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Hole formation process in ultrashort pulse laser percussion drilling

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Abstract

We performed an in-situ analysis of the percussion drilling process with ultrashort laser pulses in silicon, which acts as a model system for drilling opaque materials like metals. The investigations are focused on three parts: (1) the role of redeposition of ablation particles inside the hole which can be reduced by reduction of the ambient pressure and results in an increased achievable depth, (2) the influence of the repetition rate to analyze the heat accumulation effect, which increases the achievable depth despite a possible particle shielding, and (3) the effect and evolution of the laser generated plasma.

Keywords: laser drilling; ultrashort pulse laser; in-situ imaging; plasma evolution; debris; high repetition rate

1. Introduction

Ultrashort laser pulses emerge as an advanced tool for materials processing that offers additional advantages to laser micromachining. These features include special ablation characteristics, like a nearly direct solid-to-vapor transition and a negligible thermal effect on the surroundings of the ablation spot, see Breitling et al., 2004. Consequently, they offer the possibility to generate high quality micro-sized structures with limited melt- and burr-formation and high precision in their dimensions. Among the current industrial applications are the selective removal of surface layers, see for example the ablation of transparent conductive
oxides in solar cell production, see e.g. Booth, 2010, as well as surface engraving of cylinders for print applications, see Bruening et al., 2011, or even finishing of automotive engine parts like injection nozzles for enhanced efficiency, see König and Bauer, 2011. Nevertheless, most common applications rely only on shallow structures with small aspect ratios. The generation of deep structures with high aspect ratio, like drillings, has proven to be much more challenging in maintaining the quality since additional effects are encountered. These are for example the decrease of ablation rate until the complete drilling stop although further pulses are applied as well as changes in the cross section of the hole, depending on the hole formation process in combination with the beam properties and polarization.

Recent investigations of the percussion drilling process with picosecond pulses take advantage of the special optical properties of silicon as sample material to follow the hole shape evolution in-situ during the drilling process, see Döring et al., 2010. This material is opaque and shows an ablation behavior similar to a metal when irradiated by radiation below the band edge, see Coyne et al., 2003. At the same time, the material is transparent for radiation above the band edge, which enables a direct imaging of the hole shape without the need for a cut-and-polish process or other postprocessing. Three distinct process phases have been observed by Döring et al., 2011. At the beginning of the drilling, i.e. the first 100 to 200 pulses, a capillary with tapered sidewalls and hemispherical tip is excavated, which is ideal for the incident Gaussian beam profile. In the following, drilling continues at a significantly lower average rate. Additional effects, which only occur for high aspect ratio structures, set in during this phase. There is for example a significant ablation in transverse direction, which leads to the formation of indents and bulges or even additional branches along the sidewalls. These imperfections of the hole shape occur especially during intermediate periods of constant depth, i.e. without further forward drilling. Nevertheless, forward drilling can resume after such periods. Furthermore, the drilling direction is no longer determined solely by the incident beam but also by the pulse propagation inside the hole capillary and may lead to a bending of the hole in the lower part. The occurrence (position, size, direction and so on) of these imperfections varies to a great extent when the drilling procedure is repeated. This second phase of the drilling process can last for several thousand or ten thousand pulses, depending on the applied pulse energy. Eventually, forward drilling will come to an end, but ablation of the sidewalls can still persist in a third process phase and expand the diameter of the hole, especially in the upper part. Fig. 1(a) shows an example for the final shape of a typical hole (black) and variations of 10 holes (blue).

![Fig. 1](image.png)

Fig. 1. (a) A typical laser drilled hole (black) and variations of 10 holes (blue); Possible reasons for sideward-directed ablation: (b) deflection on the sidewalls; (c-d) scattering at ablation particles, (e) abrasive effect of ablation products and plasma.
In this study, we present a systematic investigation of the influence of each (individual) effect on the drilling behavior. Therefore, the process conditions are chosen carefully to enable a separation of the possible reasons as good as possible. At first, we conduct studies of the drilling behavior at a low repetition rate (50 Hz to 200 Hz). Due to the large temporal spacing between the pulses, interaction of subsequent pulses with ablation products propagating through the hole is negligible and particle deposition is expected to be dominant. Controlling the ambient pressure can influence this particle deposition by increasing the mean free path between collisions of ablation particles and molecules of the ambient gas for reduced pressure, but also reducing aggregations of particles as well as the density of the debris, especially in case of silicon as sample material, see Matsumura et al., 2005. In a second step, we increase the pulse repetition rate. Beside a significant interaction of subsequent pulses with ablation particles, which may result in a change of the hole shape formation, a particle shielding and also a heat accumulation effect may occur as already reported for the drilling of metals, see Ancona et al., 2008 and Ancona et al., 2009. In a third study, the plasma expansion and propagation is examined to identify its role as a secondary drilling source, as described by Klimentov et al., 2001 and Breitling et al., 2003.

2. Experimental setup

Fig. 2 shows the principal scheme of the in-situ imaging setup used for the investigations.

Crystalline silicon is used as sample due to its behavior as an opaque material at a wavelength below ca. 1060 nm and transparent properties for larger wavelengths. A picosecond laser system at 1030 nm wavelength (Trumpf, TruMicro 5050) is used for all micromachining experiments, offering a maximum pulse energy of 125 μJ and a pulse repetition rate up to 400 kHz. Its laser beam is converted to circular polarization by a quarter wave plate to average out polarization dependent effects. Percussion drilling is performed by focusing the beam to the sample surface using a meniscus-shaped lens with a focal length of 100 mm, which results in a spot size of approximately 30 μm, a typical configuration for micromachining applications. A second laser system at a wavelength of 1060 nm is then used to illuminate the sample and project the silhouette of the
emerging hole onto a CCD camera. A telescope setup is used to achieve a homogeneous illumination. The hole shape image is separated from the luminescence of the expanding plasma, which spans the complete visual spectral region, by a dichroic beam splitter. An iCCD camera (Stanford Computer Optics, 4 Picos) detects the plasma signal. This camera type intensifies the image and therefore allows detection of weak light sources. Simultaneously, gating of the image intensifier enables high temporal resolution with a minimum exposure time of 200 ps. The sample itself can be placed inside a vacuum chamber, allowing control of the ambient pressure from 1,000 mbar down to $10^{-2}$ mbar. The mean free path of molecules in air, which can be estimated to approximately 95 nm at 1,000 mbar, is inversely proportional to the ambient pressure and hence rises to 9.5 mm at $10^{-2}$ mbar, which would even exceed the expected hole depth of several hundred micrometer to one millimeter.

3. Experimental results

3.1. Influence of the ambient pressure

We observe a very similar principal drilling behavior under all pressure conditions. After a continuous increase in depth during the first 100 to 200 pulses (initial phase), the second phase shows the typical stepwise evolution of the hole depth with intermediate periods of constant depth followed by further drilling in forward direction, see examples with typical depth evolution in Fig. 3 (a). During those intermediate periods, ablation can occur predominantly in transverse direction and form indents and bulges along the sidewalls. In addition, bending or curvature of the hole is present under all pressure conditions. Fig. 3 (b) shows examples of typical hole shapes after 10,000 pulses for different ambient pressure at a pulse energy of 125 $\mu$J.

![Fig. 3. Different conditions of ambient pressure show a similar principal behavior of depth evolution (a). Bending of the hole and formation of bulges is observable after 10,000 pulses for all pressure conditions.](image)

Note the smaller entrance diameter of the hole for drilling under reduced pressure due to less nonlinear interaction of the laser pulses with the ambient gas, as also described by Breitling et al, 2004. In addition, Fig. 3 shows that branching in the lower part is more dominant under medium vacuum conditions while the upper part of the hole is less affected by indent formation.
While forward drilling already stops after some thousand pulses for atmospheric conditions, the process of depth increase continues for a significantly higher number of pulses at reduced pressure, especially for $10^{-2}$ mbar, as illustrated in Fig. 4 (a). Remarkably, in this case it is two orders of magnitude larger (ca. 800,000 pulses) compared to 1,000 mbar (ca. 8,000 pulses). With increasing number of applied pulses, the intermediate periods of constant depth become much longer and alternate with comparably short periods of depth increase. With the increasing number of pulses that contribute to forward drilling, the finally achieved depth also increases and reaches ca. 1,200 $\mu$m at $10^{-2}$ mbar compared to ca. 515 $\mu$m at 1,000 mbar. However, the region of the hole with extended depth shows a dominant branching as shown in Fig. 4 (b), whose beginning is already visible after 10,000 pulses in Fig. 3 (b). The effect is also observable at the lower part of the hole for a pressure of 1 mbar in Fig. 4 (b).

In addition, we studied the particle deposition within the hole capillary by breaking the brittle silicon sample apart after drilling and imaging the cross section by scanning electron microscopy (SEM). In contrast to cutting and polishing the sample, this simple technique does not alter the amount and distribution of ablation particles. SEM images of the hole cross sections after 10,000 pulses in Fig. 5 show a significant difference in particle deposition inside the holes. At atmospheric pressure, many of the particles generated by the laser ablation do not leave the hole but form large aggregations at the hole entrance and in the middle of the hole. Especially in the middle part of the hole, these aggregations obstruct a good portion of the hole capillary. There is also debris visible at the tip of the hole, even though with less density. In contrast, at $10^{-2}$ mbar the middle and lower part of the hole is clean and does not show any debris. Nevertheless, particle agglomerations are already present at the hole entrance. For further drilling, it can be assumed that debris will also occur in the middle and lower part of the hole with the thin capillary, but this will take a higher number of pulses. Therefore, the depth increase of the hole can also continue for a higher number of pulses at reduced pressure as shown in Fig. 4. Although the amount and distribution of debris differs largely for the two holes.
shown in Fig. 5, the SEM images reveal a similar bulging and bending of the holes comparable to the in-situ observations.

![SEM images showing bulging and bending of holes](image)

Fig. 5. After 10,000 pulses, particle depositions fill the capillary of the hole drilled at atmospheric pressure (1,000 mbar), while for drilling under vacuum ($10^{-2}$ mbar), the middle and lower part of the hole is still debris-free.

In summary, we conclude from these observations, that particle depositions only marginally contribute to ablation in transverse direction, since this is observed in a similar manner even for a clean, debris-free capillary under vacuum conditions. On the other hand, they can eventually lead to an obstruction of the pulse propagation. Therefore, we attribute them to be mainly responsible for the stop of the drilling process, once the upper and middle part of the hole is filled with debris, that scatters subsequent pulses in such a way, that they can no longer cause ablation in the depth.

3.2. Influence of the repetition rate

An increase of the pulse repetition rate affects the achievable drilling efficiency in connection with a change in the hole shape. The achieved depth after a certain number of pulses (100 to 10 million) for different repetition rates from 200 Hz to 400 kHz at a pulse energy of 60 μJ is shown in Fig. 6 (for atmospheric conditions). We observe an almost similar depth for repetition rates of 50 kHz and below. The final depth for these repetition rates is reached after ca. 10,000 pulses and does not increase further when more pulses are applied. Only a slight reduction by about 20% can be observed for repetition rates of 1 kHz to 100 kHz in
comparison to 200 Hz at 1,000 pulses, better visible on the basis of the hole shapes in Fig. 7 (b). We attribute this to an interaction of the ablation products with subsequent pulses as illustrated in Fig. 1 (d). This leads to a bulging of the hole in the upper part, which increases the diameter. Nevertheless, the effect is insignificant at a low number of pulses (N=100) and a similar final depth is reached.

Remarkably, the achieved depth increases for repetition rates of 100 kHz and higher. For 10,000 pulses we observe an increase by 40% for 400 kHz in comparison to 200 Hz. We attribute this to an accumulation of residual heat, which facilitates the ablation process, because less pulse energy is necessary for heating of the material to its evaporation threshold. In addition, forward drilling can continue for a higher number of pulses. Instead of reaching the final state prior to 10,000 pulses, depth increase still continues up to 10 million pulses at 400 kHz, see Fig. 6. Accordingly, the final hole depth increases by a factor of 4, from ca. 380 μm at 200 Hz to ca. 1600 μm at 400 kHz. The onset of the heat accumulation effect depends on the applied average power and therefore the pulse energy (as well as material properties, e.g. thermal conductivity). Hence, we observe it beginning at a repetition rate of 200 kHz for 30 μJ pulse energy and already above 10 kHz for 125 μJ.

Fig. 6. For pulse repetition rates higher than 50 kHz the achievable depth at a certain number of applied pulses successively increases, reaching a factor of 4 after 10 million pulses at 400 kHz compared to 50 kHz and lower (example for a pulse energy of 60 μJ). The connecting lines are a guide to the eye, only.

While we observe a similar hole shape after 100 pulses in Fig. 7 (a), after 1,000 pulses the interaction of subsequent laser pulses with the expanding ablation products inside the hole at repetition rates of 50 kHz and above leads to the formation of large bulges in the upper part of the hole and a more pronounced and thinner tip, similar to the observations by Klimentov et al., 2001. Taken as a whole, the diameter of the hole is increased. Therefore a better propagation of the pulse down the hole capillary can be assumed, which enables also a longer continuation of the drilling process. After 1 million pulses, see Fig. 7 (c), the holes at 200 kHz and 400 kHz show a significantly extended depth compared to lower repetition rates. This is accompanied by a larger cross section area of the hole, which extends the complete depth from top to bottom. The average diameter increases from ca. 35 μm for the final state at 200 Hz to ca. 70 μm at 400 kHz. Furthermore, we still observe fine structure like thin side arms for all repetition rates, even for the highest ones.

In summary, we observe an interaction of subsequent pulses with expanding ablation products, which results in a shielding effect and hence reduced drilling efficiency, for repetition rates of 1 kHz and above. The pulse energy is directed to the sidewalls in the upper part of the hole and leads to dominant bulging. For a
pulse energy of 60 μJ, heat accumulation overcomes this shielding effect at 200 kHz and enables a higher drilling efficiency as well as a longer process duration, which eventually leads to a much larger depth, but accompanied by a significant increase of the hole cross section.

![Graph showing the increase of the repetition rate at a pulse energy of 60 μJ](image)

Fig. 7. The increase of the repetition rate at a pulse energy of 60 μJ shows a change in the hole shape beginning at 1,000 applied pulses (b) with the formation of larger bulges for 50 kHz and above compared to 200 Hz. This leads to an increased mean diameter of the hole and finally also a larger hole depth (c), especially at a repetition rate of 400 kHz.

3.3. Influence of the laser generated plasma

In a further experiment, we studied the influence of the laser generated plasma on the drilling process by imaging the plasma luminescence at the hole entrance above the surface. The experiments were carried out under atmospheric pressure and at a low repetition rate (50 Hz). With short-time camera exposures ($t_{\text{exp}} \approx 200$ ps), we analyzed the plasma expansion velocity, which showed a constant velocity of ca. 2 km/s during the first 5 ns. For a hole depth up to 40 μm this velocity increases to about 3 km/s, which can be attributed to the confinement of the plasma in the hole during expansion and a kind of nozzle-effect on the surface. For higher depths the plasma velocity is reduced due to the longer propagation time to the surface. In this case and after 5 ns in general, the plasma shows a nonlinear decrease of its expansion velocity, which is in agreement with the Sedov-theory for the shockwave expansion, see e.g. Sedov, 1959 and Bäuerle, 2000.

Using long-time exposures ($t_{\text{exp}} \geq 5$ μs), it is possible to visualize the complete region of plasma luminescence during its expansion. Fig. 8 shows the plasma radiation above the surface in correlation with the hole shape for different numbers of applied pulses. With increasing pulse number and hole depth the plasma
luminescence at the surface gets weaker due to recombination and cooling during propagation within the capillary. Especially remarkable is the intermediate vanishing of the plasma plume at the surface, see the situation between 3,900 and 4,950 pulses in Fig. 8. During this intermediate period, the curved shape of the hole prevents a direct ascent of the plasma plume from the tip to the surface. This leads to a reabsorption of the plasma energy within the hole capillary. Abrasion, which occurs at the bending point, partially changes the shape of the bend until subsequent pulses are no longer deflected in direction of the hole tip and drilling resumes in forward direction. The plasma can then propagate within the hole without obstruction and reappears at the surface, see the period of 7,550 to 11,000 pulses in Fig. 8.

![Fig. 8. Plasma luminescence above the surface in correlation with the hole shape for different numbers of applied pulses.](image)

In summary, the plasma energy can already be absorbed within the hole and does not reach the surface, especially if direct expansion to the surface is restraint due to bending of the hole. In this case it can act as a secondary drilling source beside the laser pulses.

4. Conclusion

We experimentally investigated the percussion drilling process in silicon to study the reasons for special features of the hole shape formation like bending of the hole, formation of bulges, predominant ablation in transverse direction and the final stop of forward drilling. Our observations of the plasma expansion show, that it can cause abrasion of the hole sidewalls in situations when direct expansion to the surface is restraint by the hole shape, e.g. after bending, and we observed that the plasma energy is already reabsorbed within the hole capillary. The abrasive effect of the plasma in this situation may be mainly responsible for reshaping of the hole bend, which then enables a continuation of drilling in forward direction and leads to a further depth increase. Interaction of ablated particles, which did not yet escape the hole capillary, with subsequent laser pulses becomes relevant for repetition rates higher than several kHz. This interaction causes a shielding effect, which reduces the drilling efficiency. This effect is overcome by heat accumulation when the temporal separation of pulses is further decreased at higher repetition rates of a few hundred kHz. The residual heat facilitates the ablation process for subsequent pulses and eventually leads to a larger achievable depth. Our investigations of the particle deposition inside the hole capillary indicate that ablation in transverse direction, bulging and bending of the hole are mainly caused by deflection of the laser beam on the sidewalls of the hole, because these phenomena also occur in the absence of debris. On the other hand, large agglomerations of particles in the hole capillary can act as an obstruction for subsequent pulses and are therefore mainly responsible for the final stop of the drilling process.
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