Excimer Laser Micromachining of Polymers using Half-tone Masks: Mask Design and Process Optimization

J. E. A. Pedder and A. S. Holmes

Department of Electrical and electronic Engineering, Imperial College London
Exhibition Road, London SW7 2AZ, United Kingdom
Email: j.pedder@imperial.ac.uk

Laser micromachining by projection with half-tone masks is a useful technique for fabricating microstructures with stepped multi-level or continuous surface relief. However, design of the mask transmission function to achieve a particular surface profile is a non-trivial problem except when the surface relief is shallow compared to the focal depth of the projection optics. In this paper we describe recent progress in the development of computer simulation tools aimed at assisting with this design process. Simulation is based on pulse-by-pulse propagation of the etched surface, using an empirically derived etch function to represent the laser-material interaction. The fluence distribution over the etched surface is estimated by free-space propagation of the angular spectrum at the focal plane. This approach has been used in the iterative design of half-tone masks for a range of micro-fluidic and optical components. Results are presented for parts fabricated in polycarbonate by half-tone ablation at 248 nm wavelength.

Keywords: laser ablation, excimer laser, ablation modelling, simulation, MEMS, microstructures, polycarbonate

1. Introduction

Micromachining by laser ablation has proved to be a useful industrial technique in many fields of advanced manufacturing [1]. It has also been used, both as a stand-alone tool and as a complementary procedure alongside conventional photolithography, in the production of complex 3D structures for microsystems [2,3]. Excimer lasers can operate at a variety of wavelengths in the UV and are suitable for high precision machining of a wide range of materials. Moreover, the low spatial coherence and high peak power enable the production of large, uniform beam profiles. This is particularly useful for parallel processing of large numbers of parts.

Excimer laser micromachining systems can use a variety of mask projection methods to create complex structures. For microengineering applications requiring high precision, a chrome-on-quartz mask similar to those used for conventional photolithography is typically employed. In this case, the mask is binary (either zero or 100% transmission), and material is removed in uniform layers over the exposed region. Continuous or stepped surface relief may be achieved with this kind of mask either by mask- or workpiece-dragging or by indexed mask projection [4].

One application area of increasing importance is the production of micro-optical components for display technology. This requires rapid production of large arrays of micro-lenses with a high level of uniformity and continuous surface relief. The synchronized image scanning (SIS) method [5] is particularly well suited to this application due to its high beam utilization efficiency and good reproducibility. However, SIS is a variation of indexed mask projection, and consequently the production of large lenses (>300 µm dia.) is difficult due to the limited number of apertures that can fit on the mask. For applications requiring larger micro-lenses, a static half-tone mask with variable transmission may be a more viable option [6,7].

Half-tone ablation can achieve continuous surface relief over very large areas, but requires a relatively complex mask. The design of a half-tone mask is non-trivial in all but the simplest of cases and requires detailed knowledge of the ablation characteristics of the material. When machining deep structures, the desired surface profile is usually achieved only through an iterative design and prototyping sequence. This can significantly increase the cost of entry for the laser micromachining process.

Recently we have been developing simulation tools based on empirically derived etch-functions and standard optical theory that can reduce or eliminate the need for iterative correction of the mask design, reducing costs and time to production. In this paper, we present details of this method as applied to projection ablation of micro-lenses in polycarbonate. The results of recent experiments carried out to assess the performance of the simulator by comparison with fabricated micro-lenses are also presented.

2. Simulation of projection ablation

The effect of a laser pulse incident on a material depends on the fluence distribution at the material surface and on the material response. The fluence distribution in the region of the focal plane depends on the optical system and the pattern on the mask. In calculating the fluence we ignore the presence of the developing structure and assume free-space propagation of the light. This approximation is reasonable for structures where the surface height is slowly varying, but is expected to be less accurate where there are large step changes in the surface height.
The response of the material to each laser pulse will depend on the optical absorption and the resulting photochemical/thermal/mechanical effects. There is a significant body of literature focused on modelling of single-pulse laser ablation. However, the methods used are too computationally intensive to apply to the production of large structures. Our approach is to fit an empirically derived etch-function to calibration data. The material is assumed to remain stable and homogenous throughout the process, so the surface can be propagated on a pulse-by-pulse basis using an invariant etch function. Effects such as plume-shielding and residual heat are ignored in the current model for simplicity.

With the above assumptions, the simulation process can be divided into two distinct stages: calculation of the fluence distribution in the vicinity of the workpiece, which needs to be carried out only once at the start of the process, and pulse-by-pulse propagation of the surface. We will now consider each of these in turn.

2.1 Calculation of fluence distribution

Excimer laser workstations usually incorporate beam delivery optics that overlap sections of the raw beam to give uniform intensity and low spatial coherence at the workpiece. This can be achieved by using a fly’s eye homogeniser, as shown in Fig. 1. Each of the lenslets in the homogeniser forms an image of the mask pattern in the focal plane of the projection lens. Beyond the focal plane, these images will start to separate as the sourcelets subtend different angles at the mask.

By treating each lenslet in the array as a quasi-monochromatic point source, the instantaneous complex amplitude in the image plane of the optical system can be calculated from standard imaging theory. The complex amplitude from a given sourcelet may be written, apart from a scaling factor, as:

\[ U_i(x,y) = \tau(mx,my) \exp[i(\alpha x + \beta y)k] \odot P(x,y) \]  
(1)

where \( \tau(x,y) \) is the mask transmission function, \( m \) is the magnification of the projection lens, \( P(x,y) \) is the point spread function of the imaging system, and \( \alpha_x, \beta_y \) are the direction cosines of the sourcelet in the image space. It is assumed in (1) that the sourcelet is at infinity in the image space and hence provides plane-wave illumination.

To calculate the corresponding amplitude distribution outside the image plane, it is convenient to use the angular spectrum of plane waves corresponding to (1), which may be written as:

\[ A_i(k_x,k_y) = A_0 \left( k_x - \alpha_i k, k_y - \beta_i k \right) \cdot D(k_x,k_y) \]  
(2)

where \( A_0(k_x,k_y) \) and \( D(k_x,k_y) \) are the Fourier transforms of \( \tau(mx,my) \) and \( P(x,y) \) respectively, and \( k = 2\pi/\lambda \) where \( \lambda \) is the wavelength of the radiation. The function \( D(k_x,k_y) \) is the aperture function of the imaging system.

Given \( A_i(k_x,k_y) \), the complex amplitude at a position \( r = (x,y,z) \) outside the image plane due to the same sourcelet can be calculated as:

\[ U_i(r) = \int \int A_i(k_x,k_y) \exp[i(k_x x + k_y y + k_z z)] \, dk_x \, dk_y \]  
(3)

where \( k_z \) satisfies \( k_z = \sqrt{k_x^2 - k_y^2} - k_0^2 \).

For an excimer laser, the different sourcelets in the homogeniser can be assumed to be mutually incoherent, allowing the total energy flux vector at any point to be expressed as:

\[ \Phi = \sum_i \Phi_i = \frac{w_i}{2ik} \left[ U_i^* \nabla U_i - U_i \nabla U_i^* \right] \]  
(4)

The coefficients \( w_i \) are the (time dependent) weightings of the different sourcelets, which are normalised so that the total energy flux across the image plane is equal to the instantaneous power in the laser pulse. Similarly, we can define a local fluence vector by integrating (4) with respect to time over the duration of the laser pulse, giving:

\[ F = \sum_i F_i = \frac{w_i dt}{2ik} \int U_i^* \nabla U_i - U_i \nabla U_i^* \]  
(5)

Currently the above equations are implemented using a one-dimensional fast Fourier transform that only needs to be performed once for each mask transmission pattern.

2.2 Surface propagation algorithm

For a predominantly photothermal ablation process, it is reasonable to assume that the material removal rate due to pulses of a given wavelength and temporal profile is a function only of the energy per unit area crossing the surface. In this case, the local etch dept \( \delta n \) at any point on the surface due to a given pulse may be expressed as:

\[ \delta n = f(F \cdot \hat{n}) \]  
(6)

where \( f \) is the classical etch function or ablation curve measured at normal incidence, and \( \hat{n} \) is a unit inward normal to the surface. Equation (6) ignores angular variations in reflectivity, but the resulting errors are small for most practical materials except near grazing incidence. It is important to note that, while (6) should be a reasonable approximation for UV ablation of polymers by ns pulses, it cannot be expected necessarily to apply in other ablation regimes.

The etched surface may be propagated simply by displacing points on the surface in the direction of the local normal as illustrated in Fig. 2. Alternatively, points may be propagated along the \( z \)-direction to maintain a uniform mesh in \( x,y \), in which case the propagation distance is:

\[ \delta z \approx \delta n / (\hat{n} \cdot \hat{z}) \]  
(7)
Both of these approaches can be made to work robustly provided appropriate measures are taken to avoid instabilities.

2.3 Calibration for polycarbonate

Accurate fabrication of a desired surface profile using the half-tone technique is heavily dependent on having a good knowledge of the material etch function prior to designing the mask. Typically the etch function is measured by recording the etch depth due to a small number of shots at several different fluence levels. This method relies on having an accurate and well calibrated attenuator for adjusting the fluence, assuming the laser pulse energy is maintained constant.

A better method of calibration is to use a standard half-tone pattern comprising a number of regions with different known transmission levels. This removes uncertainty associated with the attenuator, leaving only the possibility of a scaling error due to the laser fluence measurement. The etch depths in the resulting structure may be measured using a white light interferometer or other depth measuring device. Fig. 3 shows calibration data obtained in this way for polycarbonate using a 248nm laser and a maximum fluence of 1 J/cm². Polycarbonate is widely used in the fabrication of micro-lens arrays due to good ablation characteristics in the UV and good optical transmission at visible wavelengths. Devices structured using laser ablation can also be used as masters for electroforming and subsequent injection molding.

The etch data at low fluences was found to be more accurately approximated by a polynomial than the usual “Beer’s law” curve, and consequently a polynomial approximation was used for half-tone mask design.

3. Fabrication and analysis of test structures

A range of polycarbonate test structures was fabricated to test the validity of our simulation approach. Experiments were carried out using an Exitech 7000 series workstation incorporating a KrF excimer laser (λ = 248 nm), a 6x6 fly’s eye homogenizer, and a 5X, 0.1NA projection lens. The numerical aperture of the fly’s eye illumination was 0.07 in the image space. A chrome-on-quartz mask with a writing grid of 125 nm and CD of 1 µm was produced for this work. Individual half-tone pixels were written on a pitch of 5 µm. Details of the mask design algorithm used can be found in [7].

Fig. 4 shows convex and concave cylindrical lenses produced using 550 laser pulses at a fluence of 1 J/cm². These structures have a footprint of 500 x 1500 µm² and a depth of around 200 µm which is many times the focal depth of the projection lens. The laser fluence was chosen such that the minimum fluence in the half-tone pattern was some way above the threshold as this was found to reduce unwanted effects from debris accumulation and near-threshold melting. The resulting structures were virtually free from debris even in the lowest fluence regions. Fig. 5 shows examples of other similar structures fabricated using different portions of the same mask.

![Fig. 4 Convex and concave cylindrical micro-lenses formed in polycarbonate by half-tone ablation at 248 nm wavelength. 550 shots at maximum fluence of 1 J/cm².](image)
The simulations show good agreement over the bulk of the surface, within +/-10% over the central region of both convex and concave structures. However, the simulator does overestimate the ablation in regions where the gradient is steep leading to larger errors. The discrepancies in these parts are likely to be from making the wrong assumptions about angle dependence. Errors in other parts are probably due to inaccuracies in the ablation curve.

4. Conclusions
A method has been developed for simulating the fabrication of 3D microstructures by projection ablation. Using optical modelling and an empirically derived etch-function, good agreement has been achieved between simulated and fabricated profiles in deep polycarbonate structures. With further refinement the simulator should become a useful tool for iterative correction of mask designs, eliminating the need for multiple prototyping cycles.

Further investigation of the angle dependence is needed to increase the accuracy of the simulator at high angles of incidence. The simulator also needs testing at higher magnification and in deeper structures where the effects of beamlet separation will be more pronounced.

Acknowledgements
This work was funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and Exitech Ltd, Oxford, UK. All experimental work was carried out using facilities provided by Exitech Ltd. The authors are grateful to Karl Boehlen (Exitech Ltd.) for useful discussions relating to micro-lenses.

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