Lasers in Manufacturing Conference 2021

Fluence dependence of the edge quality of microhole exits for percussion drilling with ultrashort laser pulses

Anne Feuer[a,*], Rudolf Weber[a], Thomas Graf[a]

[a]*Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*

Abstract

For many applications, edge quality and shape accuracy of microholes are crucial. One assumption is that the fluence at the tip of the microhole during drilling is a key parameter for the quality of the microhole's exit. It was therefore investigated experimentally how the fluence affects the edge quality. The experiments were performed in 0.5 mm thick steel using a Ti: sapphire laser system operating at a wavelength of 800 nm, a pulse duration of 1 ps, and a repetition rate of 1 kHz. For the quantitative analysis of the edge quality, microscope images were evaluated using a machine learning approach. Two key figures, striations amplitude and perimeter ratio, were defined that proved to be significant in characterizing the edge quality of exits. In the current talk it will be shown that the quality of exits of percussion-drilled microholes could be significantly improved if the fluence dependence is considered.

Keywords: Micro processing; Percussion drilling; Hole quality; Image analysis

1. Introduction

The exits of percussion-drilled microholes are usually characterized by striations and are known to have deteriorated edge quality. So far, helical drilling with ultra-short pulses has proven to be very suitable for producing microholes with defined shaped exits and high edge quality (Feuer et al., 2014; Kraus et al. 2016, Kroschel et al., 2018). However, this approach requires special cost-intensive optics with a typically high adjustment effort. It is not yet fully clarified why helical drilling produces significantly better results in terms of microhole exit than percussion drilling. The fluence at the tip of the microhole is regarded as a decisive influencing variable on the quality of the microhole exit. Since the fluence reaching the far end of the hole changes with the changing geometry of hole being drilled (Holder et al., 2021) the edge quality of percussion-

* Corresponding author. Tel.: +49-711-685-67882; fax: +49-711-685-66842.
E-mail address: anne.feuer@ifsw.uni-stuttgart.de.

drilled microholes was investigated in this work as a function of the number of pulses and for different peak fluences of the incident Gaussian beam. For the quantitative evaluation of the edge quality, microscope images of the microhole exits were automatically analysed using a machine learning approach. The key figures groove size and perimeter ratio, which are as well introduced, proved to be particularly significant to characterize the edge quality.

2. Methods

2.1. Experimental Setup

The percussion drilling experiments were performed using an ultrafast Ti:Sapphire laser system (Spitfire ACE, Spectra Physics) operating at a wavelength λ of 800 nm. To minimize heat accumulation effects and melt formation, repetition rate and pulse duration of the laser pulses were set to 1 kHz and 1 ps FWHM, respectively and the beam quality factor was measured to be $M^2 = 1.3$. The circularly polarized Gaussian beam was focused by a telecentric f-theta lens with a focal length of $f = 100$ mm. The focal diameter was measured to be $d_\mathrm{f} = 36\ \mu\mathrm{m}$ ($1/e^2$ diameter). The focus was positioned 5 mm below the surface of the sample. The beam diameter on the workpiece's surface therefore was $d_\mathrm{s} = 188\ \mu\mathrm{m}$. A galvanometer scanner was used to position the laser beam on the workpiece. Pulse energy (and with it the fluence) of the incident Gaussian beam and number of pulses applied to a single drilled hole were varied in the experiments. The drilling was repeated 10 times for each parameter setting. The investigation was done in 0.5 mm thick cold-rolled stainless steel (St 1.4301 / AISI 304).

2.2. Analysis of the drilled microhole exits

The effects that lead to a reduction in the quality of the microhole's exit are manifold and the characteristics of such effects range from shape deviations, striations and burr to side channels and multiple holes. In this work, the main focus is on the extent to which fluence affects the quality of the edge of the microhole. In order to evaluate the shape of the microholes quantitatively, the edge of the microhole was determined on the basis of microscope images by automated image analysis (Feuer et al., 2021). Image information at pixel level is inhomogeneous due to roughness, scratches and impurities in the material surface and varying brightness values inside the microholes. A threshold approach to discriminate the subsets "opening of the microhole" from "material surface" turned out to be insufficient. Supervised learning was used to reliably discriminate the opening of microholes from the adjacent material. In this case, a *support-vector machine* was trained by manually classified data. Each data point for training and classification contained information of a 9x9 pixel mask. The image analysis was done with the software *Mathematica 12.1*. Fig. 1 shows the microscopic image of a microhole exit (a) and the corresponding classification into the two subsets as mentioned above (b). The hole's contour with the fitted ellipse is shown in Fig. 1(c). These data can be used to determine the amplitude of striations ξ and the perimeter ratio σ (Feuer et al., 2021), which are introduced in the following.

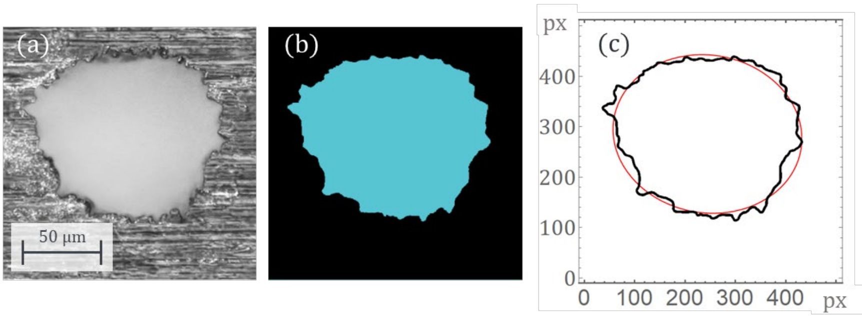

Fig. 1. (a) Microscope image of a microhole exit; (b) Classified subsets "opening of the microhole" (blue) and "material surface" (black); (c) Contour of the microhole (black line) and ellipse fitted to the edge data (red line).

Striations are defined by the deviation of the hole's contour from the fitted ellipse. The distance between the 5% and 95% quantile is used as a measure of the striations amplitude ξ. The perimeter ratio σ is defined as ratio between the length of the hole´s contour and the circumference of the fitted ellipse. The combination of ξ and σ allows to distinguish between microhole exits with good edge quality and poor edge quality.

3. Results and Discussion

The development of the edge quality of the microhole exit during the drilling process is shown in Fig. 2 for percussion-drilled microholes which were drilled with a peak fluence of 8.6 J/cm² in Gaussian beam. While Fig. 2(a) gives selected microscope images of exits for different number of applied pulses, the development of the exit radii (violet) together with the entrance radii (blue) as a function of the number of pulses is shown in Fig. 2(b). The microscope images reveal that with the parameter used, the edge quality of the microhole exit changes significantly during the drilling process. The exits formed after breakthrough and during the widening phase, show a high edge quality. The edge of the exit is even and sharp-edged and the shape is almost round. Only with increasing number of pulses, the inner wall at the microhole exit is more and more characterized by striations which shape the contour of the exit. The striations appear before the exit is fully widened. This means that the high-quality exits are reached in the widening phase, where differences of a few hundred pulses result in a difference of the exit radius of 50%.

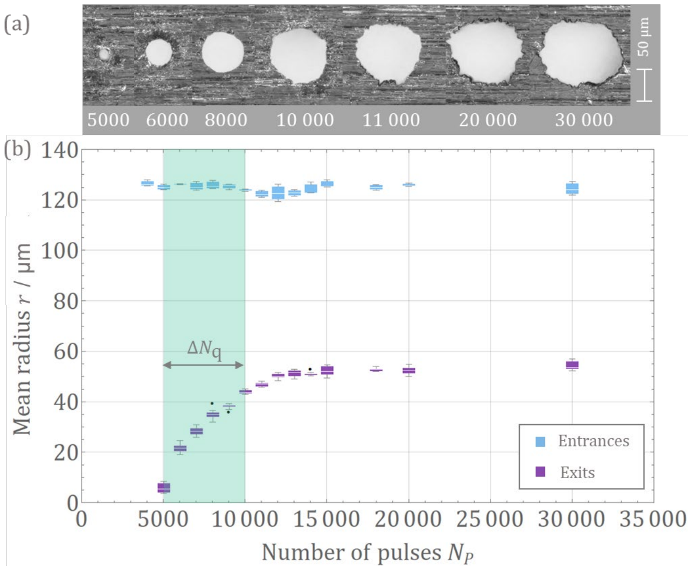

Fig. 2. Measured radii of the microhole entrances and exits using a peak fluence of 8.5 J/cm² in Gaussian beam (St 1.4301 / AISI 304, $\lambda = 800$ nm, $\tau = 1$ ps, $f_{\mathrm{R}} = 1$ kHz, $E_P = 1.2$ mJ).

The parameters ξ and σ were used to classify the exits of the microholes into two quality classes using a k-means clustering algorithm (Morissette et al., 2013). The range where the applied number of pulses leads to exits with low values of ξ and σ, producing holes with high-quality outputs, is marked in green. With the parameters used, the breakthrough was reached after about 5000 pulses. Thus, the width of the range leading to high-quality exits is $\Delta N_q = (5000 \pm 500)$ pulses after breakthrough. With a further increase in the number of pulses, a significant deterioration in the edge quality is seen (Fig 2 (a)), indicated by a significant increase in the values of ξ and σ.
The "quality range" ΔN_q was determined in the same way for the peak fluences 2.6 J/cm², 4.3 J/cm² and 6.3 J/cm². The results are shown in Fig. 3. It reveals that the quality range ΔN_q can be increased with increasing the peak fluence of the incident Gaussian beam. However, it must be considered that when the peak fluence of the Gaussian beam is increased to beyond 10 J/cm², intensity-dependent effects such as plasma formation and air breakthrough (Klimentov et al., 2001) or heat accumulation effects may occur (Kononenko et al., 2018, Weber et al., 2017), leading to altered ablation and drilling progress. Ramping up the pulse energy and dynamic focus adjustment during the drilling process are options to avoid negative effects but still achieve high fluences at the microhole exit.

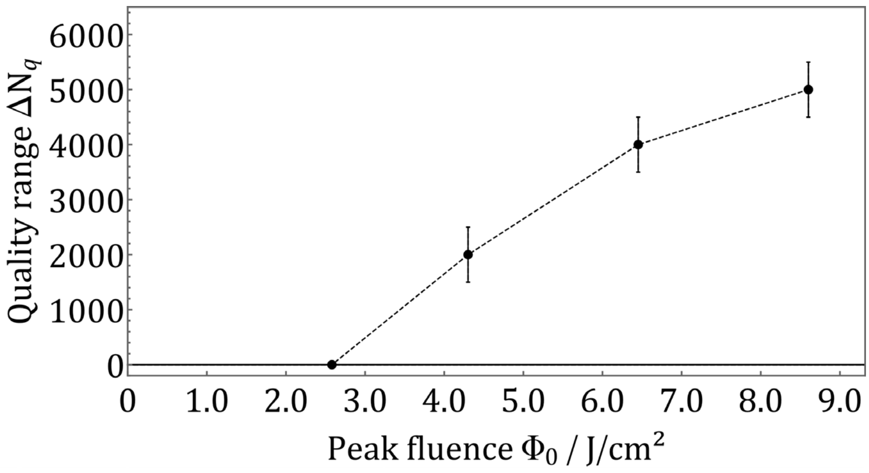

Fig. 3. Quality range ΔN_q as a function of the peak fluence Φ_0 (St 1.4301 / AISI 304, $\lambda = 800$ nm, $\tau = 1$ ps, $f_R = 1$ kHz).

4. Conclusion

In the present work the fluence and its influence on the quality of the microhole exits was investigated for percussion drilling in 0.5 mm thick stainless steel. In order to exclude as far as possible quality-reducing effects such as air breakthrough, plasmas and melt formation, the experiments were carried out at a pulse duration of 1 ps and a repetition rate of 1 kHz. The ratio of entrance diameter to drilling depth was around 1:2. The maximum peak fluence in the Gaussian beam was 8.6 J/cm².

It was shown that the edge quality of the microhole exits changes significantly during percussion drilling. In particular, it has been revealed that exits of microholes with a remarkably high quality were formed after the breakthrough. However, with increasing number of pulses the edge quality dropped due to the increased formation of striations. The width of the range ΔN_q leading to high-quality exits is (5000 ± 500) pulses after breakthrough for the maximum peak fluence of 8.6 J/cm². This means, that for a given incident fluence the range in which high-quality exits can be produced is determined not only by the fluence of the incident laser beam and the material thickness of the workpiece, but also by the number of pulses after the breakthrough. The study also reveals that the range ΔN_q in which high-quality exits are formed decreased with decreasing peak fluence in the incident Gaussian beam. Future challenges will be to achieve high fluences at the microhole exit and to actively control the number of pulses after breakthrough to ensure percussion-drilled holes with high-quality hole exits.

Acknowledgements

This work was supported by: Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag (contract number ZF4592402FH8) and funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – INST 41/1031-1 FUGG.

The author would like to thank LightPulse LASER PRECISION and FRAMA GmbH for their kind support in producing the microscope images.

References

Feuer, A., Kunz, C., Kraus, M., Onuseit, V., Weber, R., Graf, T., 2014. "Influence of laser parameters on quality of microholes and process efficiency, " In: Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XIX. SPIE LASE. San Francisco: SPIE (SPIE Proceedings), 89670H.

Feuer, A., Weber, R., Feuer, R., Graf, T., 2021. "High-quality percussion drilling with ultrashort laser pulses," to be published.

Holder, D., Weber, R., Graf, T., Onuseit, V., Brinkmeier, D., Förster, D. J., Feuer, A., 2021. "Analytical model for the depth progress of percussion drilling with ultrashort laser pulses, " In: Appl Phys A 127 (5). DOI: 10.1007/s00339-021-04455-3

Klimentov, S. M., Kononenko, T. V., Pivovarov, P. A., Garnov, S. V., Konov, V. I., Prokhorov, A. M. et al.,2001. "The role of plasma in ablation of materials by ultrashort laser pulses," In: *Quantum Electron.* 31 (5), S. 378–382. DOI: 10.1070/QE2001v031n05ABEH001958.

Kononenko, T. V.; Freitag, C., Sovyk, D. N., Lukhter, A. B., Skvortsov, K. V., Konov, V. I., 2018. "Influence of pulse repetition rate on percussion drilling of Ti-based alloy by picosecond laser pulses, " In: Optics and Lasers in Engineering 103, S. 65–70. DOI: 10.1016/j.optlaseng.2017.12.003.

Kraus, M., Walter, D., Michalowski, A., König, J.,2016. "Processing Techniques and System Technology for Precise and Productive Microdrilling in Metals,". In: Ultrashort Pulse Laser Technology. Laser Sources and Applications, Bd. 195. 1st ed. 2016. Cham, Heidelberg, New York, Dordrecht, London: Springer (Springer Series in Optical Sciences, 195), S. 201–230.

Kroschel, A., Michalowski, A., Bauer, F., Graf, T., 2018. "Calculating the Borehole Geometry Produced by Helical Drilling with Ultrashort Laser Pulses, " In: JLMN. DOI: 10.2961/jlmn.2018.03.0020.

Morissette, L., Chartier, S., 2013. "The k-means clustering technique: General considerations and implementation in Mathematica," In: TQMP 9 (1), S. 15–24. DOI: 10.20982/tqmp.09.1.p015.

Weber, R., Graf, T., Freitag, C., Feuer, A., Kononenko, T., Konov, V. I., 2017. "Processing constraints resulting from heat accumulation during pulsed and repetitive laser materials processing, " In: Optics express 25 (4), S. 3966–3979. DOI: 10.1364/OE.25.003966