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Modeling study on the surface morphology evolution during removing the optics surface/subsurface damage using atmospheric pressure plasma processing

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ABSTRACT

Plasma processing has been widely reported as an effective tool in relieving or removing surface/subsurface damage induced by previous mechanical machining process. However, the surface morphology evolution during removing the damage using plasma processing is rarely reported. In this research, this procedure is studied based on experiments and robust numerical models developed on the basis of Level Set Method (LSM). Even if some unique properties of plasma etching are observed, such as particle redistribution, the dominant role of isotropic etching of plasma processing is verified based on experiments and 2D LSM simulations. With 2D LSM models, the damage removal process under various damage characteristics is explored in detail. Corresponding peak-to-valley roughness evolution is investigated as well. Study on morphology evolution is also conducted through the comparison between experiments and 3D LSM computations. The modeling results and experiments show good agreement with each other. The trends of simulated roughness evolution agree with the experiments as well. It is revealed that the plasma processing may end up with a planar surface depending on the damage characteristics. The planarization procedure can be divided into four parts: crack opening and pit formation; pit coalescing and shallow pits subsumed by deep ones; morphology duplicate etching; and finally a planar and damage free surface.

1. Introduction

Surface/subsurface damage is inevitably induced into the optics using traditional mechanical machining methods. These damages, especially the micro-cracks, are regarded as the leading factor in lowering the strength and laser damage threshold of optical components [1,2]. When irradiated by high-energy laser, even the expansion of a few flaws in the optics could restrain the lifetime of the component [3]. Techniques in eradicating these damages have long been the research interests of scientists. Plasma processing has been recognized as a solution in mitigating or removing these damages in optics [4]. This chemical method also has other superiorities in optical fabrication such as deterministic optical surface machining owing to its near Gaussian-shaped material removal function [4,5], and high potential in manufacturing complex shaped optical surfaces [6] as well as meter scale optics [7]. Therefore, considerable studies have been devoted to develop this technique. Different types of plasma processing have been developed in fulfilling various optical manufacturing demands, such as Plasma Jet Machining [7], Reactive Atom Plasma Technology [8], Plasma Chemical Vaporization Machining [9], Plasma Assisted Chemical Etching [10] and Atmospheric Pressure Plasma Processing [11].

Understanding the surface formation using these plasma methods can help us in determining the location of the plasma methods in an optical fabrication chain, as well as in optimizing the fabrication chain to reduce the fabrication time and production costs. Consequently, researchers have been devoting to study on the surface formation using plasma processing. Jin et al. reported an experimental study on the surface morphology and chemistry evolution of fused silica surface using Atmospheric Pressure Plasma Processing (APPP) [11]. Xin et al. studied the surface formation and morphology evolution of ground fused silica parts using APPP as well. Their results indicated some similarities between the plasma method and the isotopic wet chemical etching, and the surface formation resulted from removing the surface/subsurface damage [4]. Research on surface smoothing mechanism was basically reported by Zarowin using a model based on differential surface evolution equations. A simple sinusoidal profile was used as an initial

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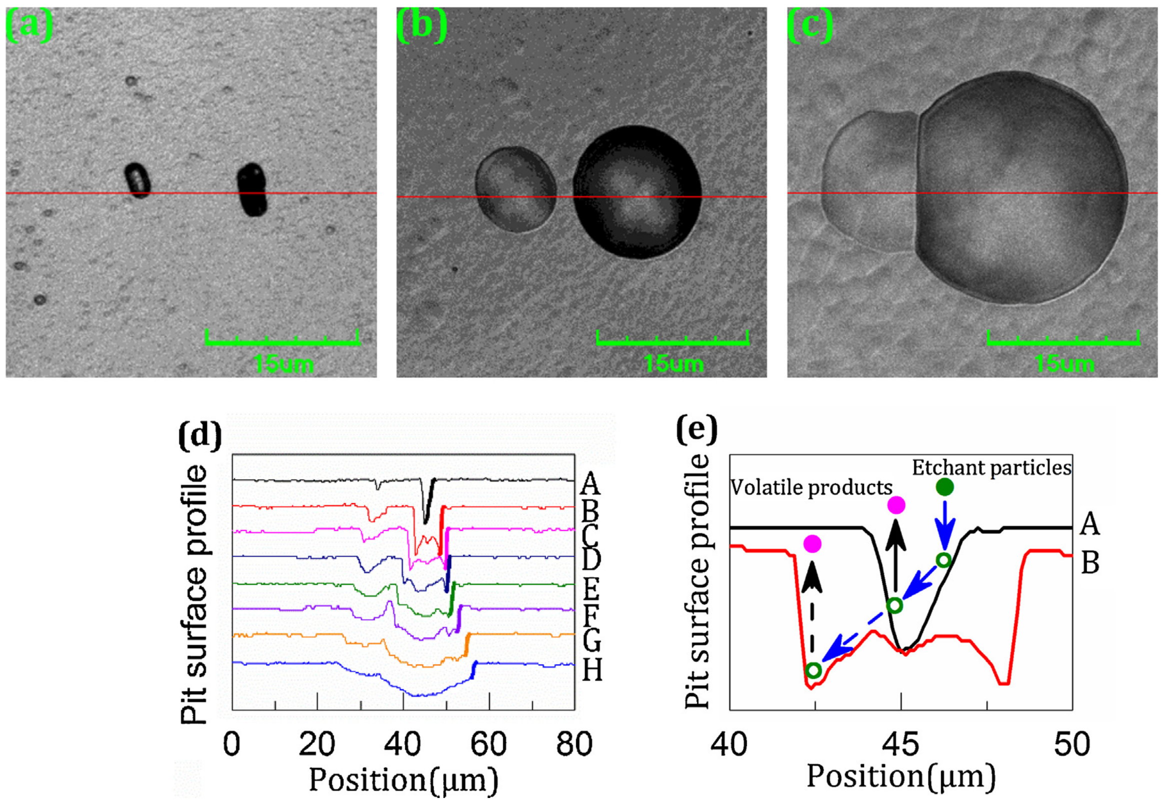

Fig. 1. The selected evolution of etched micro-cracks with various material removal depths: (a) 1 μm; (b) 8.8 μm; (c) 19.3 μm. (d) Cross section profiles for the etched pits with material removal depths: A 1 μm; B 3.6 μm; C 5.5 μm; D 7.1 μm; E 8.8 μm; F 10 μm; G 15.6 μm; H 19.3 μm. (e) Schematic drawing of the etchant particle redistribution and the formation of micro-trenches (For interpretation of the references to color in the text, the reader is referred to the web version of this article).

input for the 2D profile evolution model and a fundamental explanation on the surface smoothing mechanism was provided [12]. For surface formation in removing damage using isotropic etching, the research of Spierings showed that cusp-like surface structure was originated from surface flaws in wet chemical etching [13,14]. Wong et al. reported experimental and theoretical studies on the effect of the damage characteristics on the peak-to-valley roughness (R_{PV}) evolution with wet chemical etching [15,16]. Yet, not many studies theoretically focus on the surface formation and evolution process during removing surface/subsurface damage using plasma processing. In this paper, we demonstrate the dominate role of isotropic etching using APPP. A 2D level set method (LSM) model is then applied to simulate the development of two micro-cracks under isotropic etching, and the results are compared with the experiments to verify the demonstration. Moreover, the 2D surface profile developments considering the influences of different micro-crack characteristics are explored. Finally, 3D morphology evolution is investigated and compared with the experimental results during removing the damage.

2. Numerical modeling method and experimental setup

LSM, introduced by Osher and Sethian [17], has been widely applied in tracking the interface evolution such as fluid mechanics, combustion, computer vision, crystal growth, and etching [18,19]. This method is a robust numerical technique for tracking the evolving interfaces and providing accurate geometric properties. The interface, either a 2D profile or 3D surface, is embedded as a zero level set of a higher-dimensional function. The motion of the interface is governed by an externally generated velocity field. The corresponding level set equation for APPP processed interface is

$$\phi_t = V_n |\nabla \phi|$$

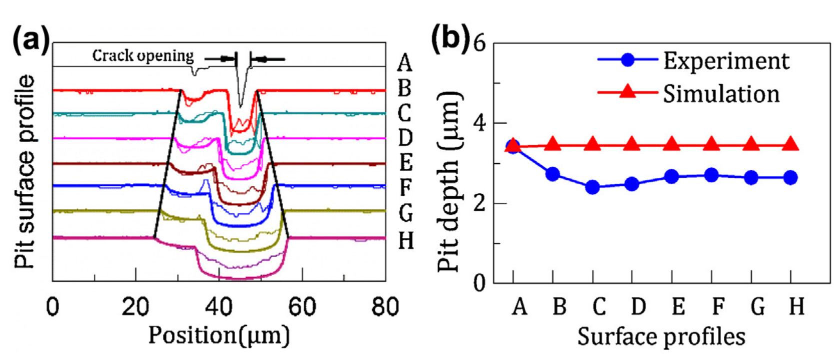

Fig. 2. Comparison between the experiments and modeling results (a) the surface profiles, (b) the big pit depth.