A laser beam model for high performance microdrilling

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Abstract. We have demonstrated the high performance of UV laser microdrilling in polymers. For instance hole diameter ~30 µm and length up to 18 mm (aspect ratio 600) can be obtained for PET when the laser beam setup is finely adjusted. In this work we further present a model for the incident laser beam which includes the optical setup and the laser source parameters (power and divergence). We show that the final hole geometry can be expressed in term of the laser source characteristics and that the optical setup composed of 2 lenses (condenser and projector) and a circular mask has to match some of the features of the source. Provided this condition is fulfilled the way to better drilling performances is outlined and will serve of guidelines for future experiments. In particular low divergence laser source can be used for smaller diameter hole or deeper drilling. This means also that the optical setup used to pattern the laser beam must be specially designed and adjusted.

1. Introduction

Laser micro-processing is a key technology for future industry, medicine and research. As we have demonstrated recently [1], microdrilling with diameter in the range of less than 50 µm is needed in many applications and can be performed with high aspect ratio [2] by laser ablation in polymers as well as in other materials. The many attempts of other groups to achieve high aspect ratios are reviewed in reference [1]. Since a good understanding of the various mechanisms involved is of high importance for future optimisation of the process, a detailed modelling is developed. We have already [3,4] proposed a model relating the micro-hole geometry to the incident laser beam. The end of drilling is characterized by stationary hole profile which can be detected experimentally by the limit hole depth \( l \). In a previous model this depth \( l \) is expressed as a function of the fluence \( F \) incident on the sample by:

\[
l(F) = z_0 \left[ 1 + 2 \left( \frac{F}{F_0} \right)^{\frac{r_0}{z_0}} \right]^{1/2} - 1
\]

where \( r_0 \), \( z_0 \), and \( F_0 \) are respectively the hole radius, the distance of the focal point to target surface and the fluence threshold for material removal. It was shown that equation (1) can be fitted to experimental depth variation with fluence. In this work we have further developed the model by including the parameters of the optical setup and the important features of the laser source, that is to say energy and divergence. We show with this theoretical approach that maximum hole drilling depth increases with increasing pulse energy and decreases with increasing laser divergence.

2. Experimental

The experiments were described in the previous publications [1-2]. We recall only the main features. The laser is a KrF excimer laser and the optical setup used to pattern the beam is composed of two lenses (condenser and projector). A circular mask is usually precisely imaged on the sample surface. In the experiment the image is demagnified with a value of \( G=5 \). The main characteristics of the
microdrilling experiment are illustrated in Figure 1. Figure 1A shows 3 regimes of drilling. The first is rapid since it is due to shallow ablation characterised by 3 dimensional expansion. Then follows the longest regime with constant rate for which the ablation front is flat and perpendicular to beam as described by Figure 1B to D. The third and last one corresponds to the end of drilling and shows a stationary profile with convergent walls in Figure 1E.

Figure 1 Main features of KrF laser microdrilling in PET (Mylar D) a hole with 25 µm diameter and 5 mm length drilled with the laser. A Drilling rate as a function of time (or pulse number); the scale is given by the onset of decrease c which takes place at 6000 pulses in this case B to E shape of the advancing ablation front at various times of the experiment. E and F hole after stationary profile (end of microdrilling), E Final sharp tip. The scale of the pictures is given by the hole diameter 25 µm and the hole image results from merging many partial images of the same hole.

3. Laser beam model
The optical set-up including laser source, the 2 lenses (C and P) the mask (M) and the sample (S) to be drilled is displayed in Figure 2 in which the variables are explained. The various reflections on the optical elements are neglected in the present model. The laser beam is assumed to be emitted by a point source CL placed at the centre of the laser cavity in a cone of divergence \( \Theta_0 \) (cone half angle). It is also assumed to be homogeneous in profile (top-hat) in any perpendicular plane along the optical setup. Therefore it is implicitly assumed as an approximation that the lenses have no aberration and therefore do not disturb the incident profile. Similarly diffraction effects on profile are neglected. The refraction of each lens is introduced by the thin lens equation only, for instance:

\[
\frac{1}{z_c} + \frac{1}{z'_{c}} = \frac{1}{f_c}
\]  

Equation (1) is easily derived in equation (3) by replacing \( r_0/2z_0 = d/2z_0 \) with the incident beam divergence \( \Theta_0 \). To obtain the new model the product \( F_0\Theta_0 \) in equation (3) is calculated as a function of laser pulse energy \( E \) and divergence \( \Theta_0 \). By using simple geometrical relationships the fluence \( F_0 \) incident on the sample can be calculated step by step as a function of previous ones \( F_1, F_2 \) and finally as a function of the laser pulse energy \( E \). The same can be done for \( \Theta_0 \) which can be expressed as a function of \( \Theta_L \). Now the optical setup composed of condenser (C) mask (M) and projector (P) has a well defined entrance cone of light \( \Theta_2 \) if other variables are adjusted to obtain a chosen fluence \( F_0 \) and diameter \( d \) on sample. To ensure full illumination of the mask and no light loss by blocking at the edge we must have \( \Theta_L = \Theta_2 \). Provided this condition is fulfilled equation (1) [4] can be transformed into a function of the laser parameters \( E \) and \( \Theta_L \).

\[
l(F_0) = z_0 \left( 1 + \frac{F_0 \Theta_0}{F_w} \right)^{1/2} - 1
\]

in which \( F_0 \) and \( \Theta_0 \) can be derived as equation (4) and (5):

\[
F_0 = \frac{E}{\pi \Theta_L^2} \frac{z_c^2 z_2}{z_c^2 Z z_0 (Z + z_1)} \quad \text{and} \quad \Theta_0 = \Theta_L \frac{(Z_c - f_c)Z}{G z_0 f_c}
\]
Figure 2 Scheme of the laser beam model developed for the understanding of the microdrilling experiments. C is the condenser lens, M is the mask, P is the projector lens and S is the sample. The variables are as indicated on the scheme: $F$ are for fluence, $D$ for diameter, $z$ for distance and $\Theta$ for divergence.

Therefore the product is:

$$F_0 \Theta_0 = \frac{E}{\pi \Theta_L} \times \frac{f_c f}{G z_0^2 (z_c - f_c) (Z + z_1 - f)}$$

(6)

The hole length at the stationary profile characterizing the end of drilling is therefore given by equation (7):

$$l(E, \Theta_L) = z_0 \left[ 1 + \frac{2E}{\pi F_s \Theta_L G z_0^2 (z_c - f_c) (Z + z_1 - f)} \right]^{-1/2}$$

(7)

which is of the form of equation (8):

$$l(E, \Theta_L) = z_0 \left[ 1 + \frac{2 E \Psi}{\pi F_s \Theta_L} \right]^{-1/2}$$

(8)

where $\Psi$ is a function of the optical setup only and independent of the laser parameters $E$ and $\Theta_L$.

4. Discussion

It is of importance to develop a laser beam model in order to identify the various parameters which can be handled to improve the high performance of the microdrilling experiment. In particular smaller hole diameters and deeper drilling might be desired in the future. The present model contains enough information to serve as guideline for upcoming experiments. In equation (8) we can see that the laser parameters appear in the form of the ratio $E/\Theta_L$, the laser brilliance. In fact this means that a deeper drilling requires a more brilliant laser since $l(E, \Theta_L)$ increases with $E/\Theta_L$. However this requirement is not sufficient since the optical setup represented by function $\Psi$ in (8) has to be adjusted for an optimum transmission of the laser source energy. In particular no radiation must be blocked by the mask whose aperture in turn must be fully and homogeneously illuminated. Therefore we think that this is obtained when laser divergence is equal to entrance divergence of the optical setup, that is to say $\Theta_L = \Theta_T$. The optical setup entrance cone angle $\Theta_T$ must be designed to match correctly the laser divergence. It is fully determined by the spatial arrangement of the optics.
5. Conclusions
A model of laser beam is necessary for a good understanding and future progress of the laser microdrilling experiment. Such model was constructed in this work and relates the geometry of the microhole to the experimental parameters including the laser source parameters like pulse energy \( E \) and divergence \( \Theta \). The microdrilled hole limit depth (end of drilling) is given by equation (8) which suggests that deeper hole can be obtained with low divergence laser with high brilliance. The optical setup for beam patterning is equally important and must be adjusted to fully take advantage of the laser source characteristics.

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