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Reactive ion beam figuring for optical freeform surfaces

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Abstract
Freeform surfaces are required in many optical applications but can be challenging to fabricate due to their complex, non-rotationally symmetric shapes. They typically require tool sizes significantly smaller than the optical element's clear aperture—a constraint that becomes particularly critical when producing small-diameter components such as laser beam shaping elements through traditional mechanical methods like grinding and polishing.

While plasma jet machining has emerged as an established technique for fabricating such optical elements in fused silica, its underlying chemical mechanism—based on silicon-fluorine reactions—limits its broader application. The adaptation of plasma jet etching to alternative substrate materials, including sapphire and additive-containing optical glasses such as Zerodur or N-BK7, remains problematic. Reactive ion beam etching offers a promising alternative, combining chemical and physical etching mechanisms for both correcting and fabricating freeform optics. This dual-mechanism approach effectively mitigates common fabrication challenges: the physical sputtering component reduces the impact of surface contaminants and metal oxide constituents that typically form masking layers during purely chemical processes. Additionally, the method demonstrates enhanced resistance to pitting caused by subsurface damage from mechanical polishing, potentially eliminating the need for post-processing across various materials. This research examines the comparative advantages and limitations of reactive ion beam etching and plasma jet machining.

Reactive Ion Beam Etching, Ion Beam Figuring, Freeform Surfaces, Plasma Jet Machining

1. Introduction

The fabrication of freeform optical surfaces represents one of the most demanding challenges in precision manufacturing. While mechanical abrasive processes have traditionally dominated optical fabrication, they face significant limitations when confronted with complex freeform geometries and small apertures. Non-mechanical approaches offer a promising alternative, circumventing many of these limitations. Ion beam figuring (IBF) and plasma jet machining (PJM) enable precision fabrication at micro- and macroscopic scales.

IBF operates through physical sputtering, where accelerated molecules or atoms transfer momentum to remove material. In contrast, PJM achieves material removal through chemical interactions, specifically the formation of volatile compounds between silicon and fluorine-containing molecules [1]. Reactive ion beam figuring (RIBF) represents an innovative hybrid approach, combining physical sputtering with chemical material removal through accelerated reactive ions as also applied in reactive ion beam etching (RIBE) for pattern transfer [2]. This dual-mechanism process significantly enhances material removal rates for silicon-based optical materials compared to conventional IBF techniques.

RIBF demonstrates particular promise in its resistance to etching inhibition, a common limitation in PJM processes [3]. This characteristic enables effective processing of both glass ceramics, such as Zerodur, and optical glasses like N-BK7. This research evaluates RIBF's capabilities in freeform optics fabrication, examining its comparative advantages and limitations relative to PJM technology.

2. Setup and Methods

The RIBF process is conducted within a vacuum chamber maintained at a base pressure of 2x10-5 Pa. Samples are manipulated using a six-axis motion system. The microwave-driven ion source produces a near-Gaussian tool function with a width of less than 3 mm (FWHM). Operating at 3 keV ion energy, the source achieves a maximum current density of 21 µA/mm², resulting in a peak material removal rate of 6 nm/s for fused silica substrates.

The plasma jet source, manufactured and distributed by Trionplas Technologies GmbH, is integrated into a three-axis CNC-machining centre and features a FWHM of 1 mm and a peak etch rate of 450 nm/s. While both systems utilize CF_4 as the primary process gas for material removal, the plasma jet system requires additional gas components for plasma stabilization and atmospheric shielding. Figure 1 illustrates the target geometry to be produced both by the RIBF and PJM process. This surface shape shows an example of a Gauss-to-Top-Hat design as used in laser beam shaping.

Processing is performed by the dwell time method. Dwell times are optimized based on the individual tool functions and machine-specific motion constraints for both systems. To mitigate influences of the line feed of the raster toolpath, both processes require a tool-width dependent extrapolation of the target geometry beyond the clear aperture. Additionally, an unavoidable base removal equalling the minimum removal depth at maximum axis velocity has to be factored in. Very high material removal rates in PJM cause a base removal of 650 nm, compared to 20 nm for the RIBF process. The total removal depth amounts to 5.6 µm for RIBF and 6.3 µm for PJM.

Only one machining run is performed for each sample without subsequent correction steps or any pre-adjustments.

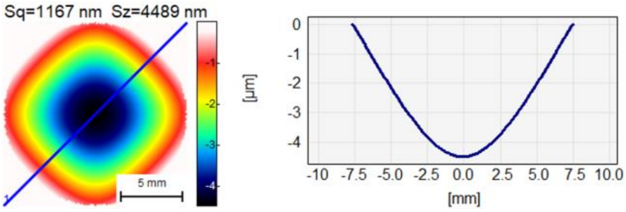

Figure 1. Target geometry with a CA of 15 mm and amplitude of 4.5µm

The surface roughness of all samples is characterized through white light interferometry and atomic force microscopy, while figure measurements are obtained through interferometric analysis. Spatial frequency characteristics of the machined surfaces are evaluated through power spectral density calculations, revealing process-specific roughening or smoothing effects.

3. Results

Figure 2 contains the residual error profiles after fitting to the height-scaled target figure. The scaling factors arise from inaccurate determination of the material removal rate (MRR) and would typically be adjusted for in the fabrication of further parts. It was overestimated by 20 % for N-BK7, 28 % for Zerodur and 5 % for fused silica. Instable ion beam neutralisation and possible (re-)deposition effects influence the locally acting MRR. In the case of PJM processing (d) MRR fluctuations are caused by the local surface temperature that slightly varies depending on the dwell time and the motion velocity, respectively. For all cases the (non MRR-adjusted) process convergence is in the range of 79 % to 95 %.

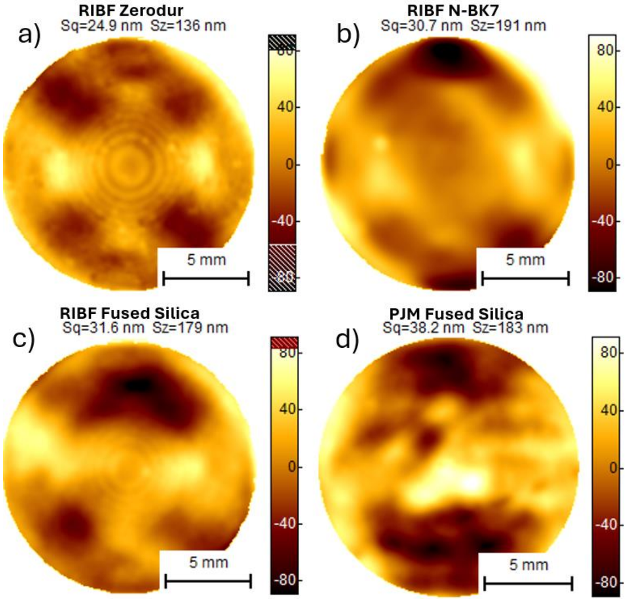

Figure 2. Height scaled residual errors for RIBF (a-c) and PJM (d) of different materials. (d) represents the mechanically polished sample

Figure 3 presents the normalised Power Spectral Density (PSD) distributions, which quantify the surface roughness evolution relative to the initial sample condition. This enables direct comparison of surface modification effects across different spatial frequencies, where values below 1 indicate surface smoothing and values above 1 represent increased roughness. The RIBF process demonstrates distinct material-dependent effects. For fused silica and N-BK7 substrates, RIBF produces significant smoothing across spatial frequencies ranging from 0.4 µm^{-1} to 24 µm^{-1} (fused silica) and 31 µm^{-1} (N-BK7), respectively. In contrast, RIBF processed Zerodur surfaces exhibit a modest increase in roughness at spatial frequencies above 7 µm^{-1}.

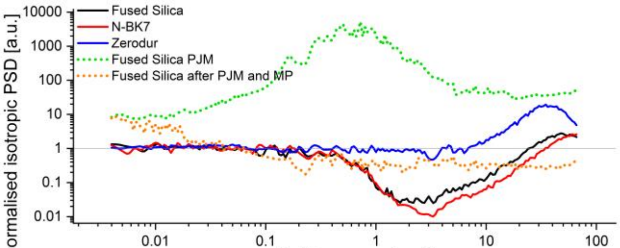

Figure 3. PSD normalised to the individual sample´s initial measurements

Plasma jet machining of fused silica results in notable surface roughening due to the purely chemical based removal. This effect typically necessitates additional processing through gentle mechanical polishing to achieve the desired surface quality with no further figure deterioration. Table 1 summarises the process duration across fabrication methods and the process convergence. For the (R)IBF process, vacuum handling introduces a fixed overhead of 1.5 hours per workpiece that is not required for PJM. However, PJM necessitates an additional 15 minutes for post-polishing operations. The calculated processing times for an inert IBF process highlight the potential of RIBF compared to inert IBF with greatly reduced processing times, while PJM has a clear advantage in production throughput capability.

Table 1 Processing times and convergence of the RIBF and PJM process

Substrate	IBF-Ar (Simulated) [hh:mm]	RIBF-CF_4 [hh:mm]	PJM-CF_4 [hh:mm]	Process convergence RIBF / PJM
N-BK7	10:21	02:31	-	84 / -
Fused Silica	08:24	02:29	0:20	95 / 93
Zerodur	12:47	02:52	-	79 / -

5. Summary and Outlook

In this study, the RIBF and PJM processes were compared for an exemplary freeform generation with a clear aperture of 15 mm. By analysing the accuracy of the manufactured figure and the roughness development in combination with the manufacturing times, the strengths and drawbacks of both techniques could be illustrated. While RIBF is a slower technique requiring expensive vacuum equipment, it can produce highly accurate shapes and low roughness, that in the case of fused silica and N-BK7 is below the initial roughness. PJM is a more time-efficient technique that provides equally good figure accuracy and does not require vacuum equipment. However, it does cause pitting and therefore requires a post-polishing step. While PJM is limited to fused silica substrates, RIBF can be employed on a variety of substrates.

References

[1] H. Paetzelt, G. Boehm, and T. Arnold, "Etching of silicon surfaces using atmospheric plasma jets," Plasma Sources Science and Technology, vol. **24**, 2015/01/27

[2] A. Finzel et al., "Reactive ion beam etching of highly dispersive, high-efficiency transmission gratings for the VIS range," Optical Engineering, vol. **58**, p. 1, 2019/05/24

[3] F. Kazemi, G. Boehm, and T. Arnold, "An investigation on effectiveness of temperature treatment for fluorine-based reactive plasma jet machining of N-BK7®," Plasma Processes and Polymers, vol. **17**, 2020/04/24