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Evolution of hole shape and size during short and ultrashort pulse laser deep drilling

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Abstract: A detailed study of the influence of the pulse duration, from the femtosecond to the nanosecond regime, on the evolution of the hole shape and depth during percussion drilling in silicon is presented. Real-time backlight imaging of the hole development is obtained for holes up to 2 mm deep with aspect ratios extending to 25:1. For low pulse energies, the hole-shape and drilling characteristics are similar for femtosecond, picoseconds and nanosecond regimes. At higher pulse energies, ns-pulses exhibit slower average drilling rates but eventually reach greater final depths. The shape of these holes is however dominated by branching and large internal cavities. For ps-pulses, a cylindrical shape is maintained with frequent small bulges on the side-walls. In contrast, fs-pulses cause only a limited number of imperfections on a tapered hole shape.

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1. Introduction

The laser pulse duration is one of the key parameters that influence the quality of structures created by laser micromachining. While ultrashort pulses in the femtosecond and picosecond regime offer high precision with negligible molten material being produced, processing with nanosecond laser pulses has to be carefully optimized to achieve high quality structures, especially for metals. The characteristics of the ablation process at the surface of materials have been subject to detailed studies [1–4], leading to the following qualitative description of the ablation process. During the interaction of a laser pulse with a metal-like material, the pulse energy is substantially absorbed by the quasi-free electrons. Typically, after a few to a few tens of picoseconds, the energy is transferred to the lattice. For ultrashort pulses with a duration below 1 ps, thermal diffusion into the surrounding bulk material can be neglected due to the very short time scales. As a consequence, a superheated layer is formed and the laser-induced stress leads to rapid phase changes, Coulomb explosions, and material ejection from the surface in the form of nano-scale particles, neutral atoms and ions [5,6]. The ablation mechanism can be considered as a nearly direct solid-vapor transition. This process causes only minor damage to surrounding areas and leads to a relatively small heat-affected zone. In contrast, for longer pulses of several tens of picoseconds to nanoseconds, heating of the surface takes place throughout the pulse duration, and heat conduction during irradiation significantly increases the heat-affected zone leading to the formation of a considerable molten layer. This limits the achievable precision and quality of laser-generated microstructures.

To gain deeper insight on the influence of the pulse duration on the evolution of the hole shape and depth, these studies need to be extended to high aspect ratio structures. Up to now, most investigations capture only depth information, relying on post-processing techniques or the use of transparent materials for observations [7–14]. In our approach, we perform percussion drilling experiments in crystalline silicon and simultaneously analyze depth and shape of the drilled holes throughout the entire drilling process. This material has the advantage of behaving similar to a metal when irradiated with a laser wavelength below the band edge [15] and allows imaging of the hole’s silhouette when back-illuminated above the band edge. Previous in situ observations of the percussion drilling process with ps-pulses revealed three characteristic phases [16]: the excavation of an ideally shaped capillary at high ablation rates within the first few hundred pulses, followed by a statistically unpredictable second phase with intermediate periods of predominant transverse growth and strongly reduced drilling efficiency, accompanied by the formation of bulges and multiple hole ends, and in a final third phase the forward drilling eventually stops, only followed by a further increase in the hole diameter. The final hole depth is chiefly determined by the applied pulse energy and is largely independent of the incident fluence. The same imaging setup is used here for the investigation of the influence of the pulse duration on the drilling behavior.

2. Experimental setup

Figure 1 shows the principal setup for the in situ imaging of the percussion drilling process. We apply a Ti:Sapphire chirped pulse amplification (CPA) system (Spectra-Physics Tsunami/Spitfire) at 800 nm for drilling. This laser system allows the change of the pulse duration from the femtosecond to the picosecond regime by changing the compressor alignment. Nanosecond pulses of approximately 10 ns duration can be obtained by operating
the amplifier in a Q-switched mode without seed. The laser beam is then focused onto the surface of the silicon sample by a plano-convex lens with 100 mm focal length resulting in a spot size of approximately 35 µm, which is a typical configuration for a micromachining setup. A quarter wave plate converts the radiation to circular polarization to avoid polarization dependent effects. During the percussion drilling, the focus remains on the sample surface and is not moved. The sample is illuminated transverse to the drilling direction by a second laser at 1060 nm (HighQ femtoTRAIN), and the silhouette of the hole is projected onto a CCD-camera by a microscope objective. The laser system for drilling operates at a repetition rate of 200 Hz and the image of the hole shape is captured at 50 fps, resulting in one image every 4 pulses. See [17] for further details on the measurement setup.

Fig. 1. A Ti:Sa CPA laser system is used for percussion drilling in a silicon sample. The silhouette of the hole is recorded in transversal direction by a CCD camera.

For the investigations, standard crystalline silicon wafers with p-doping (resistivity <20 Ω·cm) and <100> direction are used. However, the actual sample orientation with respect to the drilling laser beam shows no influence on our drilling investigations. In this study, we focused on three different pulse durations, which represent the typical regimes with different quality features: 50 fs, 1 ps and 10 ns. The applied pulse energy is varied for each pulse duration from 25 µJ to about 600 µJ, corresponding to a fluence from 5 J/cm² to about 140 J/cm².

3. Experimental results

For the deep structures with high aspect ratio investigated here, we observe a significantly different behavior for low and high pulse energies, comparable to observations at the surface where low and high fluence regimes have to be distinguished. For our experimental conditions, a pulse energy of 50 µJ is characteristic for the low pulse energy regime and will be discussed first. Figure 2 shows typical steps of the drilling progress in different shades of gray for increasing number of applied pulses. Although the absolute depth and shape of the holes vary statistically, the principal behavior and relation between the different pulse durations always show similar characteristics, as presented in this example.
Fig. 2. Formation of the bore holes in the low pulse energy regime ($E_p = 50$ µJ), shown in cumulative shades of gray. (Media 1)

After $N = 100$ pulses (white hole shape in Fig. 2) the first drilling phase ends. Here, the holes exhibit similar tapered shapes for all three pulse durations. During the second drilling phase, the hole depth increases by a factor of 2 to 4 with respect to phase 1. The final hole shape is reached after approximately $N = 5,000$ pulses for all pulse durations, see black shape in Fig. 2. Here, the hole shape features are still similar for all pulse durations. The typical taper is accompanied by the formation of bulges along the side walls and bending of the hole away from the incident laser beam direction. Position, arrangement and orientation of these imperfections are subject to statistical variation if drilling is repeated with the same parameters, but always occur in a comparable manner. Nanosecond pulses feature a lower final depth compared to the ultrashort pulse regime. This may be attributed to the higher diffusion losses into the surroundings and the correspondingly higher ablation threshold for the longer pulse duration. The increasing hole surface, once a certain depth is reached (end of phase 1), leads to a decrease of the effective fluence and hence to a decreasing ablation rate until the effective fluence falls below the threshold.

Figure 3 shows the evolution of the hole depth as a function of the number of pulses applied. We observe a similar behavior for all three pulse durations. The same three phases of the drilling process can be distinguished for every pulse width. Also, the processing times from the start to the end of forward drilling are similar for every pulse duration regime (approximately 5,000 pulses).

The drilling process for high pulse energies is significantly different from the behavior at low pulse energies. Therefore, the observations at a pulse energy of 500 µJ which is ten times as high as in the previous case will be discussed here as a typical example for the high pulse energy regime. The formation of the hole shape during the drilling process for 50 fs, 1 ps, and 10 ns pulses at this pulse energy is shown in Fig. 4.

Again, the first phase of the process with a typical tapered shape and similar depths for all holes lasts for about $N = 100$ pulses (white shape in Fig. 4). In the second process phase, both fs and ps pulses reach hole depths around 1 mm and a high aspect ratio of 10 within less than ten thousand pulses (light gray shapes in Fig. 4). These types of holes, straight with large aspect ratio and depth of 1 mm are typical for micromachining applications with ultrashort laser pulses, see e.g. [1]. In contrast, drilling with ns-pulses is significantly slower and a much shorter depth is obtained. About 50,000 pulses are required to reach a depth comparable to those of ultrashort pulses at 10,000 pulses (dark gray shape in Fig. 4). This is comparable to...
the low pulse energy case, where ns-pulses also showed a lower drilling efficiency in the second phase of the process.

Fig. 3. fs-, ps- and ns-pulses show a similar drilling behavior for low pulse energies with three process phases and a few thousand pulses till the stop of forward drilling.

Fig. 4. Formation of the bore holes in the high pulse energy regime ($E_p = 500 \mu J$), shown in cumulative shades of gray. (Media 2)

In the case of fs-pulses, the hole shows an accentuated tapered shape with a large entrance diameter and a sharp tip at the hole end. The large entrance diameter, which can reach up to two or three times the size of ps- and ns-pulse holes, may be attributed to nonlinear interactions of the highly intense laser pulses with the ambient air and also the ablation plume. Previous investigations by Breitling et al. showed that this can lead to a broadening of the beam, and hence to an enlarged ablation diameter [1].

With ps-pulses, small imperfections such as bulges occur frequently along the side walls of the hole. At the tip of the hole, multiple ends are formed. This may be attributed to changing conditions for the pulse propagation within the hole capillary due to continuous ablation at the side walls (see development of hole shape for ps-pulses in Fig. 4, Media 2), which changes the intensity distribution at the bottom of the hole and hence also the ablation direction. In addition, this effect may be caused or enhanced by non-linear focusing of the
beam in the ionic and neutral ablation products within the hole capillary [8]. The hole has an almost constant diameter and a minimal taper, i.e. it is almost cylindrical. While the hole shapes generated by ultrashort fs- and ps-pulses pulses no longer change significantly after about ten thousand pulses, drilling continues with ns-pulses. As drilling persists, large bulges at the side walls, internal cavities (domains with extended diameter), and side arms are formed (dark gray and black shapes in Fig. 4). A dominant branching of the hole can also be observed, which means after forward drilling is stopped it may resume with a slightly different angle and in the further process may also lead to a larger depth. This behavior is fundamentally different compared to ps-pulses, where multiple hole ends also occur, but instead reach similar depths. In summary, ns-pulses reach a much larger depth of nearly 2 mm at the end of the drilling process (black shape in Fig. 4), when compared to ultrashort pulses at the same pulse energy. However, note that significantly more laser pulses are required in the ns case for reaching the final depth.

![2nd phase for ns-pulses](image)

Fig. 5. For a high pulse energy of 500 µJ, fs- and ps- pulses show similar behavior with stop of forward drilling after a few thousand pulses. ns-pulses lead to a significantly extended second drilling phase up to a few hundred thousand pulses with very long intermediate periods of predominant transversal growth.

The quantitative evolution of the hole depth is depicted in Fig. 5. The first phase (100 pulses) is not clearly visible due to the scaling of the x-axis to the entire processing time of 200,000 pulses. For fs- and ps-pulses, we observe a similar behavior, with a fast increase in depth within 10,000 pulses. At this point, forward drilling stops for fs-pulses, and ps-pulses show only minor changes of the hole depth up to 40,000 pulses (see also the hole shapes in Fig. 4, Media 2). In both cases, the final hole depth reaches 10 to 12 times the depth after the first drilling phase.

Note that the absolute values of depth during the hole development are subject to change statistically within a certain range (ca. 15%, see also previous investigations in [16]) for repetitions of the drilling process under the same conditions, but the principal behavior is always similar.

A quantitative analysis of the final hole depth at the end of the drilling process (Fig. 6) reveals the two different pulse energy regimes. In the low pulse energy regime, that is $E_p < 75$ µJ for our experimental conditions, fs- and ps-pulses show a comparable increase of the final depth with increasing pulse energy. Nanosecond pulses show a lower performance in terms of absolute depth, but a stronger rise with pulse energy compared to shorter pulse durations. For a pulse energy of approximately 75 µJ, all three pulse durations lead to a similar hole depth.
For high pulse energies, that is \( E_p > 75 \, \mu J \), we observe an increasing final depth with increasing pulse duration. In addition, ultrashort pulses show a saturation behavior, which is most prominent in case of fs-pulses. In contrast, ns-pulses provide a nearly linear increase of depth with increasing pulse energy. It should be noted, that reaching these larger depths in the case of ns-pulses also takes a much longer drilling time (see comparison in Fig. 5).

![Graph showing the final hole depth increases with the applied pulse energy for short and ultrashort pulses. For low pulse energies (see insert), fs- and ps-pulses reach larger final depths compared to ns-pulses. For higher pulse energies, ultrashort pulses show a saturation of the final depth, while ns-pulses feature a nearly linear increase, which leads to an increasing hole depth for prolonged pulse durations.](image)

Another important criterion for the quality of the hole shape is the variation of the hole diameter along the hole as depicted in Fig. 7. Femtosecond and nanosecond pulses both show a strongly increasing diameter variation with pulse energy. Nevertheless, the reasons for this behavior are different: Nanosecond pulses lead to large internal cavities and a dominant branching effect which changes the diameter along the hole resulting in a large variation. The variation for fs-pulses is caused by the tapered shape itself, with a continuous reduction in hole diameter from entrance to tip, while the side walls show only minor imperfections. In contrast, ps-pulses feature a low variation in diameter especially for high pulse energies due to their almost cylindrical shape, despite the frequent imperfections along the side walls.

![Graph showing the variation of the hole diameter strongly increases with pulse energy for fs- and ns-pulses, while ps-pulses show a low variation due to their almost cylindrical shape.](image)
4. Conclusion

The pulse duration is a key parameter in laser microdrilling, not only with respect to the surface quality, but also regarding the shape of the drilled hole. For low pulse energies, in our case 50 µJ, the hole shape is nearly identical for fs- up to ns-pulses, and only shows a lower final depth for ns-pulses. This is different for higher pulse energies, e.g. 500 µJ, where the final hole depth increases with the applied pulse duration. However, the number of pulses required to reach the final depth increases drastically from a few thousand for ultrashort pulses, to a few hundred thousand for ns-pulses. Furthermore, the hole shape differs depending on the pulse duration. Femtosecond pulses show only minor imperfections on the sidewalls, but an accentuated tapered shape. Picosecond pulses lead to almost cylindrical holes with a low diameter variation, but also develop frequent bulges and imperfections along the side walls and multiple hole ends. Nanosecond pulses show very large bulges and internal cavities accompanied by a dominant branching effect.

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