Plasma jet polishing of rough fused silica surfaces

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Abstract

An alternative polishing process for smoothing of fused silica surfaces will be presented. The key part of this process is the Atmospheric Plasma Jet Machining (APJM) based on a microwave (2.45 GHz) powered atmospheric plasma jet source operating in cw-mode and working with a noble gas mixture of He and Ar. The plasma tool FWHM is about 1.5 mm. Due to the highly localised working area this process is applicable to plane, spherical, aspheric and micro structured substrates. The polishing process is based on two mechanisms: heating of the fused silica substrate by the plasma jet gas and coupling of microwave emitted by the plasma jet into the substrate surface. This leads merely to a local fusing of the surface, but no material removal occurs. The results of plasma polishing of fine ground fused silica in dependence of the plasma power, gas mixture, tool velocity and tool offset will be discussed in detail. The values of roughness and waviness before and after the plasma polishing process are measured using laser profiler, white light interferometer and atomic force microscope. For example, starting from a fine ground fused silica surface with an initial surface roughness of 551 nm Ra the plasma polishing process with microwave power of 135 W leads to 0.64 nm Ra measured by white light interferometer (50x optical magnification) and 0.27 nm Rq measured by atomic force microscope (5x5µm²), respectively.

1 Experimental setup

Local plasma jet polishing was accomplished by an atmospheric pressure plasma jet source which has been primarily developed for plasma jet etching process [1, 2]. The plasma jet source consists of a cross-shaped coaxial wave guide system powered by microwave energy at a frequency of 2.45 GHz. The microwave power was supplied by a MUEGGE microwave generator connected to the source via a coaxial cable. The inner conductor of the cross bar consists of a stainless steel tube, which ends in an outlet nozzle with inner diameter of 0.75 mm. We employ a dielectric barrier discharge in the hollow-cathode mode to form an argon/helium plasma jet. The plasma jet source was mounted on a 5-axes CNC machine. Figure 1a shows the plasma jet in contact with the fused silica surface.

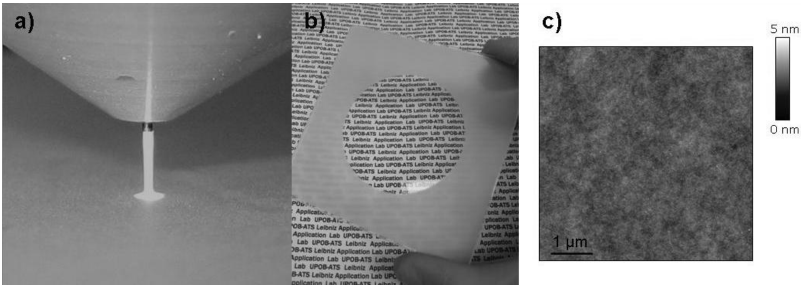

Figure 1: a) microwave (2.45 GHz) powered atmospheric plasma jet source operating in cw-mode for plasma polishing, b) plasma polishing of fused silica wafer (fine ground), polished area Ø 60 mm, c) AFM image of plasma polished fused silica with a final value of Rq = 0.27 nm (FFT filtered).

2 Results and discussion

Plasma polishing was applied by line-by-line raster scans with different process parameters (plasma power, gas mixture, tool velocity and tool offset) on fine ground rectangular 100x100mm² fused silica plates with initial roughness values of about 500 nm Ra. Figure 1 b shows a typical plasma-polished area with a diameter of 60 mm. The final micro roughness was measured by AFM (see Figure 1 c) with a value of Rq=0.27 nm. Figure 2 compares typical results for surface profile, roughness and waviness obtained on the initial and polished surface, respectively ,measured by a laser profiler. It can be seen that not only the roughness decreases but also the waviness is significantly reduced from about 1 µm RMS to less than 0.1 µm RMS.

The plasma polishing process is based on the local temperature rise up to the softening point of fused silica on the substrate surface (T_S ~ 1900K [3]) by the hot plasma jet and a microwave coupling of the plasma jet into the surface. The smoothing effect can be mainly described by thermally induced redistribution of material at the surface and a minimized surface tension similar to the laser polishing process [4]. The plasma polishing process causes no material removal and hence it is shape maintaining as well as independent on the particular surface shape. Furthermore, no mechanical forces are applied to the surface. These features make this tool very interesting for efficient manufacturing of complex shaped optical elements like aspheres, freeforms, or micro-structured surfaces.

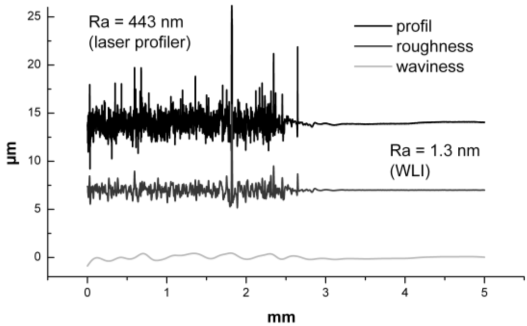

Figure 2: Plasma polishing of fused silica like sample with initial (left side) and polished (right side) surface measured by laser profiler. The final roughness value measured by white light interferometer (20x) is 1.3 nm Ra (initial value 443 nm Ra).

There is a strong dependence of the plasma polishing process performance on microwave power, tool velocity and tool offset. Table 1 summarizes the dependence on the supplied microwave power. For values higher than 135 W the roughness values were not further reduced.

Table1: Roughness values after plasma polishing of fine ground fused silica surfaces with initial roughness of about 550 nm Ra in a line-by-line process with tool speed of 1 mm/s and pitch 0.1 mm depending on the plasma power.

microwave power	105 W	120 W	135 W
Ra (WLI 50x)	76 nm	2.35 nm	0.64 nm

The tool offset (distance between the nozzle and the sample surface), which eventually influences the local surface temperature profile has to be optimized with respect to the achieved micro-roughness and waviness. For lower distances the smoothing of high spatial frequency roughness improves, whereas the mid spatial frequency roughness may become worse due to additional periodic structures resulting from steep gradients in the temperature profile in combination with the raster scan, especially if the pitch is too large. For larger distances the polishing factor (relation between roughness before and after polishing) and the polishing rate (polished area per time) decreases due to the fact that the effective plasma jet interaction area (i.e. the area where surface temperature reaches the “smoothing” point) decreases. For our experimental setup the optimum tool offset was found to be 3-5 mm.

Furthermore, the local temperature profile and hence the smoothing effect is influenced by the tool scan speed, which was varied between 1 and 5 mm/s using a pitch of 0.1 mm. For example, the polishing factor decreases from 500-1000 to 5 if the tool speed is changed from 1 to 5 mm/s.

3 Conclusion

The plasma polishing process is an alternative polishing process for smoothing of rough fused silica surfaces and surfaces of similar materials like ULE™. The key advantage of the process is the shape maintaining, contactless, and local, interaction which makes it interesting especially for the fabrication of complex shaped free form and micro-structured surfaces. Starting with roughness values of about 0.5 µm Ra, surfaces with optical quality can be achieved within one process step. Best surface quality is reached with polishing rates of about 10 mm²/min. Depending on the plasma parameters different surface roughness values are adjustable.

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