High speed laser drilling of metals using a high repetition rate, high average power ultrafast fiber CPA system

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Abstract: We present an experimental study on the drilling of metal targets with ultrashort laser pulses at high repetition rates (from 50 kHz up to 975 kHz) and high average powers (up to 68 Watts), using an ytterbium-doped fiber CPA system. The number of pulses to drill through steel and copper sheets with thicknesses up to 1 mm have been measured as a function of the repetition rate and the pulse energy. Two distinctive effects, influencing the drilling efficiency at high repetition rates, have been experimentally found and studied: particle shielding and heat accumulation. While the shielding of subsequent pulses due to the ejected particles leads to a reduced ablation efficiency, this effect is counteracted by heat accumulation. The experimental data are in good qualitative agreement with simulations of the heat accumulation effect and previous studies on the particle emission. However, for materials with a high thermal conductivity as copper, both effects are negligible for the investigated processing parameters. Therefore, the full power of the fiber CPA system can be exploited, which allows to trepan high-quality holes in 0.5mm-thick copper samples with breakthrough times as low as 75 ms.

OCIS codes: (320.7090) Ultrafast lasers; (140.3390) Laser materials processing; (140.3510) Lasers, fiber; (140.4480) Optical amplifiers.

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1. Introduction

Laser microstructuring of metals is a challenging task, owing to their high thermal conductivities and relatively low melting temperatures. Here, the ability of ultrashort-pulse lasers to fabricate precise microstructures on solid targets is opening new frontiers. The production of high quality and high aspect ratio holes in metals with ultrashort laser pulses is still an open field of research with significant technological impact on industrial applications. In the last years it has been demonstrated that the quality of ablated holes and patterns produced by femtosecond or picosecond laser pulses is much better than the quality of structures produced with nanosecond pulses [1-3]. With conventional laser systems delivering pulses of about 1 ns or longer, the ablation of metals is always accompanied by the formation of large heat-affected zones and a throw-out of the molten material. This limits the achievable precision, the quality and the reliability of the produced structures. A significant improvement can be achieved with femtosecond laser pulses and also with pulse lengths of a few picoseconds [4]. The main features of ultrashort-pulse laser ablation are very rapid energy deposition and creation of vapour and plasma phases, and negligible molten material as well as heat-affected zones. However, for laser pulses significantly longer than 10 ps large quantities of the metal are melted, being detrimental to the quality of the holes [2, 4]. Further advancements of the technology like the control of the laser beam polarization [5] together with innovative drilling techniques, like “trepanning”, have allowed to achieve high quality holes, even in ambient air and without shielding gas [6]. Laser trepanning consists in moving the beam on a circular path relative to the target, differently from percussion drilling in which consecutive pulses are superimposed in the same focal volume. This technique allows to significantly improve the accuracy of the hole shape that, in this way, depends less on the beam profile that sometimes could be distorted. A further advantage of laser trepanning is that the expulsion of the ablated material is facilitated due to the smaller size of the laser spot with respect to the channel diameter. As a result, the burr formation is reduced. In addition, for high aspect ratio holes it is possible to control the taper and obtain cylindrical profiles by inclining the beam at small angles. Holes with a negative conicity can also be produced by further inclining the beam during the circular motion [7].

Commercially available femtosecond laser sources, like Ti:sapphire based systems, allow to drill high quality holes but, unfortunately, the processing speed is still too low for many industrial applications. This disadvantage can be overcome by the new regeneratively amplified solid state laser sources, providing much higher average powers and repetition rates [8]. In addition novel high-power fiber amplifiers represent an attractive alternative to those regeneratively amplified ultrafast lasers. Recently, a 100-W-average-power, mJ-level ultrafast fiber amplifier has been demonstrated [9]. These sources are very promising for industrial micro-machining applications because of their compactness, high average power and high repetition rates that would enable a significant increase of the processing speed.

However, systematic studies of the effect of high repetition rates and high average powers on the processing speed and on the morphology of the holes are still lacking. At high repetition rates heat accumulation effects might come into play leading to melting and increased heat-affected zones. A further upper limit for the highest useful repetition rate could be the interaction of the generated plasma or ablated particles with subsequent laser pulses, since this will distort or shield the laser radiation. Recent experiments, carried out with pump and probe techniques [10,11], indicate that when a picosecond or femtosecond pulse impinges on a metal target, a plasma is formed on the sub-nanosecond time scale. This plasma is initiated by surface electron emission. After several nanoseconds [12,13] an expanding plume appears, consisting of vaporized target material. This second ablation step is ascribed to homogeneous nucleation. The particle plume initially expands with a velocity on the order of 10^6 cm/s and vanishes after several 100 ns up to a few microseconds. Based on these results an upper limit of a few hundred kHz, depending on the ablation pulse fluence, has been predicted for material processing with ultrashort laser pulses, before particle shielding begins to play a detrimental role in the process [13].

Therefore, both heat accumulation and particle shielding need to be investigated at higher repetition rates since no experimental data are available so far. In this work, we present percussion drilling experiments on copper and stainless steel sheets with a novel sub-picosecond fiber-amplifier, comprising repetition rates up to 1 MHz and average output powers up to 100 Watts [9]. The influence of the repetition rate and the average power on the drilling breakthrough time has been investigated. Experimental data have been compared with simulations of the heat accumulation at high repetition rates. The percussion drilling experiments on these two metals with quite different thermal properties allowed us to acquire important information on the highest usable repetition rates and average powers in order to avoid particle shielding and obtain melt-free holes. Based on these results, the laser trepanning technique has been employed to produce high quality holes with sharp edges and reliable geometrical characteristics with processing times below 1s.

2. Experimental setup and procedure

The laser setup used for our experiments is an ultrafast ytterbium-doped fiber CPA system with a wavelength of about 1030 nm. It consists of a passively mode-locked Yb:KGW oscillator, a dielectric grating stretcher-compressor unit, an acousto-optical modulator for pulse selector and two ytterbium-doped photonic crystal fibers, both used in single-pass configuration, as amplification stages. More details on the laser system can be found in reference [9]. In the presented study the fiber laser CPA system was operated with compressed pulses of 800 fs, repetition rates from 50 kHz to 975 kHz, and pulse energies varying from 10 μJ up to 70 μJ, i.e. average powers up to 68 Watt. The pulse energy was varied by a half-wave plate placed in front of the compressor. The energy is attenuated due to the polarization-dependent efficiency of the gratings. After the compressor the linearly polarized beam is converted into circularly polarized light with a quarter-wave plate. A fast mechanical shutter, having a full opening time of 2 ms, allows the control of the process time. Laser pulses are focused with 25-mm or 11-mm focal length lenses onto the target surface, resulting in ablation diameters below 50 μm, depending on the pulse energy and the focal plane.

The samples used were 0.5-mm thick high purity copper (99.9 %) sheets and 0.5-mm and 1-mm thick stainless steel (Fe/Cr18Ni10) sheets. For percussion drilling experiments the samples were fixed on a linear translation stage while a galvanometric scanning system was used to perform the laser trepanning experiments. The scanning system includes a 80-mm-focal-length F-Theta lens, which produces a focal beam diameter of ~50μm. All the experiments were performed in ambient air and without shielding gas, except for a transverse air flow to protect the focusing optics.

A high-speed Si biased photodiode with an active area of 13 mm^2 was used to measure the laser drilling-through time. It was placed on the side of the sample in order to collect light both from the surface and, with the help of a 45° inclined reflecting plate, also from the

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bottom of the samples. The initiation of the drilling process was detected as a spike of the photodiode signal due to plasma ignition. As long as the hole did not reach the bottom of the sample the photodiode signal stayed constant, until a sudden increase of the signal was registered corresponding to the breakthrough. It was then possible to estimate the drilling time and the number of pulses to breakthrough, by taking the repetition rate into account. For each set of process parameters under investigation at least 10 holes were drilled in order to obtain average values both for the drilling time and the number of pulses to breakthrough. By analyzing the photodiode signal behaviour after the breakthrough time, it was also possible to investigate the hole broadening.

All the holes machined with percussion drilling and trepanning techniques were inspected with the help of a scanning electron microscope (SEM) that allowed to evaluate the quality of the edges and the presence of burrs or surface melting.

3. Results and discussion

3.1 Percussion drilling on steel

3.1.1 Low laser pulse energy

We performed percussion drilling experiments in order to determine how the perforation time for a constant thickness of 0.5-mm of stainless steel scales with the repetition rate for low laser pulse energies. Therefore, we used a 11-mm focal length lens, pulse energies of 10 and 20 μJ, while the repetition rate was systematically varied in the range from 50 kHz to 975 kHz. For each parameter the number of pulses required to drill through was determined. Both pulse energies yielded similar results except for the expected lower drilling times at higher pulse energies. Therefore, Fig. 1 shows the results exemplarily for 20 μJ pulse energy.

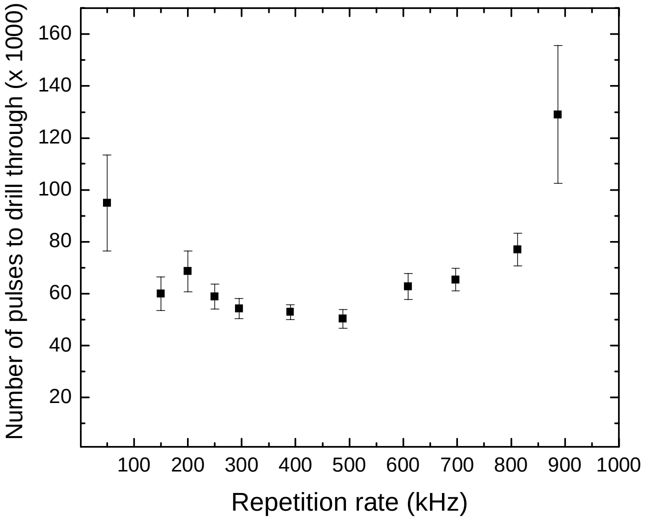

Fig. 1. Average number of pulses to breakthrough 0.5 mm thick stainless steel (Fe/Cr18Ni10) sheets at various repetition rates, for 20 μJ of pulse energy and 800 fs pulse duration.

If neither particle shielding nor heat accumulation plays a role, a constant number of pulses to drill through should be expected independent of the repetition rate. Apart from some deviations below 150 kHz, this is observed for repetition rates below 500 kHz, yielding a roughly steady value between 50000 and 70000 pulses. The deviations below 150 kHz can be explained by the following: normally, when the laser beam penetrated the entire thickness of the sheet, a sharp increase of the photodiode signal was detected from the bottom of the sample, corresponding to the full and permanent opening of the hole. As already noted, this

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time was measured as breakthrough time. In case of lower repetition rates a different behaviour of the photodiode signal was observed: multiple spikes were detected before the signal raised enduringly with further laser irradiation. This behaviour has been already observed in previous experiments carried out under analogous conditions [4] and was ascribed to the partial or complete closure of the opening of the bottom of the hole due to material re-deposition inside the capillary. When such spikes occurred more pulses were required to open the hole completely and, in addition, it was more difficult to estimate accurately the breakthrough time. This explains the deviations and the larger error bar at low repetition rates.

However, a different behaviour is found for repetition rates larger than 500 kHz. Here, the number of pulses to drill through increases with increasing repetition rates. This can be ascribed to a perturbation of the drilling efficiency caused by particle shielding. Previous experiments showed, indeed, that several tens of nanoseconds after that a ps-laser-pulse has impinged on a metal target, large particles and clusters are ejected from the surface and expand in an explosive way. This expanding particle plume is assumed to be generated by phase explosion after homogenous or heterogeneous nucleation [13]. All this conglomerating material locates in the atmosphere above the target surface and incident light is absorbed, scattered and reflected. Studies of the particle evolution, carried out by measurements of light attenuation in a pump-probe set-up, showed that this particle plume extinguishes after several 100 ns to few microseconds, depending on the laser fluence and the target material [13]. In agreement with those results we observed, at this energy level of 20 μJ, an increase of the drilling time due to particle shielding for repetition rates higher than 500 kHz, corresponding to a time separation between consecutive laser pulses of 2 μs or lower. Analogous results were found for different material thicknesses. The thicker the sheet, the longer was the time to drill through, but the particle shielding effect occurred in the same range of repetition rate, independent of the sample thickness.

3.1.2 High laser pulse energy

After characterizing the percussion drilling process at high repetition rates and low pulse energies, we extended our measurements to higher pulse energies, aiming to investigate if, besides particle shielding, heat accumulation may have a significant influence on the drilling efficiency for such high repetition rates. Three different pulse energies (30, 50 and 70 μJ) were investigated and a longer focal length of 25-mm was used in order to keep a similar laser fluence (~20 J/cm^2) as in the previous experiments. The average number of pulses to drill through 0.5-mm-thick samples was measured for different repetition rates up to 975 kHz.

Results obtained for stainless steel at different pulse energies are depicted in Fig. 2. The experimental data reveal that by increasing the pulse energy the particle shielding effect occurs already at lower repetition rates. For 70 μJ it is, in fact, already evident at 200 kHz [Fig. 2(c)]. The second and most interesting feature is that after the increase due to particle shielding an abrupt drop of the number of pulses to drill through is observed when further increasing the repetition rate. As far as the pulse energy increases, the number of pulses starts to drop at lower repetition rates (400 kHz for 30 μJ, down to 200 kHz for 70 μJ). Therefore, this mechanism seems to be energy-dependent as well.

A possible explanation for this effect is heat accumulation. Every laser pulse deposits its energy in the irradiated region. One part of this energy is required for the plasma generation and bond breaking and an additional part is carried away by the ablation particles. However, a significant fraction remains in the irradiated region, which is diffusing into the surrounding material. For high repetition rates the time between successive pulses may not be long enough for the heat to diffuse out of the focal volume before the next pulse arrives. Consequently, the energy from successive pulses accumulates in and around the focal volume. Accordingly, the temperature of the substrate increases from pulse to pulse. Due to the increased substrate temperature a lower ablation threshold can be anticipated. Even more significant changes concerning the ablation efficiency can be expected once the temperature has reached the melting threshold.

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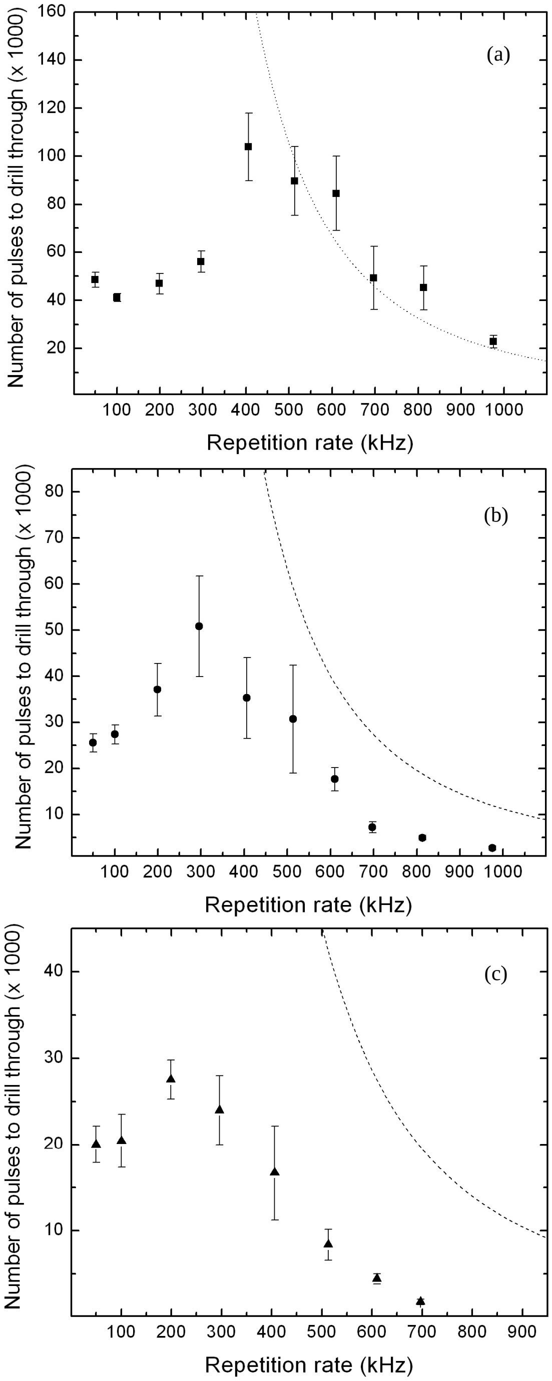

Fig. 2. Average number of pulses to breakthrough 0.5 mm thick stainless steel (Fe/Cr18Ni10) sheets at various repetition rates for (a) 30 μJ, (b) 50 μJ and (c) 70 μJ pulse energy. In all graphs experimental data are plotted in dots, while the lines represent the estimated melting threshold due to the heat accumulation effect.

On the other hand this is detrimental to the quality of the holes since melting occurs. Obviously the heat accumulation effect comes earlier into play for higher pulse energies. This explains qualitatively the experimental results depicted in Fig. 2.

For a simple estimation of the heat accumulation we neglect the complex energy redistribution on the femtosecond and picosecond time scale associated with ultrashort pulses. Starting from the analytical solution of the linear heat equation describing the pulsed-laser irradiation of a semi-infinite substrate with finite absorption and temperature-independent material parameters with a Gaussian beam, it is then possible to analytically describe the cooling cycle after irradiation by a single temporal-rectangular pulse. For times much longer than the pulse duration, the analytical expression of the temperature cooling in the laser irradiated point can be approximated by the following equation. [14]:

$$\Delta T = \frac{I_a w_0^2 \tau_l}{4\sqrt{\pi}\kappa t (Dt)^{1/2}} \tag{1}$$

where I_a is the absorbed laser-light intensity, w_0 is the radius of the laser focal spot, τ_l is the pulse duration, κ is the thermal conductivity and D is the heat diffusivity of the metal target. From Eq. (1) it is possible to calculate the target temperature at the time $t=1/\nu$ (ν is the repetition rate) when the following laser pulse arrives. The number of pulses NP_{MELT} necessary to reach the melting temperature T_M of the material is then:

$$NP_{MELT} = T_M / \Delta T \tag{2}$$

From Eqs. (1) and (2) we can obtain the following equation relating the threshold number of pulses to reach the melting temperature through heat accumulation and the repetition rate, as a function of the pulse energy E_P and the absorptivity A

$$NP_{MELT} = \frac{4\boldsymbol{\pi}^{3/2}\boldsymbol{\kappa}\sqrt{D}\cdot T_M}{\boldsymbol{\tau}_l \cdot A \cdot E_P} \cdot \boldsymbol{\nu}^{-5/2} \tag{3}$$

The predicted melting threshold due to heat accumulation has been calculated from Eq. (3) and compared with the experimental data in Fig. 2 (dashed lines), for each pulse energy. We assumed an averaged thermal conductivity and heat diffusivity, between ambient and melting temperature, corresponding to values for stainless steel of κ = 0.217 W cm^{-1} K^{-1} and D = 0.0475 cm^2 s^{-1}, respectively [15]. The absorptivity (A = 0.8) was estimated based on direct measurements of the transmission of a 1050-nm probe laser beam traversing the ablation plume at 1 μs after laser irradiation of steel and copper targets with fluences (20 J/cm^2) similar to our experiments [13]. It was furthermore assumed that, due to multiple reflection phenomena inside the hole cavity, all the incident laser energy was trapped and absorbed inside the sample [16].

From Fig. 2 one can see that, at high repetition rates, the experimental data follow fairly well the trend of the curves representing the threshold number of pulses that produce melting. This result strongly supports our hypothesis that, for high average powers, heat accumulation is responsible for the decrease of the drilling time. At higher pulse energies the experimental data still qualitatively follow the same trend of the heat accumulation simulations but a quantitative discrepancy begins to appear. Recent fs-laser ablation experiments in 1-atm air have shown that the residual thermal energy inside the sample increases with the pulse energy [17, 18]. However, the simple estimation based on Eq. (3) does not take this effect into account. This could explain why the numerical simulations of the heat accumulation do not fit the experimental data anymore at higher pulse energies [Figs. 2(b), 2(c)].

Figure 3 shows SEM images of two holes drilled in stainless steel with the same pulse energy of 30 μJ and different repetition rates. For 100 kHz a rippled structure inside the hole can be recognized. Previous investigations have demonstrated that these ripples can only be observed in melting-free holes as a result of light interference effects [4]. At 400 kHz

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smoother surfaces inside the hole are present and a tall rim of molten material is formed all around the hole surface. This confirms that heat accumulation plays an important role already at this repetition rate at least in case of stainless steel.

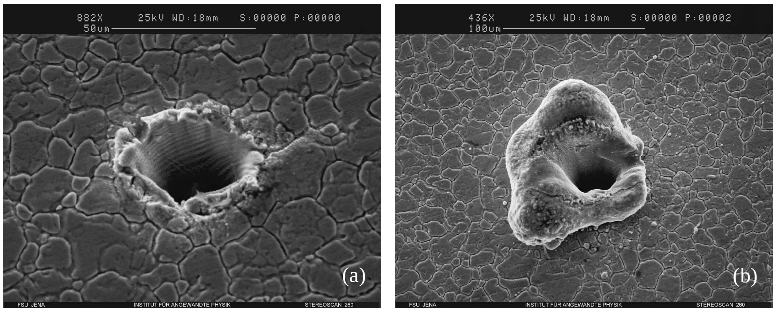

Fig. 3. SEM pictures of the entrance of holes drilled in 0.5-mm-thick stainless steel sheets with the percussion drilling technique with an energy of 30 µJ and (a) 100 kHz and (b) 400 kHz repetition rate.

Since we have seen that at high average powers the heat accumulation effect overbalances particle shielding, the overall result is a continuous and even more pronounced decrease of the breakthrough time with increasing repetition rate. This is clearly shown in Fig. 4, where the drilling time data of 0.5 and 1 mm thicknesses of steel are reported for 70 µJ pulse energy. It is important to note that for 975 kHz it is possible to drill through steel with 1-mm thickness in less than 10 ms. Unfortunately, the quality of the hole is not attractive and useful for precise machining applications due to the large amount of molten material. Nevertheless, in section 3.3, it will be shown how the hole quality can be improved by the use of the laser trepanning technique and careful selection of the processing parameters.

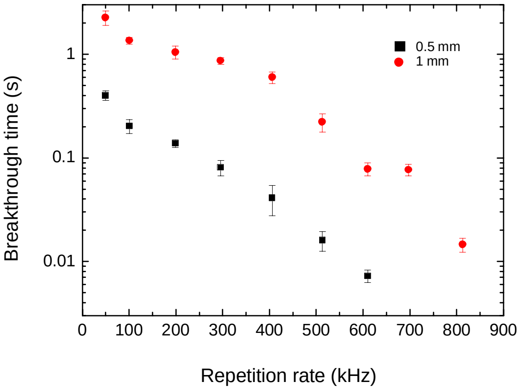

Fig. 4. Drilling time to breakthrough 0.5-mm and 1-mm thick steel sheets at various repetition rates for 70 µJ pulse energy.

3.2 Percussion drilling on copper

In order to better comprehend the mechanisms underlying the laser percussion drilling process at high repetition rates, we performed the same experiments with the same range of process parameters on 0.5-mm-thick pure copper sheets. Indeed, it is well known that the thermal conductivity and heat diffusivity of copper are almost 20 times higher than austenitic steel.

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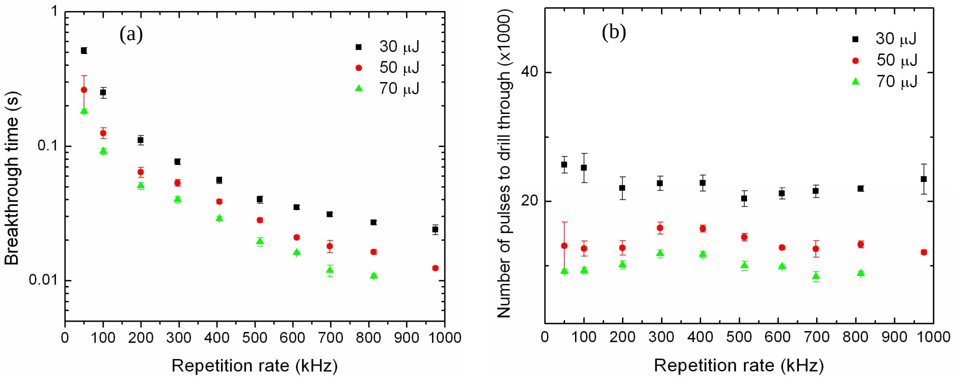

Fig. 5. (a) Time and (b) number of pulses to drill through 0.5-mm-thick copper sheets at various repetition rates for different pulse energies.

Figure 5 shows the results obtained for the drilling time (a) and the number of pulses (b) for breakthrough, respectively. Except for the highest repetition rates the process is generally faster than for steel and again, the higher the pulse energy the shorter is the drilling time. The most interesting feature is, that for each pulse energy, the perforation time scales linearly with the repetition rate. This results in a constant number of pulses to drill through irrespective of the repetition rate. This means that the high thermal conductivity and heat diffusivity of copper prevent any heat accumulation effect perturbing the process at high repetition rates. It is worth noting that the particle shielding effect is also negligible. This is probably due to the fact that the high thermal conductivity of copper reduces the formation of the superheated layer that originates the emission of particles due to phase explosion caused by homogeneous nucleation [13].

SEM pictures of holes drilled at 50 kHz and 975 kHz for 50 μJ pulse energy, shown in Fig. 6, confirm that the ablated structures are mainly vaporized and practically melting-free. In agreement with the experimental results we have found that, by substituting the thermal properties of copper into Eq. (3), the estimated number of pulses to approach the melting threshold due to heat accumulation is orders of magnitude higher than the measured number of pulses for breakthrough. The simulations predict that the heat accumulation effect may become significant in percussion hole drilling of copper at repetition rates of 4 MHz or higher.

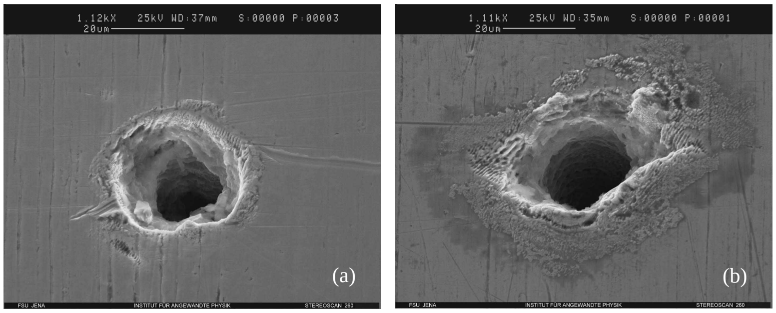

Fig. 6. SEM pictures of the entrance of holes drilled on 0.5-mm-thick copper sheets with the percussion technique with an energy of 50 μJ at 50 kHz (a), and 975 kHz (b) repetition rate.

3.3 Laser trepanning

The final objective of this work was to drill high quality holes at high repetition rates and high average powers. Percussion drilling may be useful to acquire important information on the physical mechanisms underlying the laser-matter interaction, because of less process parameters involved. However, laser trepanning is more suitable to obtain holes with sharp and clean edges and reliable geometrical characteristics. For this purpose we performed several experiments on both materials (steel and copper) using a scanner system with a focal length of 80 mm. In addition to the pulse energy and the repetition rate we varied several other parameters like the trepanning radius, the rotation speed and the number of rounds. In order to achieve melting-free structures and reduced occurrence of burrs on stainless steel we had to keep the average power below 13 W in agreement with the results of section 3.1. Best results on steel are shown in Fig. 7(a) and are obtained for a repetition rate of 500 kHz, 25 μJ of pulse energy, 75 μm of trepanning radius and 265 rounds/s of rotating speed. The measured breakthrough time for steel sheets of 0.5-mm thickness is 800 ms.

In case of copper we exploited the full average power and repetition rate of the laser system since the percussion drilling experiments showed that no melting occurred in this regime. The hole trepanned with 75 μm radius, 50 μJ pulse energy, 975 kHz repetition rate and a rotation speed of 106 rounds/s is shown in Fig. 7(b). One can clearly see that the microstructure inside the hole is melt-free and burrs on the surface edges are negligible. The little heterogeneity of the surface inside the hole is due to the fact that the laser beam is not perfectly circularly polarized, it has a small component of linear polarization [5]. The measured breakthrough time is as low as 75 ms. This is obviously very attractive for industrial applications.

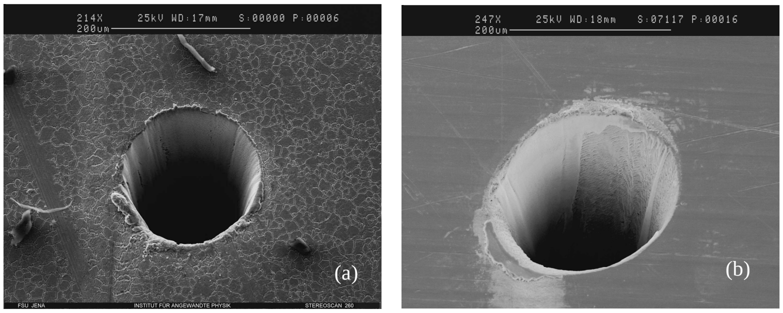

Fig. 7. SEM pictures of the entrance of holes drilled with the trepanning technique in 0.5-mm-thick (a) steel sheets with an energy of 25μJ at 500 kHz, using a trepanning radius of 75 μm and a rotation speed of 265 rounds/s and (b) copper sheets with an energy of 50 μJ, a repetition rate of 975 kHz, a trepanning radius of 75 μm and a rotation speed of 106 rounds/s. The time to breakthrough is 800 ms for steel and 75 ms for copper, respectively.

4. Conclusions

Laser percussion drilling and trepanning experiments have been carried out with a novel ytterbium-doped fiber CPA system producing high average power ultrashort laser pulses.

Percussion drilling experiments focused on the ablation of stainless steel and copper targets with 800-fs pulses, repetition rates from 50 kHz to 975 kHz and pulse energies from 10 μJ to 70 μJ. The number of pulses and the drilling time to breakthrough for 0.5-mm and 1-mm thick sheets have been measured with a photodiode. For stainless steel we observed an increase of the number of pulses at higher repetition rates due to particle shielding. Particle shielding has been shown to come into play at 500 kHz for low laser fluences and already at 200 kHz for pulse energies of 70 μJ. Furthermore, due to the relatively low thermal conductivity and heat diffusivity of stainless steel, the accumulation of heat was found to have a significant influence on the drilling time at even higher repetition rates. Under these circumstances the time between subsequent pulses is so short that the deposited heat cannot diffuse out of the irradiated zone. Consequently, the temperature increases from pulse to pulse. When it approaches the melting temperature a significant decrease of the number of pulses for breakthrough is observed due to the less energy required for vaporization. This

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overbalances the particle shielding effect. However, the heat accumulation is detrimental to the quality of the holes since a large amount of molten material is generated and a tall rim is observed on the edges of the holes produced with the percussion drilling technique. The experimental data have been found to be in good qualitative agreement with the estimated number of pulses necessary to reach the melting temperature, based on the analytical solution of the linear heat diffusion equation for pulsed laser irradiation.

Both particle shielding and heat accumulation were found to have a negligible influence for copper due to its higher thermal conductivity. In this case, the full power of the fiber laser amplifier can be exploited and melt-free, high aspect ratio holes have been drilled at 975 kHz within less than 10 ms. The simulations predict that it would be possible to drill holes up to 4 MHz without any negative influence of the heat accumulation effect.

Finally, high quality holes have been drilled with the laser trepanning technique at a reduced average power (13 W) in case of steel, in order to avoid burrs and at 50 W in case of copper. The extremely short breakthrough time (75 ms), even by using the trepanning technique, will open new applications in the field of industrial ultrafast laser micromachining of a variety of materials.

It is important to note that the effects of particle shielding and heat accumulation which have been demonstrated in this work to limit the useful range of process parameters especially in case of percussion drilling, strongly depend on the size and geometry of the structures to be ablated. Larger structures, in fact, might allow to operate at higher average powers and repetition rates. In addition, different processing techniques, e.g. percussion drilling and trepanning, might also result in different limits concerning repetition rate and average power.

Studies on the influence of the pulse duration and the laser wavelength in laser ablation processes at high average power and high repetition rates will be the objective of future experimental investigations with the same fiber laser system.

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