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Ripple formation during deep hole drilling in copper with ultrashort laser pulses

A. Weck, T.H.R. Crawford, D.S. Wilkinson, H.K. Haugen, J.S. Preston

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A. Weck
McMaster University, Department of Materials Science and Engineering. 1280 Main Street West, Hamilton, ON, Canada. weckag@mcmaster.ca
T.H.R. Crawford
Department of Engineering Physics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7.
D. Wilkinson
McMaster University, Department of Materials Science and Engineering. 1280 Main Street West, Hamilton, ON, Canada.
H.K. Haugen
Department of Engineering Physics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7.
J.S. Preston
Department of Engineering Physics, McMaster University, Hamilton, Ontario, Canada, L8S 4L7, also with the Department of Physics and Astronomy, McMaster University.

Abstract

Cross sections of deep holes produced by ultrashort laser pulses and showing a variety of microstructural formations are presented. After tens of thousands of 800 nm wavelength pulses, the walls of the holes show distinct ripples with a period of ∼300 nm. It is demonstrated that these ripples are the result of light interference effects. Indeed the ripples are perpendicular to the electric field of the laser beam and their spacing scales with the laser wavelength. Additional fine ripples with spacing of ∼75 nm were also observed.
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During ultrashort laser machining of metals, light is initially absorbed by electrons over a time frame of less than a picosecond. Energy is then transferred to the lattice and for pulse durations smaller than the electron-phonon coupling time (a few picoseconds in metals), heat conduction will be decreased. This will result in a smaller heat affected zone, lack of plasma shielding and higher precision [1]. For precision laser machining, it is also important to understand and be able to control the changes in properties and structure of the material [2]. Structure formation is detrimental in applications such as laser lithography because it limits the resolution and affects the smoothness of the surface [1]. It may be beneficial in other applications, however, such as surface roughening to improve adhesion of other materials [1]. In microfluidic devices machined with femtosecond pulses, the wall roughness is also relevant [3]. Femtosecond lasers have in addition been used to drill through-vias for connections through wafers [4]. The fabrication of a metal mold for copying to a polymer replica could be performed with a femtosecond laser, with a roughened or rippled mold surface affecting the hydrophobic properties of the polymer [5]. These experimental applications are examples of the importance of laser-induced surface morphologies.

A significant amount of work has been devoted to a specific type of surface morphology frequently called 'ripples'. Surface ripple formation during laser irradiation of solids has been reported for various materials [1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. These ripples are typically attributed to interference effects between the incoming laser beam and scattered beams at inhomogeneities on the material surface. Theories have been proposed to explain the ripple spacing Λ and the following equation has frequently been used [6, 7, 8, 9, 19]:

$$\Lambda = \frac{\lambda}{1 \pm \sin(\theta)} \tag{1}$$

where λ is the laser wavelength and θ is the angle of incidence of the laser on the sample surface. The effect of varying the angle of incidence θ has been demonstrated for a wide range of angles [6, 7, 8, 9, 10]. Typically, prominent ripples run perpendicular to the electric field direction [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. In most studies shallow holes were produced providing a simple geometry because $\theta \approx 0°$ over the beam profile. However, when the crater becomes deeper the angle between the laser beam and the walls of the holes varies [15], leading to a geometry which is more difficult to analyze. In this paper, by drilling deep holes (100 μm in depth) with a sufficient number of pulses (30000 pulses per hole), an angle approaching $\sim$90° has been obtained between the propagation direction of the incoming laser beam and the normal to the wall of the holes. This allows us to have a fully formed hole in a steady state configuration which provides a simple geometry. Some studies have been performed on the drilling of deep holes with ultrashort pulses [2, 4, 20, 21, 22] but the morphology of the hole walls is typically not examined. In this work, we present a systematic study of the evolution of microstructural formations within the hole.

For detailed information on the experimental set-up, the reader is referred to [23] but a brief description is included here. The sample is placed inside a small chamber mounted on a translation stage. Pulses at 1 kHz repetition rate are obtained from a regeneratively amplified Ti:Sapphire laser system employing chirped pulse amplification. By changing the compression within the system, the pulse length can be varied from $\sim$150 fs to $\sim$30 ps. The laser pulses have a center wavelength of 800 nm and an energy of 10 μJ. The second harmonic wavelength (400 nm) is generated using a 150 μm thick β-BaB_2O_4 crystal. Pulses are focused on the sample surface via a 5$\times$ microscope objective resulting in a peak fluence of $\sim$22 J/cm^2. Laser holes were drilled on 100 μm thick sheets of annealed high purity (99.9999%) copper in air atmosphere. The samples are then cut along the length of the hole as shown in Fig. 1. The sample is cut using a microtome which consists of an extremely sharp diamond knife, ensuring a clean cut without introducing damage in the material. Cross sections of the holes can then be observed in a scanning electron microscope (SEM). The SEM images in this work are taken from the middle of the hole and are representative of the whole length of the hole except as noted otherwise.

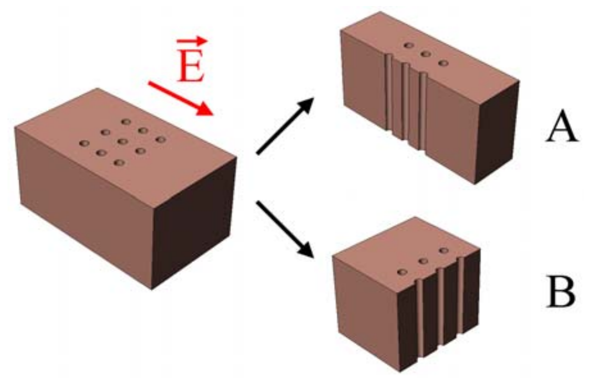
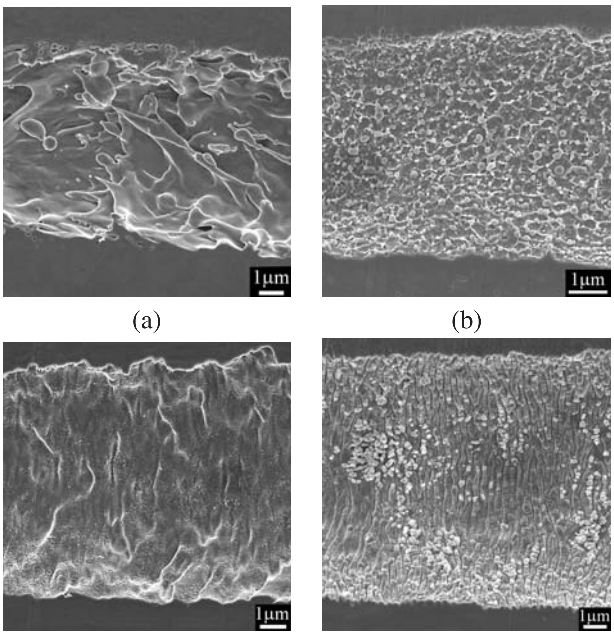


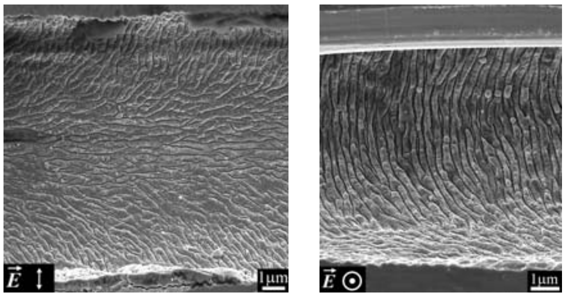
Figure 1: Schematic drawing showing on the left a 100 μm thick sheet containing 10 μm in diameter through holes and on the right the results of a microtome cut. For linearly polarized light the cut can be either (A) perpendicular or (B) parallel to the electric field $\overrightarrow{E}$ of the laser beam.

The first experiment consists of drilling laser holes with a pulse length of $\sim$150 fs, a spinning half wave plate (rotating $\sim$15°/ms) and with 100, 1000, 10000 or 30000 pulses per hole. Fewer than 160 pulses were sufficient to drill through the foil corresponding to an average ablation rate of $\sim$0.6 μm/pulse. However, it has been reported that the ablation rate drops significantly as the hole is developed [20]. Figure 2 shows the evolution of the hole inner surface as the number of irradiation pulses is increased. After irradiation with 100 pulses, substantial resolidified material from the melt is observed (Fig. 2(a)). As the number of pulses increases, the hole diameter widens and the material is exposed to a lower fluence in the wings of the Gaussian spatial profile. Therefore, less material is being melted and smaller scale microstructural formations can occur such as droplets (Fig. 2(b)) and interference effects such as ripples (Fig. 2(c) and (d)). The fluence is near the ablation threshold when the number of pulses is high (Fig. 2(c) and (d)) because the hole diameter is no longer changing significantly. The ripple spacing



(a) (b) (c) (d)

Figure 2: SEM images of the walls of laser holes drilled with a spinning polarization, a pulse length of ∼150 fs and a laser wavelength of 800 nm. The number of pulses per hole is (a) 100 (b) 1000 (c) 10000 (d) 30000.



(a) (b)

Figure 3: SEM images of the inside walls a laser hole drilled using (a) a vertical polarization on the figure and (b) a polarization out of the page.

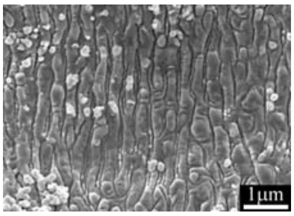
is approximately 300 nm and in additional experiments we have found that the spacing does not vary significantly with pulse length (between ∼150 fs and ∼30 ps). This spacing is somewhat lower than the value of 400 nm predicted using equation 1 [1] with an angle of 90° and a plus sign in the denominator. However for ultrashort pulses at perpendicular incidence, ripples with a period somewhat smaller than the spacing predicted by equation 1 have been previously reported [5, 12, 13, 14, 15, 16, 17, 18].

To verify that the ripple formation on the sample surface is due to interference effects, holes have been drilled without the spinning half wave plate. As before, 30000 pulses per hole and a laser wavelength of 800 nm were used but a pulse length of ∼10 ps was employed as it produced more distinct ripples. The samples were then cut with the microtome either parallel or perpendicular to the electric field of the laser beam as shown in Fig. 1. The results presented in Fig. 3 show that the ripples do run perpendicular to the electric field. This strongly suggests that the ripples come from interference effects. Using a spinning polarization causes ripples to all form with the same orientation as seen in Fig. 2(d) where ripples are nowhere parallel to the laser propagation direction.

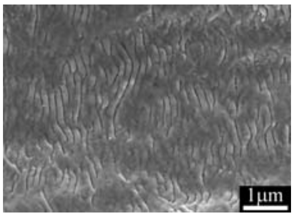
If the ripples are indeed due to interference effects, their period should be a function of laser wavelength. To investigate this, experiments were performed using 400 nm and 800 nm wavelengths, each with a pulse length of ∼150 fs and 30000 pulses per hole. The SEM images of the hole cross section presented in Fig. 4 show the ripple structure for both wavelengths. The ripple spacing decreases from ∼300 nm with the 800 nm wavelength to ∼160 nm with the 400 nm wavelength. These results again tend to support the theory that the ripples are due to interference effects.

Finally, we report that fine sub-wavelength ripples have been observed at the entrance side of a laser hole drilled with a pulse length of ∼30 ps, 30000 pulses per hole and a wavelength of 800 nm (Fig. 5). The ripple spacing is approximately 75 nm. It is not clear whether these ripples are due to interference effects or if they come from melting instabilities. High spatial frequency ripples have been observed in various materials [12, 15, 16, 17, 18] but we have only found one mention of it for metals in the literature [17]. The relative lack of high spatial frequency ripples on metals compared to other materials could give

[1] In this paper, when using equation 1 we only used the plus sign in the denominator. We are also neglecting electromagnetic waveguiding effects which can occur in small diameter holes in metals.



(a)



(b)

Figure 4: SEM images of the inside of a laser hole drilled with 30000 pulses per hole, a pulse length of ∼150 fs, an energy per pulse of about 10 μJ and a laser wavelength of (a) 800 nm and (b) 400 nm.

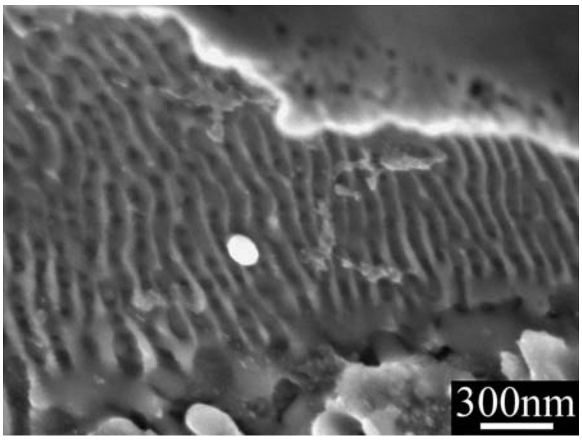


Figure 5: Fine ripples observed at the entrance of a laser hole drilled with 30000 pulses, a pulse length of ∼30 ps and with a spinning half wave plate. The ripple spacing is approximately 75 nm.

insight into the mechanisms for forming such structures. Further work, more fully examining the range of parameters under which fine ripples on metal form, is warranted. A more comprehensive picture of the formation of fine ripples is the goal of further investigation.

In summary, ripple formation has been systematically observed for deep hole drilling with ultrashort laser pulses. The geometry that is obtained is simple, as the propagation direction of the laser beam makes an angle approaching 90° with the normal to the wall of the holes and can therefore be analyzed using models in the literature. These ripples only form after many pulses have gone through the hole at which point the laser energy incident on the walls has become sufficiently low (close to the ablation threshold). Under these conditions material is preferentially ablated where constructive interferences occur. It has been demonstrated that these ripples are due to interference effects as their orientation depends on laser polarization (they are always perpendicular to it) and their spacings scale with laser wavelength. Additional fine ripples with period of $\sim \lambda/10$ were observed and their origin is subject to further investigation. The knowledge and control of the hole surface morphology could be important in a variety of scenarios including laser lithography, microfluidics, and applications requiring certain adhesion properties and wettability of surfaces. Overall, higher numbers of pulses tend to produce smoother sidewalls with finer features. However, at large pulse numbers, the ripples become well defined. Therefore, for some application an intermediate number of pulses may be optimal.

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