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ANALYSIS OF MICRO-PROFILE IN EXCIMER LASER DRAGGING USING RECTANGULAR MASK

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ABSTRACT

The excimer laser machining has been widely applied to micromachining of various materials. An excimer laser dragging process to ablate a groove pattern on a polycarbonate (PC) sheet through a mask opening is analyzed in this paper. Currently, a large number of papers studying the interaction between the laser machining parameters and various materials are presented. However, the prediction of the cross-sectional profile after the laser dragging is rarely reported for the fabrication of micro-components. This work predicts the profile made by the excimer laser dragging process with a rectangular mask. To accurately predict the machined profile during the dragging process, a mathematical model describing the relationship between laser machining parameters and the produced profile is presented in this work. The proposed model shows the machined profile is determined by the machining parameters. To fabricate a complex micro-component, a method with multi-path scanning in different directions is proposed based on the modeling of the machined profile in single laser dragging. The laser machining parameters include the dragging velocity, pulse repetition rate, pulse number, fluence and the opening dimension of the mask pattern. The material PC is used in this study because of its good absorption coefficient for ultraviolet light and the excellent optical properties at the wavelength of 193 nm. The rectangular shape of mask is used during the laser dragging process. The results show the profile can be effectively predicted in laser dragging.

KEYWORDS: Excimer Laser; Dragging; Micropattern; Polycarbonate; ArF

1. INTRODUCTION

Several micromanufacturing techniques have been developed in response to the demand for fabricating micro-components [1]. The excimer laser machining is extensively applied to micromachining since it was first presented in 1982 [2, 3]. The spontaneous removal of material from the illuminated region of the sample by pulsed ultraviolet laser radiation has given rise to scientific interest in the physical and chemical reaction during machining process [4, 5]. For micromachining, the excimer lasers possess relatively high pulse energies, short pulse duration, and high average and peak power. With the rapid expansion of micro-electromechanical systems (MEMS), excimer laser micromachining has been extensively used for machining of various polymers [6, 7], laser LIGA [8, 9], and for the fabrication of micro-optical components [1, 10]. Some papers have been devoted to studying the fundamental physical and chemical processes in excimer laser ablation, and numerous models have been proposed to explain the observed ablation behavior of various polymer materials, in particular polyimide (PI), and polymethylmethacrylate (PMMA). The ablation process can be divided into three categories, namely photochemical reaction [11, 12], photothermal reaction [13, 14], and the combination of these two reactions [15, 16]. More complex models with such aspects as thermal diffusion, plume effects, nonlinear absorption within the material, and incubation effects are presented to explain the errors from this ablation behavior [17, 18]. A large number of papers have investigated the interaction between excimer laser operating parameters and materials [19, 20]. However, the prediction of the cross-sectional profile of micro-components after the laser dragging is rarely studied. This work predicts the profile machined by the excimer laser dragging process with rectangular shape of the mask, taking into account the mask pattern, the laser fluence, the operating parameters, and ablation characteristics of PC material. To fabricate a complex micro-component, the method of multi-path scanning in different directions is also proposed.

2. EXPERIMENTAL PROCEDURES

The excimer laser micromachining system consists of an ArF excimer laser source, an optical delivery system, a moving stage, and a mask holder. The excimer laser source is the EX50 Gam Laser. Its wavelength, maximum pulse energy, pulse duration, and maximum repetition rate are 193 nm, 35 mJ, 16~20 ns, 250 Hz, respectively. The available laser output modes are constant voltage and constant pulse energy. The laser beam can be shaped by lenses to form the beam size of 6×6 mm^2. The shaped beam size is uniform illumination on the mask plane with the intensity variation less than ±5% root mean square (RMS). This ensures that the laser beam is able to achieve a uniform energy distribution on the workpiece because the variations of energy lead to depth variations of the image during laser ablation. The mask pattern with 3×3 mm^2.is projected onto the workpiece surface by high-resolution projection lens. The projection lens with 10x demagnification factor is utilized to transfer the mask pattern onto the workpiece. The focused spot size of laser beam is 0.3×0.3 mm^2 on the workpiece. The workpiece is mounted on a precision XY stage. To guarantee high machining quality, the Z-axis must be readjusted according to the thickness of each workpiece. During operation, all experiments are conducted in air. The ambient temperature is kept at 21 °C when the repetition rate is higher than 100 Hz for maintaining laser stability and cooling efficiency. The irradiated surface was perpendicular to the direction of incident laser beam. The PC sheet with 1 mm thickness made by Goodfellow is used. The ablation depth is measured by a surface profiler and WYKO optical profiler that measures the height from 0.1 nm to several millimeters with resolution down to 0.1 nm.

3. PRINCIPLE OF LASER DRAGGING

The 3D microstructure can be manufactured by laser dragging process with appropriate mask design, precise motion of the stage and control of the laser operating parameters. When the laser beam illuminates on the mask, the laser beam will go through the transparent portion of the mask onto the material surface and ablate the material. In this study, the workpiece moves with a regular velocity in one direction while the laser is firing. The machined result is illustrated in Fig. 1. The cross-section of the groove pattern is determined by the shape of the mask because the ablation depth of the groove pattern is proportional to the height of mask pattern during the dragging process. Fig. 2(a) shows the height H of the mask pattern is a function of x, and Fig. 2(b) shows that the ablation depth D of the profile increases when the laser dragging velocity decreases in Y direction.

The operating parameters of the dragging process include the workstation dragging velocity (V), pulse repetition rate (f), pulse number (S), fluence (F), width of the mask pattern (W), and height of the mask pattern in the scanning direction (H). They are used as experimental variables to generate various depth and desired profile. Based on experimental study, the relation can be expressed as [19]

$$H(x)= \frac{S(x)\times V}{f} \tag{1}$$

where f is the pulse rate (Hz), S(x) is the laser pulse number of a function of x, H(x) is the height of mask pattern of a function of x (μm), and V is the workstation dragging velocity (μm/sec). Eq. (1) reveals that H(x) is proportional to S(x) while V and f are constant. When a larger H is exposed to the laser beam energy, the deeper ablation depth of workpiece will be produced. One also knows that the ablation depth is correlated with laser pulse number.

$$D(x) \propto S(x) \tag{2}$$

where D(x) is the ablation depth of a function of x (μm), and

$$D(x) \propto \frac{f\times H(x)}{V} \tag{3}$$

The effect of the photochemical reaction and ablation characteristics of PC material can be incorporated in this study [20]. The equation can be expressed as

$$D(x) \propto \frac{1}{\beta}\ln(\frac{F}{F_{TR}})\times\frac{f\times H(x)}{V} \tag{4}$$

In addition, the effect causing the difference of ablation depth between laser dragging and machining at fixed point has to be also considered. The proposed model for PC material removal in the current study is as follows

$$D = \frac{1}{\beta}\ln(\frac{F}{F_{TR}})\times\frac{f\times H}{V}\times\frac{d_{drag.}}{d_{fixed}} \tag{5}$$

where d_{drag}. is the ablation depth by laser dragging process; d_{fixed} is the ablation depth by machining at fixed position.

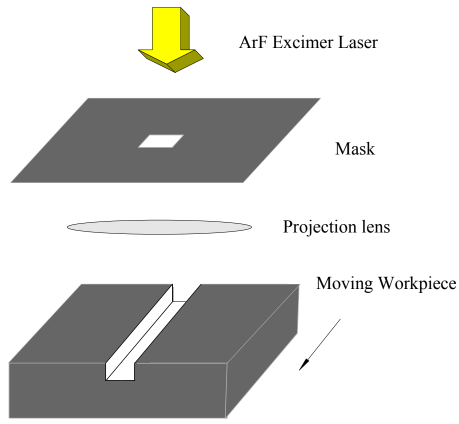


Fig. 1 Schematic drawing of excimer laser dragging process

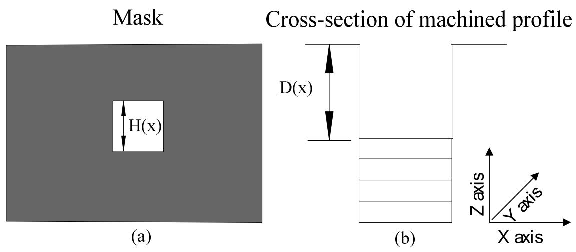


Fig. 2 Mask and machined profile
(a) The height of the mask pattern H(x);
(b) The ablation depth of machined profile D(x) increases when the dragging velocity in Y-direction decreases

4. RESULTS AND DISCUSSIONS

4.1 Experimental Results

The experiments have been carried out to verify the proposed model of the ablation depth. Fig 3 shows the relationship of ablation depth as a function of fluence for PC material removal. From the experimental results, one can obtain the threshold fluence and absorption coefficient of the material, 85 mJ/cm^2 and 10 μm^{-1}, respectively. Fig. 4 describes the relation between the ablation depth and pulse number. It shows that higher laser pulse number results in higher ablation depth at constant pulse repetition rate and fluence. The relationship between ablation depth and pulse number shows an excellent linearity, while the influence of various frequency on ablation depth is insignificant. Fig. 5 observes the relation of the ablation depth versus area of the mask. It illustrates that the ablation depth is independent of area of the mask. Fig. 6 describes the ablation depth produced by both dragging method and machining at fixed position at areas of 0.3×0.3 mm^2 and 0.5×0.5 mm^2, respectively. The reason causing the slight error is attributed to the production of debris. It shows that higher laser pulse number produces more debris. The production of debris by machining at fixed position is more than that by dragging method. Fig. 7 shows the good agreement of the proposed model with the experiment.

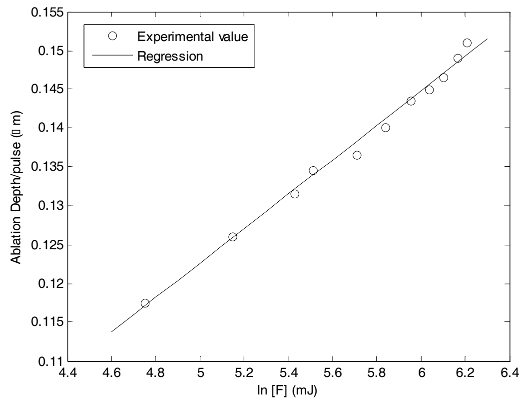


Fig. 3 Experimental ablation depth per shot varying with fluence

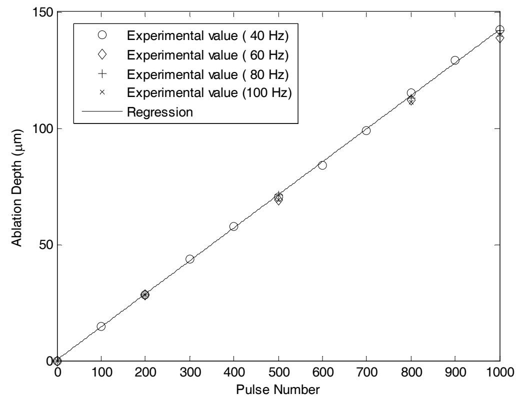


Fig. 4 Experimental ablation depth varying with pulse number

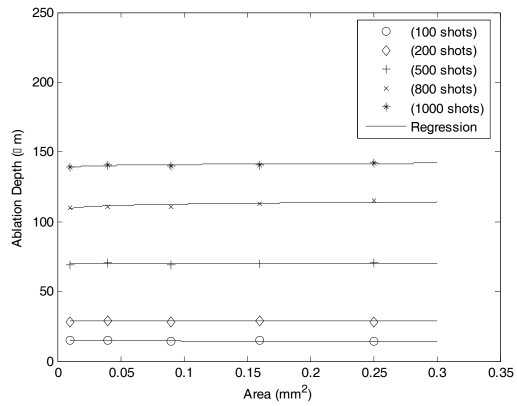
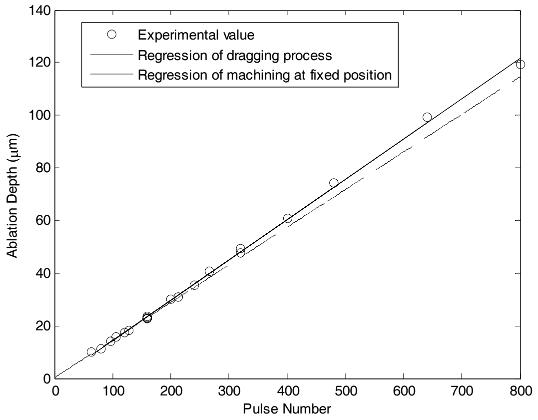
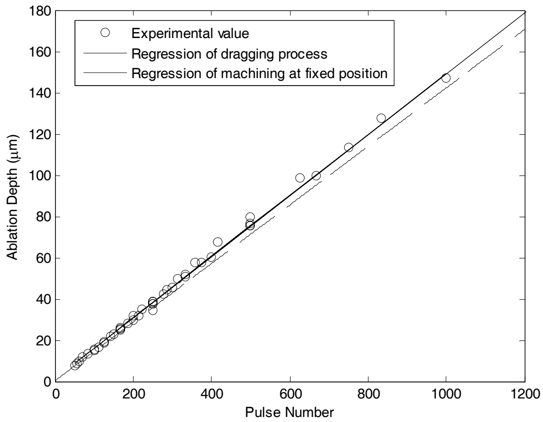


Fig. 5 Experimental ablation depth versus the area of mask opening

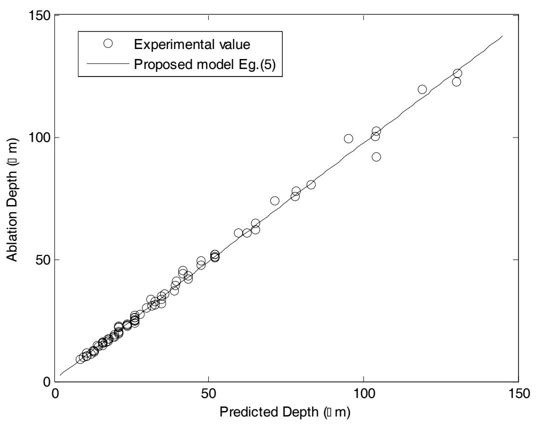


(a) area of 0.3×0.3 mm^2

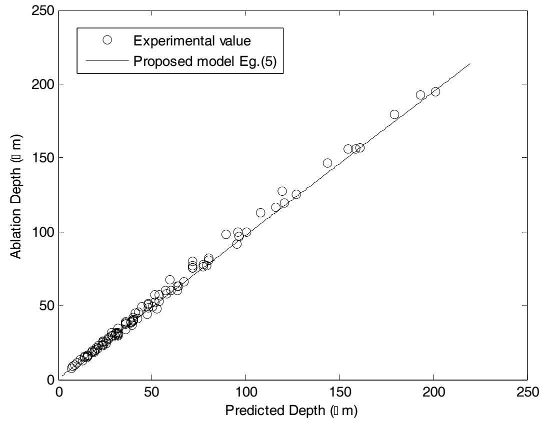


(b) area of 0.5×0.5 mm^2

Fig. 6 Ablation depth produced by dragging or machining at fixed position



(a) area of 0.3×0.3 mm^2

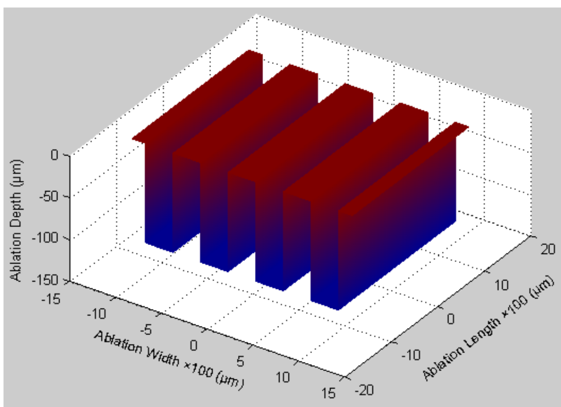


(b) area of 0.5×0.5 mm^2

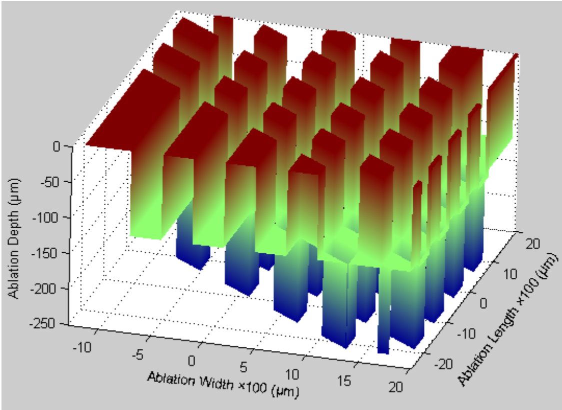
Fig. 7 Experimental verification of the proposed model

4.2 Numerical Results

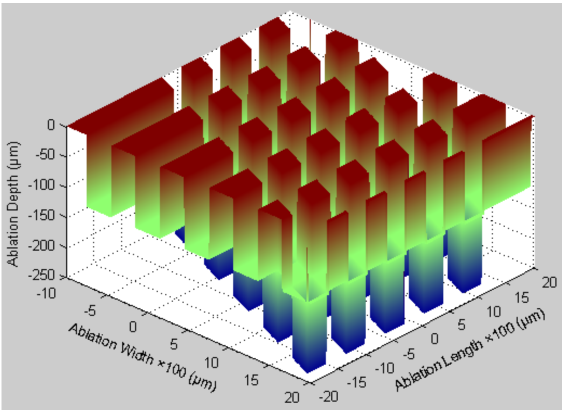
The numerical simulation can not only reduce the amount of laser dragging experiments, but also can assist the design of the microstructures. The rectangular shape of the mask is applied in this simulation. The dragging in one direction is first predicted as shown in Fig 8(a). Subsequently, the simulation of scanning twice in different directions is performed, that the workpiece is moved in one direction to form a profile and then repeating the dragging operation after rotating the workpiece to form another profile. The rotating angles are 0°, 45°, 60°, and 90°. The simulated results are shown in Fig. 8(b) to 8(d), respectively. Fig. 9 shows the SEM image made by laser dragging in one direction. The groove depth obtained by numerical and experimental method is 119 μm and 115 μm respectively. It shows good agreement between the experiment and simulation.



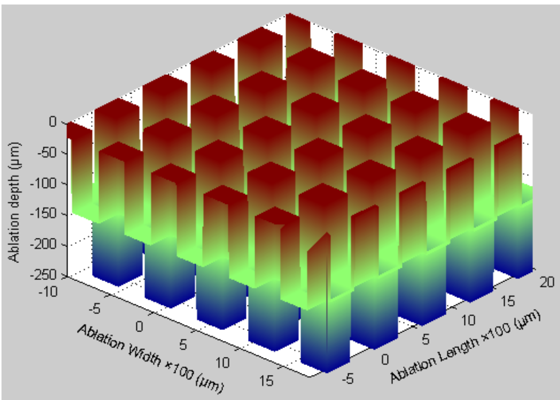
(a) Dragging in one direction



(b) Dragging in 0° and 45° directions



(c) Dragging in 0° and 60° directions



(d) Dragging in 0° and 90° directions

Fig. 8 Simulated machined features (Fluence = 422 mJ/cm^2, Velocity = 0.04 mm/sec, Frequency = 100 Hz, Area = 0.3×0.3 mm^2)

5. CONCLUSION

A mathematical model predicting the machined groove depth of PC material by the ArF excimer laser dragging with rectangular mask is presented. The ablation depth is proportional to the pulse number, while the ablation depth does not depend on frequencies and area of the mask. The proposed model shows good agreement with experimental results. A method of multi-path scanning in different directions is also proposed for fabricating more complex micro-features.

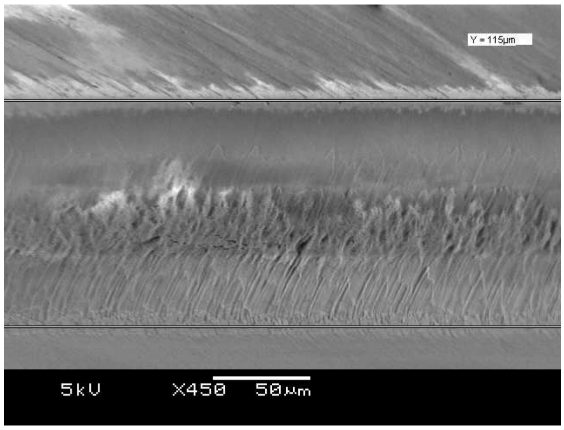


Fig. 9 SEM of machined feature by dragging in one direction (Fluence = 422 mJ/cm^2, Volecity = 0.04 mm/sec, Frequency = 100 Hz, Area = 0.3×0.3 mm^2)

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