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The progress of microhole formation during laser percussion drilling of steel observed by highspeed synchrotron x-ray imaging

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Abstract

The formation of microholes during the percussion drilling of metals using ultrashort laser pulses remains poorly understood. The quality of a microhole can be affected by heat accumulation, the development of side channels, and microhole bulging due to plasma formation. Highspeed synchrotron X-ray imaging was applied to capture the space- and time-resolved evolution of the microhole shape during laser percussion drilling of stainless steel. The recorded images show that heat accumulation leads to the formation of a melt film on microhole walls, which dynamically fluctuates during drilling. Additionally, the formation of side channels was observed in the region of the maximum drilling depth where the overall fluence on the microhole walls drops below the threshold fluence. The experimentally captured quantities agree well with existing models and will significantly improve their prediction accuracy.

Keywords: Microholes, Percussion drilling, Ultrashort laser pulses, Highspeed synchrotron X-ray imaging

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1. Introduction

Hole formation during percussion drilling of metals with ultrashort pulses has been studied extensively in previous work, e.g. by Breitling et al., 2002, Michalowski et al., 2008, Holder et al., 2021 and Förster et al., 2018. Understanding irregularities and defects, such as irregular hole shapes, bending, and side channels, is challenging, due to limitations in conventional diagnostics. Despite advancements in in-situ depth measurements using optical coherence tomography (OCT) and associated analytical models, as presented by Holder et al., 2021, the findings are limited because of the aforementioned irregularities.

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In previous studies, Döring et al., 2014, realized in-situ imaging of the microhole formation during drilling of silicon, which served as a model material. The transparency of silicon at laser wavelengths above 1100 nm and opacity at lower wavelengths enabled transillumination with an illumination laser while being processed with an ultrashort pulsed laser. However, investigating the dynamic shape changes during laser drilling of metals requires an alternative approach. Recent publications on laser welding and cutting highlight high-speed X-ray imaging as a valuable tool for visualizing laser material processing, as presented by Wagner et al., 2021 and Lind et al., 2021. The high-quality X-ray beam of a synchrotron enables highest spatial and temporal resolutions in X-ray imaging. For the first time this enables to capture the formation of a borehole during the drilling process. In this work we show that this technique allows for a detailed observation of the formation of side channels and bulges, which provides valuable insights into the drilling process.

2. Experimental Setup

The experiments were conducted at the DESY (Deutsches Elektronen-Synchrotron, Hamburg, Germany), which is described in detail by Schell et al., 2013. The applied experimental setup for the investigation of laser material processing is extensively described by Wagner et al., 2021. The energy of the X-ray beam was adjusted to 89 keV to meet the requirements of stainless steel. For the drilling experiments, the setup was supplemented by an ultrashort pulsed YB:YAG laser (Carbide CB3-80) from Light Conversion (Vilnius, Lithuania). After circular polarization by a λ/4 wave-plate, the laser beam was directed via mirrors onto a quartz lens with a focal length of 160 mm and focused on the surface of the sample. This resulted in a focal diameter of d_f = 50 µm. The laser beam parameters are listed in Table 1.

Table 1: Laser beam parameters and optical setup.

Dimension	Unit	Carbide CB3-80
Wavelength (λ)	*nm*	1035
Laser Power (P)	*W*	10
Pulse energy (E_p)	*µJ*	200
Repetition rate (f_{rep})	*kHz*	50
Pulse duration (τ_p)	*ps*	1
Beam Quality (M^2)	-	< 1.1
Beam diameter (D_r)	*mm*	4.6
Polarization	-	circular
Focal length (f)	*mm*	160
Focus diameter (d_f)	*µm*	50

The parameters listed in Table 1 result in a peak fluence of approximately 20.4 J/cm² in the laser focus. The sample material was stainless-steel (1.4301) with a width of 0.5 mm in the X-ray beam direction. The X-ray image sequence was post-processed in two steps according to Wagner et al., 2021. The sequence was processed with a flat field correction to avoid misinterpretations due to the intensity profile of the X-ray beam. Subsequently, a Kalman filter was applied.

3. Results

Fig. 1 shows an X-ray image sequence of a percussion drilled microhole in stainless steel at discrete points in time. The images are arranged horizontally according to their chronological order, which is represented in the horizontal axis by the number of pulses and the corresponding time. A fast depth progress can be observed within the first 500 ms. After 500 ms the depth progress stagnates, which is associated by the formation of a bulge at a depth of around -0.4 mm. This effect may result from a particle-induced plasma within the microhole, as discussed by Breitling et al., 2002. The progressing drilling process results in a longitudinal expansion of the bulge. After approximately 4 s, the formation of side channels can be observed. The formation of side channels indicates, that the overall fluence on the microhole walls undercuts the threshold fluence of the material, as stated by Förster et al. After 5 s the hole reached its maximum depth of approximately 1550 µm.

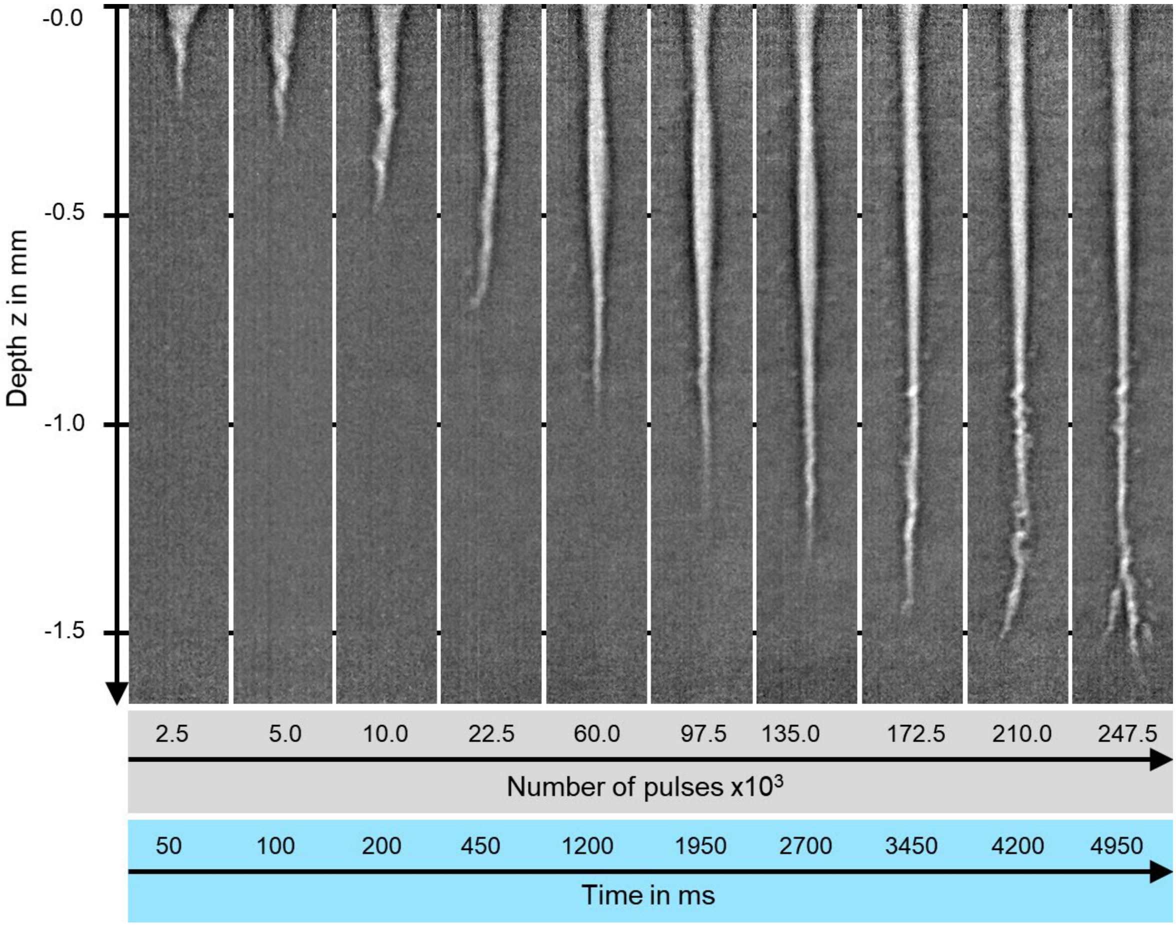

Fig. 1 X-ray image sequence of a percussion drilled microhole in stainless steel at discrete points in time.

4. Conclusion and Outlook

This study utilized high-speed X-ray imaging to capture the formation of irregularities and defects during percussion drilling with ultrashort pulses. By overcoming the limitations of previous diagnostic possibilities, these investigations present for the first time the formation of a microhole during laser drilling at high temporal and spatial resolution. The sequence of X-ray images presented in this work presents the dynamic changes of the bore hole geometry during the formation of side channels. The image sequence showed a fast initial depth progression, followed by stagnation of the depth progress and the formation of a bulge, which indicates the presence of a particle-induced plasma within the microhole. The bulge formation was followed by the formation of side channels, suggesting the fluence on the microhole walls undercut the fluence threshold. This work highlights the start of a series of studies aiming to enhance our understanding of microhole formation and the associated defects.

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