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Calculating the optimal combination of pulse-to-pulse distance and fluence for scribing and surface ablation with ultrashort pulsed lasers

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Abstract

The application of ultrashort pulsed lasers for surface structuring or line scribing enables precise control of the ablation depth. A general challenge for high quality laser ablation is to find the optimal combination of pulse-to-pulse distance and fluence in order to minimize the surface roughness.

In this study, a model was developed to calculate the surface roughness as a function of the pulse-to-pulse distance and fluence. In the model, the surface is irradiated by a laser pulse with a Gaussian fluence profile; ablation starts if the fluence is above a certain threshold fluence, while the depth is proportional to the logarithm of the fluence. This model is used to calculate the surface profile generated by multiple adjacent craters. The surface roughness was determined as a function of the pulse-to-pulse distance and the peak fluence.

The calculations indicate that the surface roughness reaches a first minimum when the pulses begin to overlap. If the distance between the pulses is reduced further, several minima and maxima can be found. The pulse-to-pulse distances, where the minima of the surface roughness are located, increase with the square root of the logarithm of the fluence.

Keywords: ultrashort pulse; ultrafast; laser; ablation; scribing; patterning; surface roughness; modelling

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1. Introduction

The application of ultrashort pulsed lasers for surface ablation or line scribing enables precise control of the ablation depth. A general challenge for high quality laser ablation is to find the optimal combination of pulse-to-pulse distance and fluence in order to minimize the surface roughness and to maximize ablation rate as shown e.g. in Neuenschwander et al. (2010).

In recent years, a simple model to calculate the crater shape has established. With help of this model, Neuenschwander et al. (2010) showed that the peak fluence of a Gaussian Beam F_0 should be e^2-times the ablation threshold fluence F_{th} in order to achieve the maximum ablation efficiency. It was demonstrated that this model can be used to optimize the ablation rate for a wide range of materials, as shown in Neuenschwander et al. (2012) or Neuenschwander et al. (2010). This leads to the question, if this successful model could be also used to optimize the ablation quality for line scribing and surface ablation. For this reason, the goal of this study was to extend the model in order to calculate the surface roughness as a function of the pulse-to-pulse distance and fluence for these two applications.

2. Material & Methods

A simple model to calculate the shape of a crater, which is ablated by single pulse laser irradiation, is described in Raciukaitis et al. (2009), Neuenschwander et al. (2012) and Furmanski et al. (2007). It is assumed that the surface is irradiated by a laser pulse with a Gaussian fluence profile. The fluence decreases exponentially with the depth according to Beer's law. The condition for ablation is that the fluence $F(x,y,z)$ must be larger than a certain threshold fluence F_{th}. It is written as

$$F(x,y,z) = F_0 \exp\left(-\frac{2\left(x^2+y^2\right)}{w_0^2}\right)\exp\left(-\frac{z}{\delta}\right) \geq F_{th}\,, \tag{1}$$

where w_0 is the radius at the $1/e^2$ fluence level and δ is the energy penetration depth in Neuenschwander et al. (2012). The radius of the ablated crater, where $z = 0$, can be calculated replacing $(x^2 + y^2)$ by r_{th}^2 and solving equation (1) for r_{th}:

$$r_{th} = \frac{1}{2} w_0^2 \ln\left(\frac{F_0}{F_{th}}\right). \tag{2}$$

The depth profile of a crater is obtained by solving equation (1) for z. The resulting function is a parabola. The function would return a negative ablation depth if the fluence F drops below the ablation threshold fluence F_{th}. For this reason, the function is defined piecewise and returns $z = 0$ outside the crater radius r_{th}. The piecewise defined function of the ablation depth is written as

$$z(x,y) = \begin{cases} \delta\left(\ln\left(\frac{F_0}{F_{th}}\right) - \frac{2\left(x^2+y^2\right)}{w_0^2}\right) & \text{if } \sqrt{x^2+y^2} < r_{th} \\ 0 & \text{if } \sqrt{x^2+y^2} \geq r_{th} \end{cases}. \tag{3}$$

Fig. 1, left shows an image of the calculated surface profile.

The surface profile for a multi pulse ablation $z_{nm}(x,y)$ is calculated by summing up $2n+1$ craters in x and $2m+1$ craters in y. These craters are shifted in x and y by the pulse distances d_x and d_y, respectively. The function for the surface profile for multi pulse ablation is thus written as

$$z_{nm}(x,y)=\sum_{i=-n}^{n}\sum_{k=-m}^{m}\begin{cases}\delta\left(\ln\left(\frac{F_0}{F_{th}}\right)-\frac{2\left((x-id_x)^2+(y-kd_y)^2\right)}{w_0^2}\right) & \text{if } \sqrt{(x-id_x)^2+(y-kd_y)^2}<r_{th}\\ 0 & \text{if } \sqrt{(x-id_x)^2+(y-kd_y)^2}\geq r_{th}\end{cases}. \quad (4)$$

Fig. 1, right shows an image of the calculated surface profile for multi pulse ablation with 11x11 pulses.

It should be noted that the average ablation depth increases and the pattern width and length decreases (if the pulse number is constant) with decreasing pulse distance. In addition, the width of the side wall increases and the size of the flat plateau at the bottom shrinks. At a certain pulse distance the pattern looks like an inverse pyramid. The average ablation depth was determined only at the flat plateau at the bottom. Here, it is calculated for $p = q = 51$ points, which are distributed inside a rectangle that is centered at the origin and has the side lengths nd_x and md_y. The average ablation depth $\langle z\rangle$ calculated for pq points is

$$\langle z\rangle=\frac{1}{pq}\sum_{i=1}^{p}\sum_{k=1}^{q}z(x_i,y_k) \quad (5)$$

The surface roughness R_a is the arithmetic average of absolute values. It is calculated by

$$R_a=\frac{1}{pq}\sum_{i=1}^{p}\sum_{k=1}^{q}\left|z(x_i,y_k)-\langle z\rangle\right| \quad (6)$$

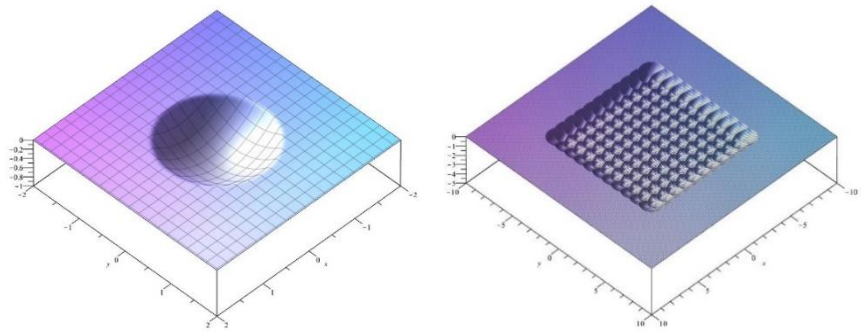

Fig. 1 Left: Calculated surface profile of a crater formed by single pulse irradiation with a fluence $F = e^2F_{th}$. Right: Calculated surface profile of pattern created by 11x11 adjacent pulses with a fluence $F = e^2F_{th}$ and a pulse distance $d_x = d_y = w_0$.

3. Results & Discussion

3.1. Line scribing

A section of the calculated surface profile of a line scribed with 21 pulses with a distance of $d_x = w_0$, is shown in Fig. 2, left. The peak fluence was chosen to be $F_0 = e^2F_{th}$. This is the fluence ratio where a maximum ablation efficiency is expected according to results from Neuenschwander et al. (2010). The focus radius is $w_0 = 1$ and the energy penetration depth is $\delta = 1$. The image of the corresponding cross section is shown in Fig. 2, center. The roughness R_a at the trench bottom is plotted as function of the pulse distance in Fig. 2, right.

The adjacent pulses overlap at a pulse distance of $d_x = 2w_0$ and a fluence of $F = e^2F_{th}$. If the pulse distance is reduced, the calculated surface roughness reaches a minimum at $d_x \approx 1.4\ w_0$. If the distance between the pulses is reduced further, the peak to valley ratio at the bottom oscillates and several minima and maxima can be found. The roughness minimum decreases with pulse distance.

These results suggest that the pulse distance should be reduced as much as possible in order to get the minimum surface roughness. It should be noted that effects like particle deposition in the trench shown in Crawford et al. (2005), and Domke et al. (2015), particle shielding shown in Ancona et al. (2008), heat accumulation shown in Domke et al. (2015) and Ancona et al. (2008), and the formation of laser-induced periodic surface structures (LIPSS) shown in Crawford et al. (2005) are not taken into account in the model. Particle deposition can increase the surface roughness significantly which can be expected when choosing small pulse distances below $d_x < 0.5\ w_0$. However, these results indicate that the surface quality should be improved by choosing the process parameters to be at these local minima.

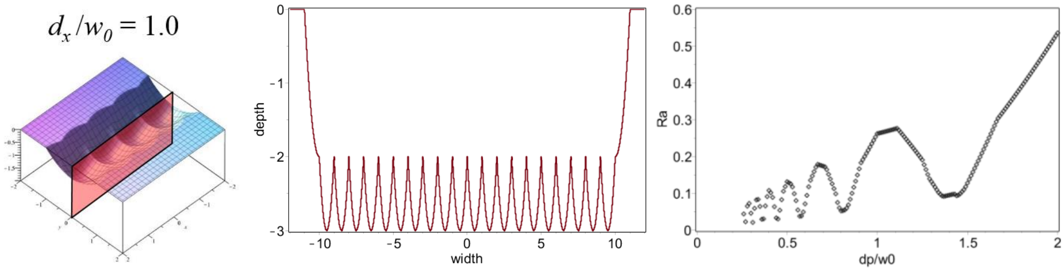

Fig. 2. Left: Calculated surface profile of a line scribed with a fluence $F = e^2F_{th}$ and a pulse distance $d_x = w_0$. The semi-transparent surface indicates the cross section which is shown in the image in the centre. Right: Calculated surface roughness R_a at the trench bottom as a function of the pulse distance.

3.2. Surface patterning

The calculated surface roughness R_a at the bottom of a pattern of 11x11 adjacent pulses as a function of the pulse distance and fluence is shown in Fig. 3, left. The surface roughness R_a has several minima if the fluence is kept constant. The pulse distances where the roughness minima are located shift with the fluence. The pulse distance of the 1st, 2nd, 3rd, and 4th minimum (when counted starting at the minimum at $d_{x,y}/w_0 \approx 1.35$ at $F/F_{th} = 15$ to lower pulse distance values) is plotted as a function of the fluence in Fig. 3, right. A logarithmic function is fitted to the data points:

$$\frac{d_{x,y_{\min}}}{w_0} = k \ln\left(\frac{F_0}{F_{th}}\right)^n , \tag{7}$$

where k is a constant and n is the exponent of the logarithmic function.

The least square fits of equation (7) to the data points in Fig. 3, right returned for the first maximum $k_1 = 0.827(2)$ and $n_1 = 0.505(3)$, and for the second maximum $k_2 = 0.531(3)$ and $n_2 = 0.500(7)$. These results suggest that the pulse-to-pulse distances, where the minima of the surface roughness are located, increase with the square root of the logarithm of the fluence.

As already discussed above, droplet formation and particle deposition on the pattern can increase the surface significantly. A strong deviation can be expected if the pulse distance is $d_{x,y}/w_0 < 0.5$, as shown in Neuenschwander et al. (2010). The minimum surface roughness at a fluence of $F_0 = e^2F_{th}$ – the fluence ratio where the maximum ablation efficiency can be achieved – is located at $d_{x,y}/w_0 \approx 0.75$. These calculations agree with the results of Neuenschwander et al. (2010), suggesting that the optimal pulse distance should be between $0.5\ w_0$ and $1.0\ w_0$.

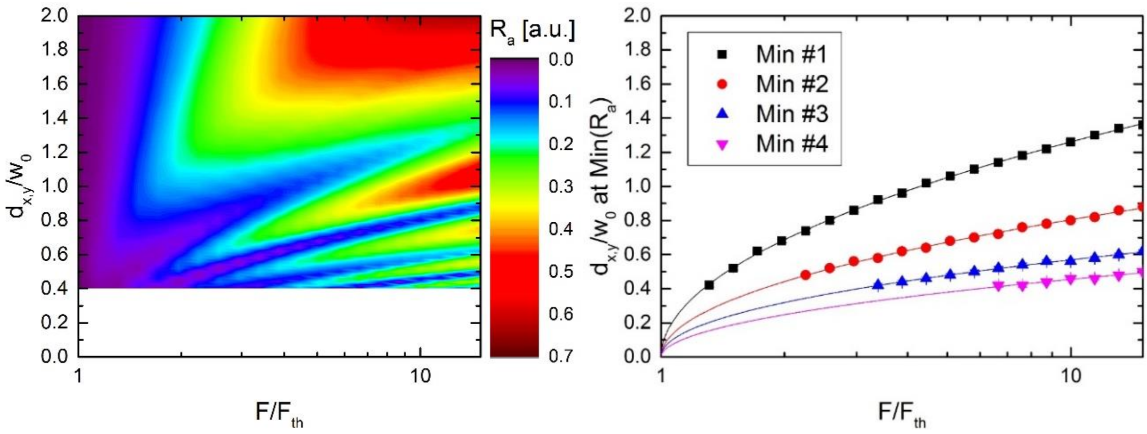

Fig. 3. Left: Calculated surface roughness Ra at the bottom of a pattern of 11x11 adjacent pulses as a function of the pulse distance and fluence. Right: Pulse distance of the 1st, 2nd, 3rd, and 4th minimum of the surface roughness (when searching from $d_{x,y}/w_0 = 2.0$ to lower values) as a function of the fluence. The solid curves represent a fit of equation (7) to the data points.

4. Conclusion

In this study, a model was developed to calculate the surface roughness as a function of the pulse-to-pulse distance and fluence for line scribing and surface patterning. For both cases, the calculations indicate that the surface roughness reaches the first minimum at a pulse-to-pulse distance of $d_x/w_0 \approx 1.4$ and $d_{x,y}/w_0 \approx 1.2$, respectively. If the distance between the pulses is further reduced, several minima and maxima can be found. For surface patterning, it was found that the pulse-to-pulse distances, where the minima of the surface roughness are located, increase with the square root of the logarithm of the fluence. The minimum surface roughness at a fluence of $F_0 = e^2F_{th}$ – the fluence ratio where the maximum ablation efficiency can be achieved – is located at $d_{x,y}/w_0 \approx 0.75$.

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