Advances in precision freeform manufacturing by plasma jet machining -INVITED

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Abstract. Atmospheric pressure plasma jet machining technology provides a flexible and efficient way to fabricate precise freeform optics. Due to the pure chemical material removal mechanism based on a dry etching process using fluorine containing gas, the choice of materials that can be treated is limited. Fused silica, Si, SiC or ULE® are easy to machine since the etching products formed are solely volatile. Recently, plasma jet machining has been also adopted to treat optical glasses like N-BK7® which contain amongst others alkali metals that form a solid residual layer during etching. In the paper a new approach to apply deterministic plasma jet etching on optical glass coping with complex etch characteristics caused by the residual layer is introduced.

1 Introduction

Current developments in the field of modern optics are aimed at miniaturization, quality improvement and reduction of the assembly effort for optical systems, for example by increasing the complexity of the optical functional surfaces used. Especially optical freeform surfaces have become increasingly important in recent years, since they allow optical assemblies with a reduced number of optical surfaces compared to systems without freeform surfaces, and therefore they are much more compact and lighter. In addition, losses in radiation power can be minimized and, in some cases, completely new optical functionalities can be achieved.

However, the flexible and efficient production of precise optical freeform surfaces is a major challenge. Unlike spherical or aspherical surfaces, freeform surfaces do not have rotational symmetry, but generally have six degrees of freedom, which can be described mathematically with polynomials or splines. Due to the locally changing curvature, locally acting, so-called sub-aperture processes must be used for free-form surfaces. In order to achieve high-precision surfaces correction and finishing techniques are applied. A range of deterministic methods exist, such as bonnet polishing, magnetorheological finishing, or ion beam finishing.

Mechanical abrasive techniques can be applied on nearly every kind of optical material. However, a challenge is to achieve a sufficiently high removal rate to eliminate sub-surface damage (SSD) while maintaining the form after the shaping process, which is usually already within the specification range. Beam based techniques such as ion beam figuring potentially yield ultra-high precision on surfaces but the removal rates are very low and costly vacuum equipment is necessary. As an alternative plasma jet machining was introduced that provides a flexible and efficient way to fabricate precise freeform optics at atmospheric pressure using inexpensive equipment [1].

2 Plasma jet machining

Plasma jet machining (PJM) technology is a sub-aperture surface manufacturing method based on a reactive plasma jet etching process that allows precise material removal controlled by pure chemical interaction between the tool and the surface. The plasma jet tool exerts virtually no forces to the surface and thus induces no SSD. Furthermore, the rotationally symmetric near-Gaussian tool function that can be scaled from 0.3 mm to 4 mm (full width at half maximum) enables to generate a desired freeform shape with nearly no geometric limitations. A microwave-driven plasma nozzle generates an Ar/He plasma jet at atmospheric pressure where reactive gases like CF_4 and O_2 are admixed in order to create free fluorine atoms by means of dissociation. The fluorine atoms react with the substrate material to form volatile compounds, and material removal from the surface is achieved. Figure 1 shows a photograph of the plasma jet interacting with an optical surface and a typical cross section of the arising tool function profile. For easy-to-etch materials such as fused silica, silicon, ULE®, or SiC a simple etch chemistry is utilized leading to exclusively gaseous reaction products in the form of SiF_4 and CO_2. Hence, the material removal rate which can reach up to 20 mm^3/min remains constant as long as a constant substrate surface temperature distribution is maintained during the process. For the surface machining process the plasma nozzle is moved relative to the surface by a CNC motion system. Shaping or surface figure error correction is

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performed by applying dwell time methods that are usually employed in deterministic surface machining. As in most cases the heat flow from the plasma jet to the surface alters the surface temperature distribution and thus the etching rate in the course of the machining process, it must be taken into account by the dwell-time calculation software based on additional input data obtained from temperature and etch rate measurements.

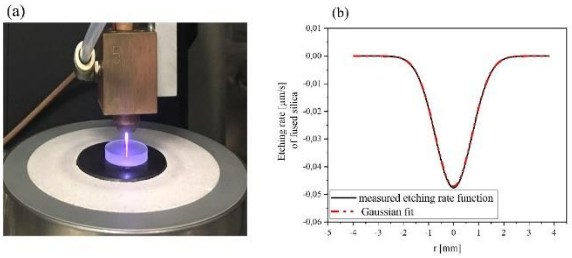

Fig. 1. (a) Plasma jet on substrate, (b) Typical plasma jet etching tool function on fused silica.

3 Plasma jet machining of N-BK7

Different to the above mentioned easy-to-etch materials optical glasses like N-BK7® contain alkali metal oxides in addition to silicon dioxide. Although SiO_2 is also converted into volatile products here, the chemical interaction between the plasma-generated fluorine radicals and the metal components of N-BK7 leads to the formation of non-volatile compounds such as KF and NaF, which remain as residual layers on the surface. Consequently, the fluorine attack to the surface is inhibited or eventually stops completely. Hence, the local etching rate function is not constant in time anymore but rather depends on the local layer thickness that develops depending on the applied etching time. In Figure 2 (a), the radial etch rate distribution is shown depending on the residual layer thickness while the N-BK7 substrate is approx. at room temperature. The data illustrate that the etching rate varies strongly in a nonhomogeneous way over the radial dimension. It is observed that in the center the etch attack stops for layer thickness of approx. 0.3 µm, whereas in the periphery the etching process can proceed. It is clear that such complex and irregular behaviour is not suitable for a deterministic machining process. However, it is shown in Figure 2 (b) that heating the substrate to achieve elevated temperatures of approx. 350 °C results in a much more uniform etching rate distribution maintaining a Gaussian tool function throughout the etching process. The reason for this is a structural change of the residual layer from a densely closed layer occurring at room temperature to a porous layer found at elevated temperature. Thus, the fluorine atoms can penetrate the layer reaching the N-BK7 interface to proceed etching [2, 3]. Although the absolute values of etching rate gradually decrease with increasing layer thickness, such a homogeneous behaviour is more suitable to be taken into account in a dwell-time based machining algorithm. An enhanced approach to dwell time calculation has been tested where the target topography (either a prescribed surface shape to be generated, or a measured surface error topography) is deconvolved by an assumed constant Gaussian tool function in order to obtain a dwell-time matrix. In a next step, the calculated local dwell times are convolved with a spatio-temporally varying rate function gained from preliminary measurements (i.e. the rate function in Figure 2 (b) which is additionally corrected for temperature effects). Performing a virtual machining process using a Matlab® model yields then a topography that differs to some extent from the target topography. Taking the difference topography as a correction to the initial target topography and recalculating dwell times by deconvolution yield an improved estimation of machining data. This procedure can be iterated in order to minimize the difference of the prescribed and calculated topography. The procedure resembles the van Cittert algorithm used for numerical deconvolution. As a proof-of-principle, a freeform surface on N-BK7 featuring a sinusoidal test structure with PV of 800 nm has been fabricated by plasma jet machining using the described method. For interferometric surface measurement the residual layer was removed by rinsing in water/ethanol. In Figure 3 the shape and corresponding horizontal cross sections are depicted. Additionally, the target topography is shown. The measured profile has a PV of 817 nm, which is about 2% higher than the prescription profile. Presumably, local surface temperature fluctuations were still not completely corrected in the model.

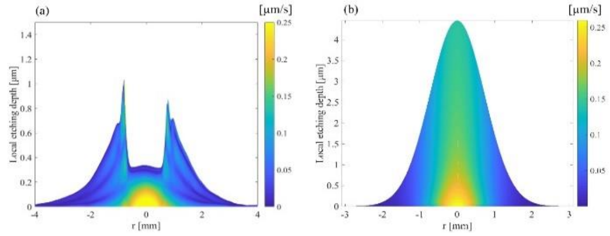

Fig. 2. Radial etch rate distribution functions on N-BK7 obtained from static footprint etching depending on layer thickness at different surface temperatures: (a) T_S=25°C, (b) T_S=350°C.

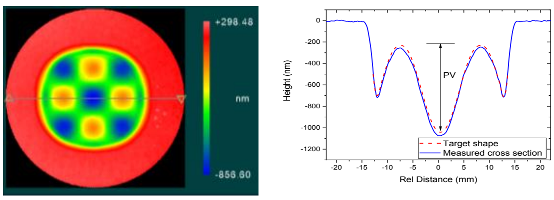

Fig. 3. Interferometric measurement of a test structure on N-BK7 and corresponding horizontal cross section (blue: measured, dotted red: target shape.

The described method and the experimental result show a potential way to cope with residual layers formed in the etching process that locally and temporally influence the etch rate function in plasma jet machining of optical glasses.

References

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