Simultaneous atmospheric pressure plasma jet etching and laser irradiation for ultra-precise optical glass processing

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Abstract. The use of beam-based technologies to process optical elements with nanoscale precision enables the fabrication of freeform surfaces. In particular, atmospheric pressure plasma jets (APPJs) have desirable properties, e.g., depth precision < 5 nm, low surface roughness and processing at atmospheric conditions. However, the composition of optical glasses and glass ceramics, containing metal oxides, leads to the formation of non-volatile reaction products that remain on the substrate surface. These residues reduce the etching rate and cause severe roughening of the surface. Laser irradiation has already been demonstrated as a promising option for removing the residual layer and the aim of the current work is to integrate it into the APPJ system for simultaneous processing. Therefore, an excimer laser (λ = 248 nm; t_{Pulse} = 20 ns) with a maximum pulse frequency of 100 Hz was added to a plasma jet setup and experiments with varying laser fluences as well as laser frequencies were performed on N-BK7 substrates. White light interferometry was used to analyse the samples. The experiments showed an improved etching result with higher removal rates for the combined process at high laser pulse frequency (100 Hz) and fluences in the range of 0.1-0.45 $J \cdot cm^{-2}$.

1 Introduction

Modern high performance optical elements e.g., aspheres and free form surfaces, require deterministic surfacing procedures, such as ion beam figuring, magnetorheological finishing, corrective bonnet polishing or plasma jet etching. In addition to the low surface roughness with excellent depth precision, these processes also cause minimal damage to the remaining glass/glass ceramic material. Most of these processes require vacuum conditions, which increases processing costs and maintenance effort. Atmospheric pressure plasma jet (APPJ) etching, on the other hand, offers dry, flexible material removal under atmospheric conditions. It uses fluorine-containing gases which, when excited by microwaves, form fluorine radicals which react with the substrate material to form volatile compounds. Fluorine based atmospheric plasmas are already used as an beneficial tool for SiC, Si and fused silica.[1, 2] Commonly used optical materials based on silicon oxide have additional admixtures of various oxides to modify optical or thermal properties. N-BK7 and Zerodur® in particular have a significant share in the optical industry. The presence of metal oxides in their composition leads to the formation of non-volatile reaction products during APPJ etching. These compounds remain on the substrate surface as a residual layer, causing masking effects, a reduced removal rate and surface roughening.[3] Laser removal of the residual layer on N-BK7 and Zerodur has been demonstrated in previous studies with a residue-free surface without damaging the glass/glass ceramic.[4] An alternating approach of APPJ etching and laser cleaning of N-BK7 resulted in nearly constant etch rates and significantly lower roughness compared to APPJ processing alone followed by solvent-based cleaning.[5]
In the present work, the simultaneous processing of plasma jet and laser is analyzed.

2 Methodology

The setup consists of a sample holder mounted on a computer-controlled x-y-z stage system that moves the sample relative to the fixed plasma jet source and laser system (see Fig. 1). To enable simultaneous processing, the plasma jet is tilted at an angle of 45°. The plasma jet source is excited by 2.45 GHz microwave pulses with a pulse length of 20 µs and an average power input of 18 W with a peak power of 300 W. The process gas contains 300 sccm He, 0.8 sccm CF4 and 2 sccm O_2. For a stable plasma jet formation 400 sccm N_2 are fed separately as a shielding gas. The laser beam is provided by an excimer laser (λ = 248 nm; t_{Pulse} = 20 ns) with a maximum pulse frequency of 100 Hz and is focused on the centre of the plasma jet footprint on the substrate. N-BK7 disks with a diameter of 50 mm and 3 mm thickness were used as samples.
Stationary etchings with simultaneous laser irradiation at a fluence of 0.04-0.45 $J \cdot cm^{-2}$ were performed with varying dwell times and pulse frequencies. As a reference, the samples were etched with the same parameters but without laser irradiation. After etching the remaining

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residual layer was removed by solvent-based cleaning with a 50:50 mixture of DI water and ethanol and the samples were analysed by white light interferometry.

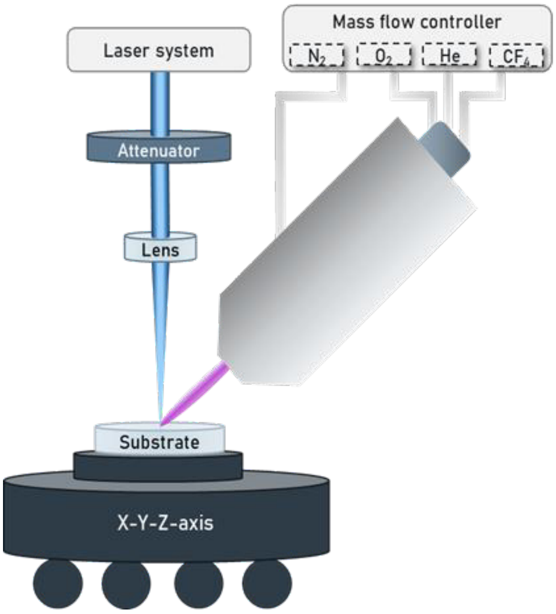

Fig. 1. Sketch of the experimental setup for combined plasma jet etching and laser irradiation

3 Results

In order to determine the best possible combination of parameters for simultaneous processing, different laser frequencies were first tested at varying fluences. This resulted in an etch stop at <150 nm etching depth for lower frequencies (2 and 10 Hz), regardless of the fluences tested, and improved etching for 100 Hz compared to the reference without laser irradiation, as shown in Fig. 2. In a fluence range of 0.1-0.45 J·cm^{-2} the etching depth for 100 Hz is constant. As the fluence is further reduced, the etching depth decreases to 900 nm for 0.04 J·cm^{-2}.

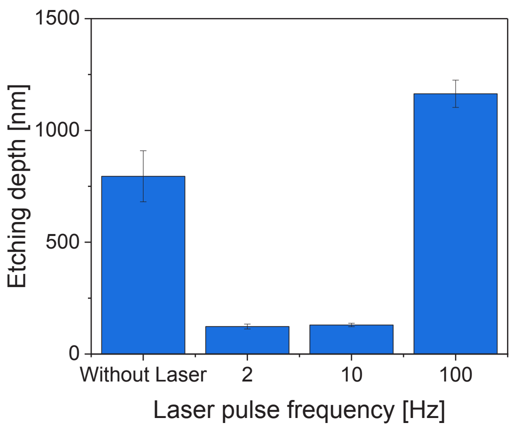

Fig. 2. Etching depth of APPJ etchings for a dwell time of 5 s depending on the pulse frequency of assisting laser irradiation compared to a reference without laser.

A comparison of the etching rates of plasma jet alone with laser assisted APPJ at a fluence of 0.26 J·cm^{-2} and 100 Hz pulse frequency etching shows significantly higher etching rates for the combined process, as shown in Fig. 3. The increase in etching rate with increasing dwell time is due to the increase in surface temperature caused by the thermal energy provided by the plasma jet.

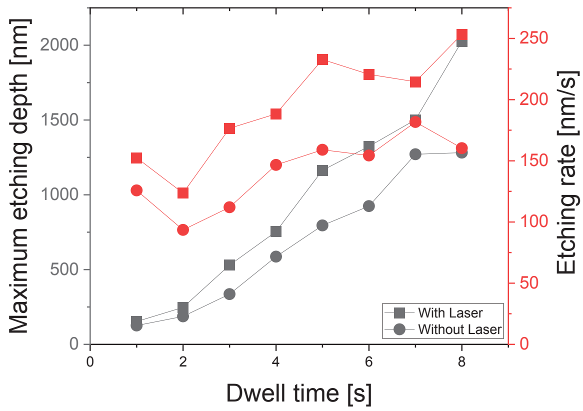

Fig. 3. Maximum etching depth and etching rate for APPJ alone and with laser assistance at a fluence of 0.26 J·cm^{-2} and 100 Hz pulse frequency.

It has been shown that the etching rate can be significantly increased by using simultaneous laser processing with an appropriate parameter set. Further studies are required to investigate the material removal phenomena and the extent to which the roughness can be reduced by laser assistance.

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