Plasma jet assisted polishing of fused silica freeform optics

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Abstract. Atmospheric pressure plasma jet machining technology not only provides a flexible and efficient way to generate and correct optical freeform surfaces made of fused silica, it can also be applied as a surface smoothing or polishing technique. Thermal plasma jet treatment leads to softening and redistribution of the material. An accurate temperature regime during the process is inevitable to achieve a uniformly smoothed surface. The possibilities for in-process temperature control are demonstrated. Surface roughness values can be significantly reduced by a factor of 1000 depending on the initial roughness of the ground surface.

1 Introduction

The steadily increasing demand for precision freeform optics e.g. for laser beam shaping or imaging applications call for innovative optical fabrication technologies that allow for highly flexible processes combined with high efficiency. Since freeform surfaces exhibit varying slopes, locally acting sub-aperture tools and computer-controlled machines are employed in the machining processes.
A range of deterministic surfacing methods exist, such as freeform grinding, bonnet polishing, magnetorheological finishing, ion beam finishing, or plasma jet machining (PJM). PJM has been developed during the recent two decades as an alternative process for surface figure generation, figure error correction, as well as for surface smoothing [1,2]. It has been shown that with PJM freeform optics made of fused silica can be produced employing a series of processing steps that rely on the plasma jet technique.
Plasma jet machining technology utilizes a localized plasma dry etching process for precise material removal.
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 reactive species such as free fluorine and oxygen 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. For materials like fused silica, silicon, ULE®, or SiC the etch chemistry leads to the formation of gaseous reaction products in the form of SiF_4 and CO_2. When interacting with the substrate surface the plasma jet tool exerts nearly no mechanical forces. Thus, no sub-surface damage is induced. The tool influence function exhibits a rotationally symmetric near-Gaussian shape. Depending on the type of plasma source, the applied microwave power and gas flow rates a lateral removal profile of 0.3 up to 4 mm (full width at half maximum) can be adjusted.
In order to perform a machining process, the plasma nozzle is moved relative to the surface by a CNC motion system. Shaping or surface figure error correction is executed by applying dwell time methods that are usually employed in deterministic surface machining.
Since the dry chemical etching process on fused silica removes the polishing layer, existing residual sub-surface damage will be exposed. Depending on the quality of pre-machining steps like grinding or polishing and the amount of material removal during PJM the resulting surface roughness increases. In order to obtain optical quality with Sq < 1 nm a post-polishing step is often required. In the case of freeform surfaces with relatively small workpiece dimensions of 5 mm up to 50 mm diameter exhibiting steep surface gradients, bonnet polishing may lead to surface form deterioration due to varying tool influence functions. Hence, an alternative smoothing step is required. The application of plasma jets provides the possibility to smooth fused silica surfaces via a thermal interaction similar to laser polishing. In the paper we discuss several aspects of the plasma jet assisted smoothing process, such as process stabilization and investigations to identify optimum process parameters to obtain surface roughness Sq values of less than 1 nm.

2 Plasma jet polishing

A microwave-driven plasma jet source is employed which is fed by inert gases helium and argon with a total gas flow rate of approx. 300 sccm. The effective microwave power is adjusted in the range of 120 W – 170 W.
The smoothing of the optical surface is a thermal process where the substrate is locally heated by the plasma jet. When the jet contacts the substrate, convective local heating of the substrate by the plasma gas near the softening point $T_s(\eta = 10^{7,65}$ dPas) = 1585°C results in softening of the glass material and a viscous flow on the

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surface. The resulting minimized surface tension leads to a reduction in roughness.

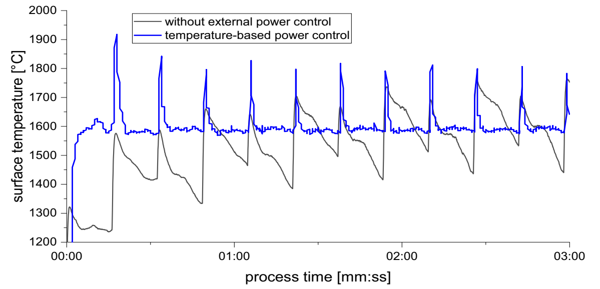

Fig. 1. Plasma jet induced surface temperature with and without PID control system. Temperature peaks occur due to end of scan line deceleration of the motion system.

The resulting maximum temperature distribution while the plasma jet moves in a meander pattern over the surface depends on the applied heat flux as well as on the scan velocity, the thermal properties of the glass, and the thermal coupling of the substrate to the environment. If the microwave power is set constant, a non-uniform temperature profile is observed (Fig.1: black curve). Since a constant temperature is required for uniform processing, a PID-based control system was developed that adjusts the microwave power to reach and hold a preset temperature measured by pyrometer in the center of the plasma jet. The microwave is applied in form of pulses of a frequency of 60 kHz with peak power of approx. 180 W. The control system uses pulse width modulation to adjust the power necessary to reach a maximum temperature of $T_{surf} = 1600°C$ (see Fig. 1). In order to determine the local smoothing capability of the jet, discrete rectangular structures have been produced by ultra-short pulse laser micromachining that were subsequently smoothed by the plasma jet. A fitting algorithm that assumes a Gaussian filter function has been applied to the areal measurement data of the initial and smoothed structures to obtain the 2D-filter size. Fig. 2 shows the original, the plasma smoothed and the filtered original structure. The filter function exhibits a cut-off wavelength of approximately 0.190 mm.

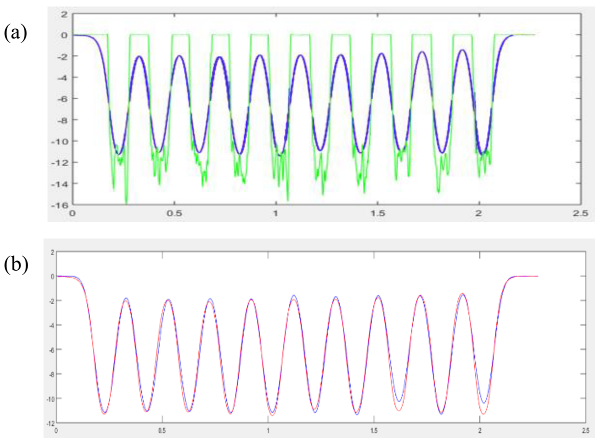

Fig. 2. (a) Cross section of laser machined rectangular line structures (green) and plasma jet smoothed profile (blue), (b) Comparison of plasma smoothed profile (blue) and filtered original profile using the calculated Gaussian filter function.

Areal smoothing of a ground surface with initial roughness of Sq = 330 nm in the spatial wavelength range of 0.8 µm – 40 µm) and waviness of Sq = 230 nm in the spatial range of 8µm – 200 µm was performed with a scan velocity of 2 mm/s and line feed of 0.3 mm. WLI measurement yield a roughness of Sq = 0.3 nm and a waviness of Sq = 9 nm. The PSD functions show that low wavelengths are smoothed more efficiently. Depending on the applied temperature a stronger smoothing effect is observed.

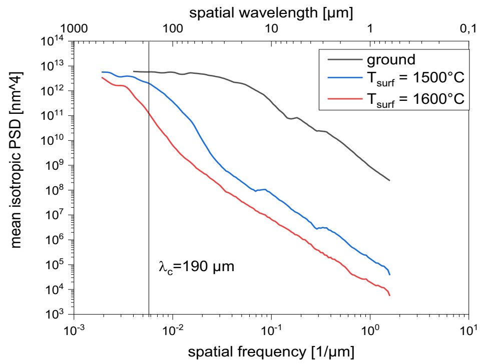

Fig. 3. Isotropic power spectral density (PSD) function of ground and plasma polished surface.

Plasma jet smoothing was applied as final step in a plasma based freeform manufacturing process. The target shape exhibiting a PV of 1300 µm on a diameter of 25 mm is shown in Fig.4 (a). In Fig. 4(b) the process convergence (residual error RMS) is plotted. Starting from a planar surface, shape generation was performed by PJM (step 1). After bonnet polishing (step 2) the form deteriorated. Subsequent PJM error correction steps (step 3,5) with intermediate soft polishing (step 4) could decrease the residual figure error. Finally, plasma polishing (step 5) lead to surface roughness of Sq 0.4 nm, while the figure error was preserved below the specified 1 µm RMS.

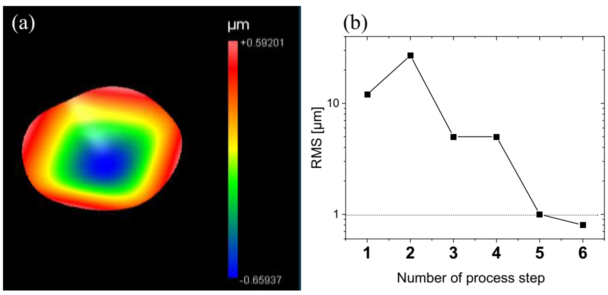

Fig. 4. (a) Freeform target design, (b) process convergence in terms of residual error RMS.

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References

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