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Picosecond-laser drilling limits for deep precision microholes in tool steel

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Abstract

A novel approach using liquid CO_2 for lubrication during the deep-drawing process requires conical microholes with smallest diameters < 100 µm in > 6.7 mm thick tool steel. Ultrashort laser pulses are a very promising tool for drilling of such deep, precision microholes. The capability of Femto- and Picosecond lasers for drilling microholes in virtually any material is state of the art for holes with a depth of up to about 2 mm. However, to extend the depth it is crucial to know the drilling limits with respect to depth. Furthermore, a significant part of each laser pulse is converted to heat, which remains in the material. This heat is accumulated from pulse to pulse depending on the process parameters. If the resulting temperature increase exceeds the melting temperature the hole quality is significantly reduced, which is another important limit for laser drilling.
To determine the above-mentioned limits, we used near infrared laser pulses with a pulse duration of 10 ps to drill through holes in tool steel samples up to a thickness of 8 mm. We will present the limits of ps-laser drilling regarding the maximum achieved depth for a given pulse energy in the range from 250 µJ to 2 mJ and repetition rates in the range of 15 kHz to 300 kHz. Furthermore, forming tools were successfully drilled and used for CO_2-lubricated deep drawn steel sheets.

Keywords: laser deep drilling; heat accumulation; high energy picosecond laser pulse; CO_2 lubrication.

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1. Motivation

Alternative lubrication media recently raised attention of sheet metal forming industries (Vollersten et al., 2014). Environmental considerations encourage these industries to substitute oil-based lubrications. Recently it has been demonstrated that liquid gas, i.e. liquid CO_2 or N_2 can reduce the friction coefficient between the metal surfaces effectively and could be an appropriate candidate for reducing the friction (Wörz et al., 2016). Due to rapid evaporation of these media in atmospheric pressure, no post cleaning of the produced part is needed; the produced parts can directly undergo painting or coating processes.

However, delivery of the fluid to the contact area is still a challenge which has to be solved. Microholes with the suitable geometries in the forming tool would allow to inject the liquid gas in the area where the material need to be flown plastically and suffers high forming forces and temperatures. It has recently been reported that microholes with a diffusor geometry (inlet of 200 µm and outlet of 600 µm) cause the formation of CO_2 snow at the outlet resulting in a further decrease of the friction (Umlauf at al., 2016). As the forming force is usually large, the forming tool should be very rigid, therefore they are made of thick and massive hardened steel making the drilling of microholes very challenging.

The laser is a promising tool to drill microholes with a defined geometry into the forming tool. Using femto- and picosecond laser pulses the material is mostly removed by direct sublimation. However, a part of each laser pulse is converted to heat, which remains in the material. This heat is accumulated from pulse to pulse depending on the process parameters. If the resulting temperature increase exceeds the melting temperature of the material the hole quality is significantly reduced which is an important limit for laser drilling as it is reported in (Weber et al., 2014). Furthermore, heat accumulation might lead to cracks in sensitive workpieces such as hardened steel.

During laser drilling with ultrashort laser pulses, each pulse (which usually has a spatially Gaussian distribution) ablates a specific volume depending mainly on the temperature of the irradiated point (Niso et al., 2014) and the peak fluence (Neuenschwander et al., 2012). For steel, the ablation depths can range up to 250 nm per pulse (Finger et al., 2014). The first pulse usually hits a flat surface. As a capillary is formed, succeeding laser pulses hit on an increasing surface with increasing depth of the capillary. The increasing area leads to decreasing effective fluence on the wall surface. At some point during the drilling process the effective fluence drops below the ablation threshold. In this situation the drilling process stops and the absorbed energy does not contribute to the drilling progress anymore. As an example, Fig 1. shows the cross sections of microholes for an increasing number of pulses.

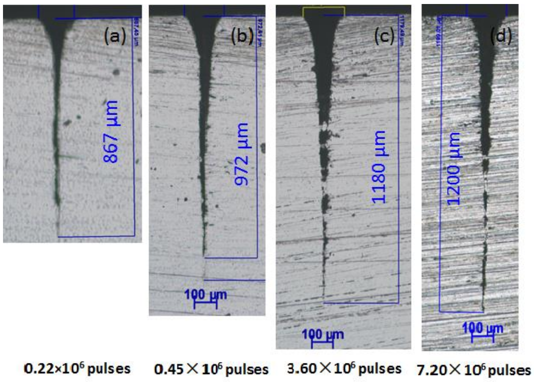

Fig. 1. The cross section of the microholes drilled with the pulse energy of 250 µJ and repetition rate of 15 kHz. 0.22×10^6 pulses (a), 0.45×10^6 pulses (b), 3.60×10^6 pulses (c), 7.20×10^6 pulses (d). The drilling depth did not significantly increase after(c).

The holes were drilled with picosecond pulses at a fluence of 4.6 J/cm² with a repetition rate of 15 kHz. After shooting 3.6×10^6 pulses, the ablation has stopped and the drilling with this pulse energy has reached its limit. The limit of drilling depth in any given pulse energy has also reported by (Döring et. al., 2012).

However, drilling in the forming tool required to reach a depth of 6.7 mm. Therefore high pulse energies are required for drilling of deep holes in order keep the fluence inside the capillary higher than the ablation threshold.

In this report, we present the limits of *repetition rate* and *pulse energy* as two critical parameters which determine the heat accumulation and maximum drilling depth, respectively. Each limit, will be compared with a simple analytical model that can be used for estimating of required parameters for any similar drilling process.

2. Laser system

For this study we used the IFSW prototype kW-class picosecond laser source (Negel et al., 2015) for the experiments. The experimental laser parameters used are summarized in Table 1.

Table 1. Properties of the IFSW-Laser.

Parameter	value	unit
Pulse duration	8	ps
Wavelength	1030	nm
Max. pulse energy	2.5	mJ
Max. pulse repetition rate	300	kHz
Polarization state	Circular	-
Beam propagation factor	1.3	-

A plano-convex lens with a focal length of f = 300 mm was used to focus the collimated beam (d_L = 5.2 mm {1/e²}) on the surface of the sample to a focus diameter of 100 µm. The substrate of the lens is made from fused silica with antireflective coating for the above mentioned wavelength. The drillings were performed on samples made from tool steel 1.2379 (D2 steel) in different thicknesses ranging from 5 mm to 8 mm.

3. Limits and Results

The inlets of the microholes were analysed by means of an optical microscope without any post cleaning. Afterward, cross sections of the samples were made to measure the depth of drilling. By polishing and etching of the cross sections of the microholes, the size of heat affected zone became visible.

3.1. The heat accumulation limit

The study was performed with a pulse energy of 1.3 mJ. This resulted in an average fluence of 17.3 J/cm² in the focal plane of the lens. For different repetition rates varying from 30 kHz to 300 kHz an equal number of pulses of 2.25 $\times10^5$ was applied. The radius of the tempered area around the inlet of the holes was measured, as shown in Fig. 2. The blue color in the tempered area can be used as a sign for a temperature increase up to about 570 K and the brown for about 520 K. For the hole entrance shown in Fig. 2 (a), a repetition rate of 30 kHz was used; there is no blue tempered color visible. As the repetition rate was increased to 60 kHz (Fig 2 (b)), a slight brown color generated at a radius of approximately 1050 µm. Finally at the repetition rate of 300 kHz, the blue tempered color extends to the radius of 3 mm and also the molten material near the inlet was formed as a result of the high temperature increase. It should be mentioned that the black area surrounding all of the holes is due to deposition of sublimated material on the surface. With these results it can be estimated that below about 60 kHz no heat accumulation effects should influence the process.

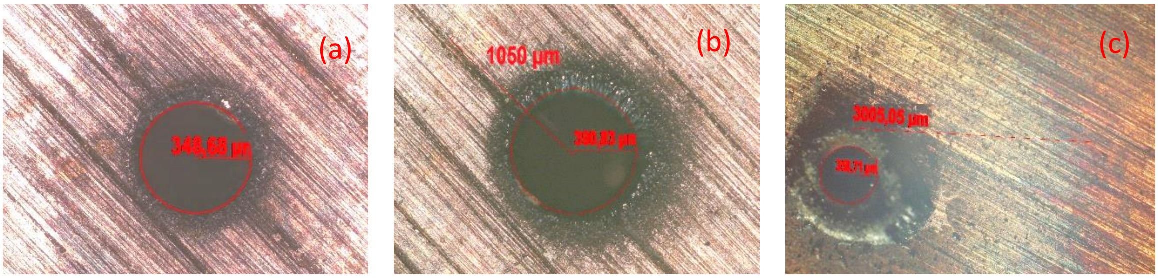

Fig. 2. Entrance of laser generated microholes with a pulse energy of 1.3 mJ and an equal number of 2.25 $\times 10^5$ pulses. Repetition rate: 30 kHz (a), 60 kHz (b) and 300 kHz (c). The blue tempered color (c) indicate a temperature increase up to 570 K: for a repetition rate of 60 kHz, tempered color just appeared as a consequence of heat accumulation.

In Fig 3 (a) cross sections of the microholes are shown which were used to study the limits of heat accumulation in the depth of the microholes. The microholes were drilled with the repetition rates of 60 kHz (left) and 100 kHz (right). While there is not any significant phase transition around the microholes which drilled with 60 kHz, the diameter of almost 1 mm has affected by the heat accumulation in the microhole that drilled with 100 kHz. It appears as orange coloured region after etching. This confirms, that the results shown in Fig. 2 also apply inside the material.

Fig. 3. The effect of heat accumulation on drilling with a pulse energy of 2 mJ and a repetition rate of 60 kHz (left hole) and 100 kHz (right hole). The orange colour indicates the heat affected zone which is revealed after etching of the cross section.

3.2. The drilling depth limit

If the capillary is assumed as a cone, and the hole is deeper than its diameter (i.e. the pulse energy E_P is completely absorbed), the diameter is about the focal spot diameter d_f, the average fluence on the wall is can be approximated by

$$\Phi_{av} \approx \frac{4 \cdot E_P}{\pi \cdot d_f \left(d_f + 2 \cdot \pi \cdot s_{Hole}\right)} \overset{\left(\pi \cdot d_f \cdot s_{Hole} \gg d_f\right)}{\approx} \frac{2 \cdot E_P}{\pi \cdot d_f \cdot s_{Hole}} . \qquad (1)$$

where s_{Hole} the actual depth of the microhole. As the drilling process stops, when $\Phi_{av} \approx \Phi_{th}$, i.e. the ablation threshold, the maximum hole depth can be estimated with

$$s_{Hole,max} \approx \frac{2 \cdot E_p}{\pi \cdot d_f \cdot \Phi_{th}} \qquad (2)$$

With d_f = 100 µm and ablation threshold to 0.1 J/cm² the depth of 8.3 mm can be drilled with the pulse energy of 1.3 mJ. This simple model predicts that the drilling depth of 1.6 mm can achieve with a pulse energy of 250 µJ and the same focal point diameter which is in good agreement with the results shown in Fig. 1 and Fig 4(a).

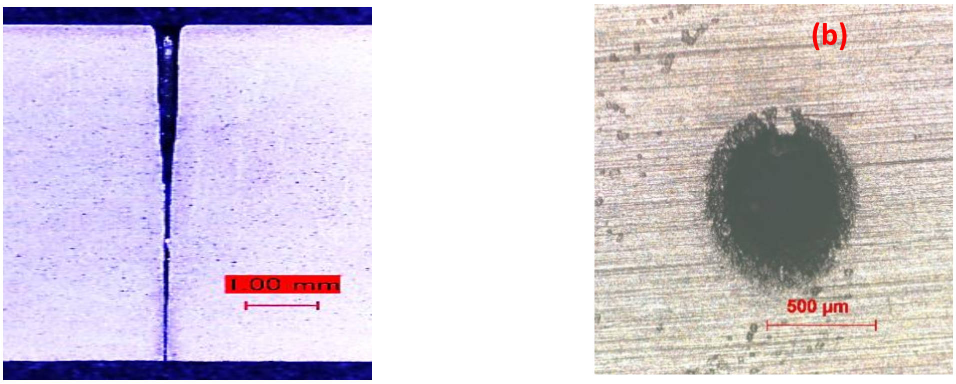

Fig. 4. The drilling depths of 8.0 mm achieved with the pulse energies of 1.3 mJ in the repetition rate of f_R =30 kHz (a), the inlet quality (b). No phase transition is observed in the depth and on the surface.

4. Conclusion

Based on the estimations described above for the temperature increase and the maximum drilling depth, 132 microholes of a depth of 6.7 mm were successfully drilled in the forming tool of hardened steel with a pulse energy of 1.3 mJ and a repetition rate of 30 kHz. In total 44 seconds were needed for each single hole to drill through. The injection of CO_2 stream from the embedded channels into the surface through the microholes is shown in Fig 5.

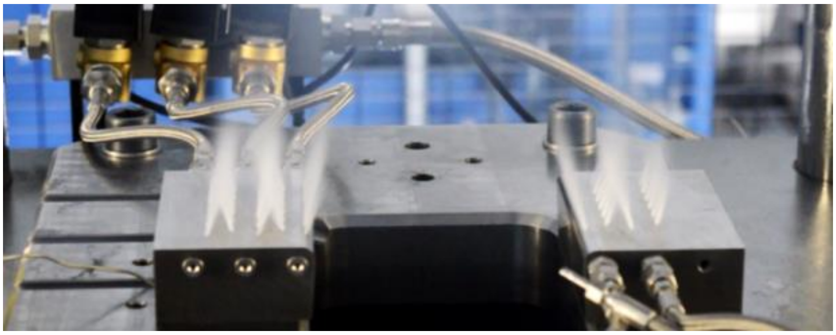

Fig. 5. The fountain of CO_2 stream from the forming tool which has been drilled through 6.7 mm.

Acknowledgements

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