reduced the aspect ratio of the microhole. Although energy loss and redistribution due to plasma scattering may be expected (Breitling et al., 2004), a large amount of the energy may still reach the tip of the microhole due to the widened capillary, possibly improving the shape of the microhole exit. In addition, material ejection during the drilling process would be considerably facilitated. Which fluence prevails finally under the given settings in the tip of the drilling channel and how it affects the quality of the outlet is the subject of further investigations.

5. Summary

In sum, it could be shown, that a simplified analytical model can be used to calculate the maximum available depth up to 5 mm in stainless steel. The breakthrough occurs in the final drilling phase of the drilling process. That means, that at the minimum peak fluence $\Phi_{0,\min}$for drilling through, the tip of the borehole is split into several narrow side channels. In order for a defined hole to be formed without side channels, the fluence must exceed $\Phi_{0,\min}$ by factor of 10. However, the shape of the microhole exit remains irregular. Only at higher fluences (35 x $\Phi_{0,\min}$) a high-quality microhole with a roundness deviation of < 15 % could be produced in a 1 mm thick sample. At these high intensities the formation of laser-induced plasma in air leads to the widening of the capillary and thus to a reduction of the aspect ratio of the microhole, which significantly changes the ablation process.

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