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High-speed process observation of pulsed laser drilling in non-transparent materials

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Abstract

In previous studies dielectric or semi-conducting materials like silicon were used to get an insight into the pulsed laser drilling process. The process was analyzed at a wavelength at which the material is transparent. This method was very successful providing time-resolved information about the drilling progress or the formation of side-channels. However, at the moment there is no diagnostics available which allows time- and space-resolved observation of the drilling process in metals and other non-transparent materials.
Within this study a method which allows to observe the pulsed laser drilling process when drilling in non-transparent materials is introduced. A glass plate is put in front of a sample. The laser is focused from top into the interface of these two pieces to process both, the sample and the glass plate. The drilling process is observed through the glass plate using a high-speed camera. With this setup it was possible to observe the drilling process in steel and to investigate the drilling progress. The formation of a side channel was observed during drilling of a ceramic sample.

Keywords: micro processing; laser drilling; process observation; non-transparent materials

1. Introduction

Pulsed laser drilling with pulse durations in the range of nanoseconds or even pico- and femtoseconds is a convenient tool for the production of small holes in different materials. Different studies show how to produce the holes fast and with a good quality. Ancona et al., 2008 used a femtosecond fiber laser to drill

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samples out of steel with a thickness up to 1 mm in less than 10 ms when using a repetition rate of 975 kHz and a pulse energy of 70 µJ. Kamlage et al., 2003 showed experiments with a very high quality of the drilled holes. They used a femtosecond laser at 1 kHz repetition rate with a pulse energy of 0.9 mJ to produce 1 mm deep holes. Döring et al., 2012 showed results for the evolution of the hole shape and size with femtosecond, picosecond and nanosecond laser pulses when drilling a silicon wafer. The maximum hole depth of nearly 2 mm was reached with the nanosecond pulses at a repetition rate of 200 Hz. The depth of the holes which were typically produced was in the range of one or two millimeters.

However, when it is necessary to drill holes with a depth in the range of 3 mm to 6 mm, for example for the production of spinning nozzles which have to withstand a pressure of up to 200 bar, different issues, like melt or burr might occur. Other problems encountered are a reduced repeatability of the hole shape or the roundness of the holes exit, and an increased drilling time until completion of the hole. One method to investigate the deep hole drilling process is direct process observation with a high temporal and spatial resolution.

Using transparent materials like glass or diamond the drilling process can be directly observed. This has been done in Kononenko et al., 2001 using diamond. However, transparent materials show a different absorption behavior than metals. Using ceramics, like silicon carbide or silicon nitride, is also possible to get an insight into the drilling process if the thickness of the ceramic sample is in a range in which the semi-transparent behavior of the ceramic can be used. Abeln, 1996 observed the drilling process using a 200 µm thick silicon nitride ceramic (Si_3N_4) while drilling with a laser in the IR-regime and illuminate with a cold light source. Döring et al., 2010 used silicon carbide (SiC) with a thickness of 500 µm and an illumination laser with a wavelength of 1060 nm at which SiC has a bandgap and acts semi-transparent which allows it to observe the drilling process.

Dietrich et al., 2008 investigated a method to observe the drilling speed in non-transparent materials like steel . They were drilling near the edge of the material and were able to observe the deformation of the material which occurs when the material is processed. However, a direct observation of the drilling process of non-transparent materials or thick ceramics is not possible using the methods mentioned above.

In this paper we describe a method with which it is possible to directly observe the drilling process of non-transparent materials with a high temporal and spatial resolution. This method provides a direct insight into the drilling process itself. It is possible to observe the material removal as well as the effects which occur inside the hole and affect the laser drilling process which could lead to the formation of side channels.

2. Experimental Setup

A CAD-drawing of the experimental setup is shown in Fig. 1. A fused silica glass plate is placed in front of the sample and the sample is pressed against the glass plate by three screws. The laser is focused into the interface of the glass plate and the sample from top to process both materials, the glass plate and the sample. This allows to observe the drilling process in the metal with a high-speed camera through the glass plate. For illumination of the process zone an illumination laser with a wavelength of 808 nm is used (not shown in the figure). The illumination laser is guided onto the sample via a copper plate (not shown in the figure) to get diffuse illumination. To avoid an overexposure of the camera a bandgap filter for the wavelength of the illumination laser is used within the objective of the high-speed camera. The focal position of the laser was on the top of the samples surface and placed half onto the sample and half into the glass plate.

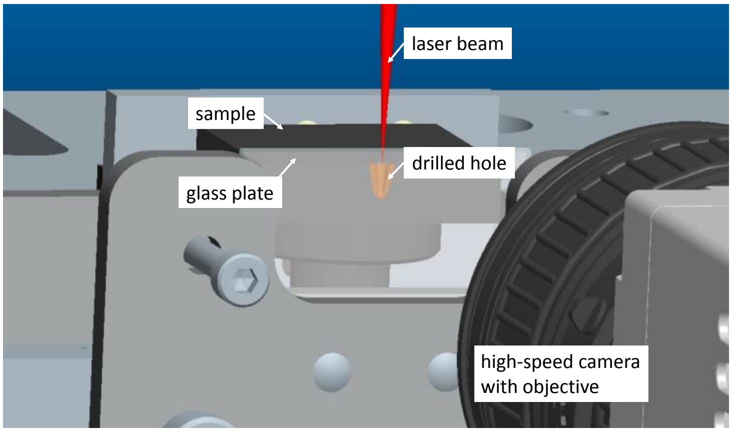

Fig. 1. CAD-drawing of the experimental setup for drilling behind glass. The sample is pressed against the glass plate and the laser beam is focused into the interface of the glass plate and the sample. The drilling process can be observed with the high-speed camera.

3. Observation of the drilling progress

3.1. Drilling progress in stainless steel

Fig. 2 shows six frames of the first 238 ms of the drilling process in a stainless steel sample (1.4301) which were recorded with a framerate of 28000 fps. The dark bar in the pictures is caused by the chamfer of the glass plate. Because of the chamfer the glass plate is placed a little bit higher than the surface of the sample to guarantee an observation of the beginning of the drilling process. The side of the sample, which is pressed against the glass plate, was milled to guarantee a plane surface. For the drilling process a laser with a wavelength of 1047 nm, a pulse energy of 4 mJ at a repetition rate of 4 kHz with a pulse duration of 22 ns was used. The processing time was 1.4 s and the final depth of the hole was 1.92 mm. Within the first 191 ms (Fig. 2a) to Fig. 2e)) one can see a fast increase of the drilling depth. After 191 ms the hole has already reached a depth of 1.2 mm, see Fig. 2e). For processing times larger than 191 ms the drilling depth does not increase as fast as before which can be seen by comparing Fig. 2e) and Fig. 2f). The increase of the drilling depth between the drillings shown in Fig. 2e) and Fig. 2f) is in the range of 0.1 mm whereas it was about 0.3 mm between the drillings shown in Fig. 2a) to Fig. 2e).

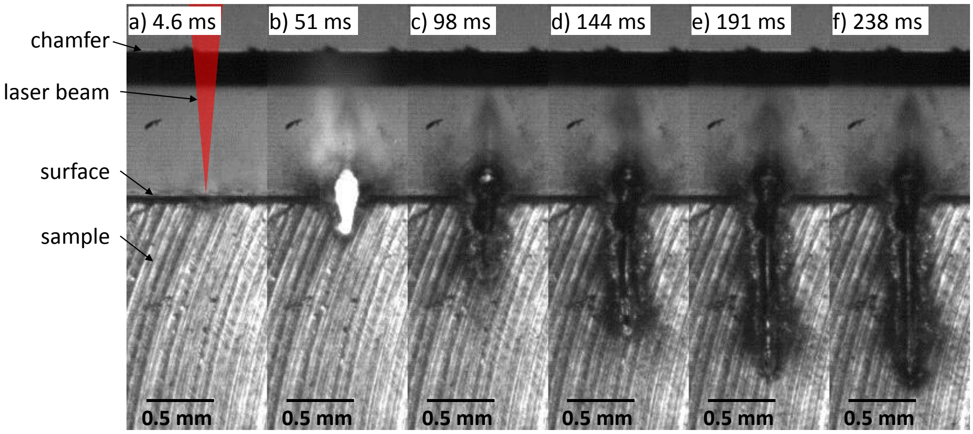

Fig. 2. Six frames of the first 238 ms of the drilling process with a repetition rate of 4 kHz, a pulse energy of 4 mJ and a pulse duration of 22 ns with a wavelength of the laser of 1047 nm. The whole drilling process lasted 1.4 s. The frame rate of the camera was set to 28000 fps.

This can be clearly seen in Fig. 3 in which the drilling depth (blue curve) is shown as a function of the drilling time. The red curve shows the derivation of the drilling depth, i.e. the actual drilling speed as function of the drilling time. A moving average of three values was used for each data point of the drilling speed curve. In the first 0.005 s of the drilling process a depth of 0.07 mm is reached. The drilling speed ranges in a nearly value of about 4 mm/s to 5 mm/s until a drilling time of 0.025 s and a drilled depth of 0.14 mm. After that the drilling speed increases to a value of about 10 mm/s followed by short period of drillings speed 0 mm/s at a drilling depth of 0.26 mm. 0.014 s later the drilling speed increases to more than 10 mm/s and does not fall below this value for the next 0.06 s. During this time the drilling depth increases from 0.26 mm to 1.06 mm. After this there is again a significant decrease of the drilling speed and the drilling progress stops again after 0.18 s at a drilling depth of 1.27 mm. Until a drilling time of 0.4 s one can see a slight increase of the drilling speed to a value of about 5 mm/s to a drilling depth of 1.48 mm. In the remaining drilling time of 1 s the drilling speed decreases slowly to a value below 1 mm/s. The final depth of the hole after 1.4 s of drilling is 1.92 mm.

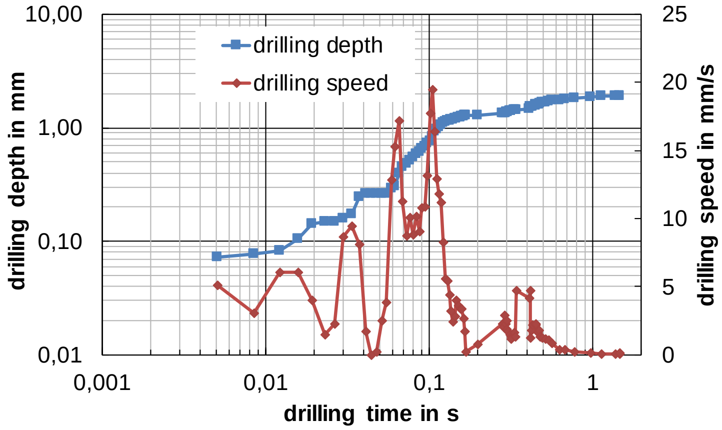

Fig. 3. Increase of the drilling depth and the derivation of the drilling depth per drilling time, dz/dt, as a function of the drilling time. The used laser had a wavelength of 1047 nm with a pulse energy of 4 mJ at a repetition rate of 4 kHz and a pulse duration of 22 ns.

3.2. *Formation of side channels in Si_3N_4*

Fig. 4a) to Fig. 4e) show the formation of a side channel during the drilling of a Si3N4 sample with a thickness of 4 mm. The total processing time was set to 5.3 s and the frame rate of the high-speed recording was set to 6000 fps. The used laser system had a wavelength of 1030 nm, a pulse energy of 250 µJ at a repetition rate of 300 kHz and a pulse duration of 8 ps. The five frames show the lower part of the sample which means Fig. 4a) shows the drilled hole after a drilling time of 4.6 s where the hole has reached a depth of 2.86 mm. Until this depth the formation of the hole was straight and no bending could be seen but at this depth of the hole the formation of a side channel inside the hole starts. The side channel has an angle of 12 degree and moves to the left side of the picture, see Fig. 4b). After 0.14 s it doesn´t move on to the left but gets broader and a little bit deeper with the ongoing drilling process, compare the red marks to the contour of the hole in Fig. 4c). This expansion of the side channel goes on, Fig. 4d), until the formation of the hole continues straight forward as expected before the forming of the side channel started, see Fig. 4e). The total time from the formation of the side channel until the drilling process goes on as expected lasted 0.42 s. After a total drilling time of 5.3 s the laser is turned off and the hole has reaches a final depth of 3.42 mm.

Döring, 2011 mentioned that the formation of side channels could be caused by internal reflections of the beam or particles and plasma inside the hole. Another possible solution may be that the effective fluence is below the threshold fluence as reported by Döring et al., 2012. This is in good agreement with studies which showed an effect of the effective fluence onto the formation of side channels, see Filiz, 2014, Haspel, 2014 and Welther, 2016. However, the reasons for the formation of side channels are not clear yet and will be part of further investigation with the presented method of drilling behind glass.

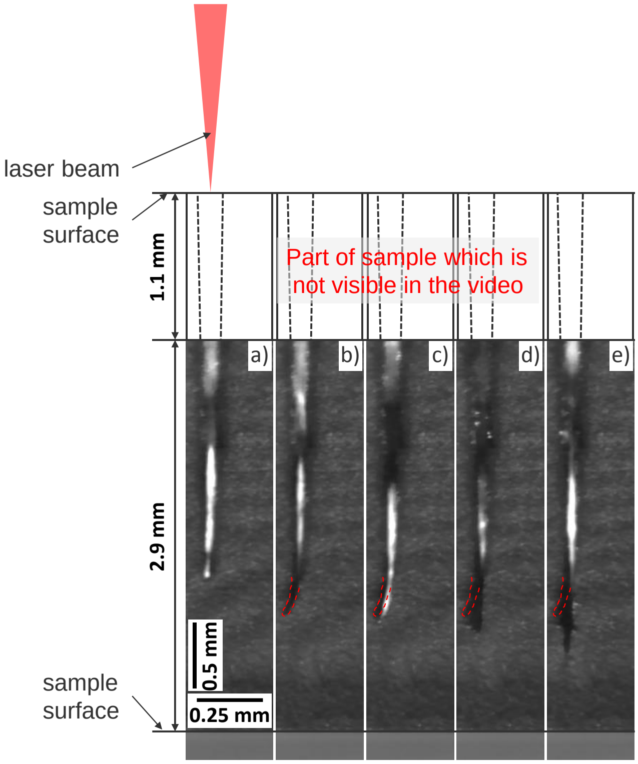

Fig. 4: Five frames of a high-speed video which show the formation of a side channel. In a) the formation of the side channel begins after a drilling depth of 2.86 mm. The whole formation lasts for 0.42 s. d) shows the end contour of the formed side channel and in e) one can see the end contour of the drilled hole after a total drilling time of 5.3 s. The used laser parameters were a repetition rate of 300 kHz, a pulse energy of 250 µJ and a pulse duration of 8 ps with a wavelength of 1030 nm.

4. Conclusion and outlook

With the novel method of drilling behind glass it was possible to get an insight into the pulsed laser drilling of non-transparent materials with a high temporal and spatial resolution. A high-speed camera was used to observe the drilling process and to examine different effects inside the drilled hole. First tests have been done with this setup to observe the drilling process. The formation of a side channel could be observed. The formation of the hole was observed and the drilling speed was measured.

Further work has to be done to determine the effect of the glass plate onto the drilling process and to investigate the formation of side channels. The effect of melt caused by heat accumulation, process gas, plasma, particles and removed material inside the hole onto the drilling process will be investigated with this new method.

Acknowledgements

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