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The Satisloh Plasma Polisher: the science, technology development, and commercialisation of atmospheric pressure surface figuring for ultra-precision optics

Dr. Adam Bennett[1,2], Dr. Katherine Gobey[1], Steffen Moos[3], Paul Sauer[3], Hans-Joerg Schlemper[3], Dr. Jürgen Bode[3]

[1]*Cranfield Plasma Solutions Limited, College Road, Wharley End, Cranfield, MK43 0AL, England;*
[2]*Cranfield University, College Road, Wharley End, Cranfield, MK43 0AL, England;*
[3]*Satisloh GmbH, Wilhelm-Loh-Straße 2-4, 35578 Wetzlar, Germany.*

a.d.bennett@cranfield.ac.uk

Abstract
The precision optics technology sector requires rapid surface figuring capability that is aligned with both financial and environmental sustainability. Plasma Figuring, operating at atmospheric pressure, is designed to create the same figure correction capabilities as Magneto Rheological Finishing (MRF) and Ion Beam Figuring (IBF). Plasma Figuring can achieve higher optics manufacturing rates compared to both MRF and IBF; furthermore, it is a technology that uses no harmful chemicals and emits no pollution. The Satisloh Plasma Polisher (SPP) is an atmospheric pressure Plasma Figuring technology that targets mid-spatial frequencies in the 1 mm to 2 mm range. The technology uses a reactive plasma jet to chemically surface figure optics. The plasma jet is powered by a solid-state microwave generator, which operates at less than 50 W average power utilising pulse power mode to reduce the plasma temperature; the ability to discharge a non-thermal plasma at circa 100 ˚C increases the repeatability of the etched Gaussian trenches and maintains the optical surface finish. The SPP is designed to have both lower capital expenditure and lower operational expenditure compared to both MRF and IBF, which is achieved by the relatively low power consumption, the size of the machine, and the system parameters; furthermore, the SPP only consumes 1 L/min of total process gas flow. The presentation will discuss the physics and chemistry that underpins this state-of-the-art technology, the scale-up journey from university to Satisloh, and the successful commercialisation. Results with the SPP are reported that shows the fast figure correction of fused silica on spheres and a-spheres. The presentation concludes with other materials and future directions.

Plasma, Figuring, Optics, Free-Forms, Efficiency, Sustainability.

Introduction

State-of-the-art optics technology applications are driving surface engineering specifications ever closer to the atomic scale [1]. Surface specifications of 10 nm RMS form accuracy and 0.1 nm RMS surface finish are now required in ultra precision applications, which include Acousto-Optic Devices [2], Extreme Ultraviolet (EUV) lithography [3], extremely large telescopes [4], and laser fusion technology [5]. Magneto Rheological Finishing (MRF) and Ion Beam Figuring (IBF) are mature technology solutions used in the final stage of the manufacturing chain of ultra precision optics; however, both technology solutions have very high capital and operational expenditure: the Capital Expenditure of MRF ranges from $500k USD to $1.2M USD and IBF starts at $1M+ USD. Furthermore, MRF is a dirty manufacturing process that uses slurry, with correction limitations set by the size of the contact tool; and, IBF is a very slow process, which is limited to the size of the vacuum chamber. The Plasma Figuring technology described in this paper overcomes all of the aforementioned negatives of the other technologies.

Plasma Figuring technology was developed in Cranfield University (CU) and the Leibniz Institut für Oberflächen Modifizierung (IOM) [6]. Plasma Figuring is a non-contact material removal process that operates at atmospheric pressure and low temperature. MRF and IBF are physical material removal technology; however, Plasma Figuring is a purely plasma chemical etching technology, which avoids the risk of generating sub-surface damage. The low temperature plasma, operating at circa 100 ˚C, yields high thermal control of the substrate and hence high repeatability in the material removal function [7 - 12]. The material removal mechanism is based on a purely chemical reaction between fluorine radicals, which only exist in the plasma, and the surface of the optic. Plasma Figuring of silicon and silicon based optical surfaces has been previously shown [13 - 20].

The Satisloh Plasma Polisher (SPP) is an atmospheric pressure Plasma Figuring technology designed to figure correct optics to the same form accuracy and surface finish as MRF. The SPP targets Mid Spatial Frequency (MSF) errors in the 1 mm to 2 mm range. The SPP is designed to have both lower capital expenditure and lower operational expenditure compared to MRF and IBF, which is achieved by the relatively low power consumption, the size of the machine, the system parameters, and the consumables; furthermore, the SPP only consumes a maximum of 1 L/min of total process gas flow. The Plasma Figuring technology is a clean, environmentally friendly, process that is performed at atmospheric pressure within the SPP chamber. The only byproducts of the process are SiF_4 and CO_2, which are at very low levels, and are none-the-less captured within a bespoke filtration system; measurements of the byproducts are significantly below the Lowest Exposure Limits.

The physics and chemistry that underpins the technology is described in the first SPP paper [21] and the results generated in the Beta Test are shown in the second SPP paper [22].

The paper we now present here describes a summary of the technology, its development, and the latest results.

The Satisloh Plasma Polisher

Technology

The Satisloh Plasma Polisher (SPP) machine has a rapid figuring capability covering a 300 mm by 150 mm area. The five axis precision motion system enables the plasma torch to be moved over the surface of a sphere, asphere or free-form optic to a place in 3D space within ±10 µm. A solid state microwave generator is connected, coaxially, to the plasma torch. A copper tube is inserted into the middle of a brass nozzle. The helium carrier gas, carbon tetrafluoride reactive gas, and oxygen tertiary gas are injected into the copper tube, at flow rates of 400 sccm, 1 sccm, and 1 sccm, respectively. Furthermore, nitrogen shield gas is used to protect the plasma jet from interactions with the air, which would cause instability. The shield gas flow rate matches the carrier gas flow rate.

The microwave generator frequency (the frequency of the photons that are emitted into the gas to generate the plasma) was set to 2.45 GHz. The pulse repetition frequency (the number of microwave pulses per second) was set to 4 kHz. The pulse width (the time period in each ON-OFF cycle that each microwave pulse is ON) was set to 15 µs. The peak power (the maximum amplitude of each microwave pulse, which was the same for each pulse) was set to 250 W. The mean input power, P_m, of the plasma jet was then calculated to be 15 W from

$$P_m = P_p \times f_p \times t_p \quad (1)$$

Where, P_p is the pulse peak power in W; f_p is the pulse repetition frequency in kHz; and, t_p is the pulse width in µs [21].

Figure 1 shows a schematic of the plasma torch processing the surface of an optic.

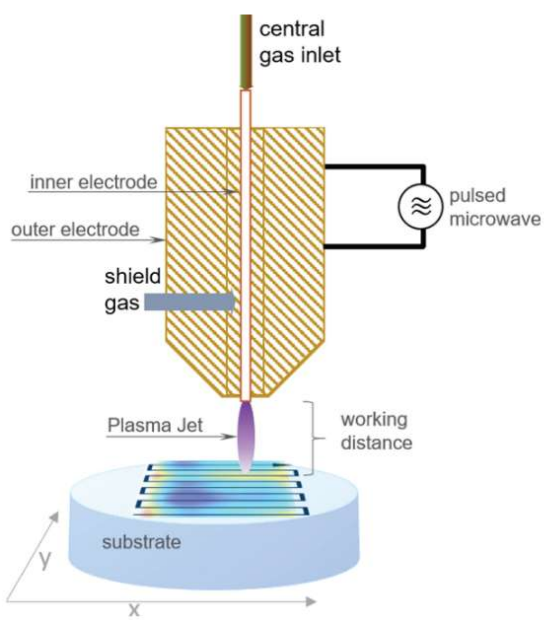

Figure 1. Plasma Torch Process Schematic.

Figure 2 shows the plasma torch during figuring operation over the surface of convex and concave optics. Spheres, a-spheres, and free-forms have been processed. Investigations with customers directed the initial focus, which was on fused silica, followed by ULE, silicon, and finally BK7.

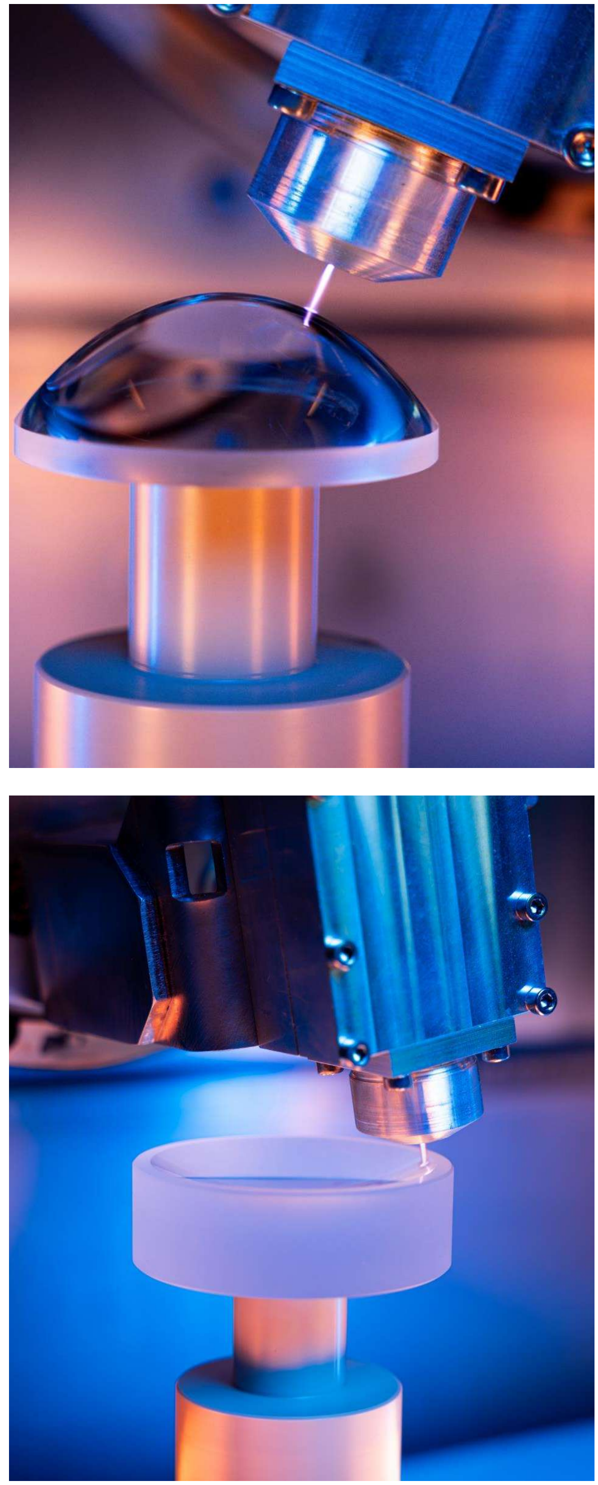

Figure 2. Top: Plasma Figuring Convex Optic; Bottom: Plasma Figuring Concave Optic.

Material Removal Mechanism

The plasma jet discharge is 99 % helium. Helium plasma on its own will only clean the surface of the optic [23]; however, the helium plasma is a stable energy beam, which is used to convert the carbon tetrafluoride inert gas into atomic fluorine and atomic carbon. Fluorine radicals, upon contact with silicon atoms, react and produce SiF_4 gas, which is extracted and stored in a bespoke scrubber unit. The principal chemical reaction, for the case of fused silica, is given by

$$SiO_2 + 4F\bullet \rightarrow SiF_4 \uparrow + O_2 \uparrow \tag{2}$$

Where F• is a fluorine radical. The oxygen tertiary gas was injected to react with the carbon in the plasma and extract it in the form of carbon dioxide gas, which prevents any carbon-based deposition onto the surface of the optic [21].

The material removal reaction rate, R, was dependent on the local surface temperature, which is given by an Arrhenius equation

$$R = C\, j_F exp^{\left\{-\frac{E_A}{k_B T_S}\right\}} \tag{3}$$

Where C is a constant; j_F is the reactive particle flux ($m^{-2}\ s^{-1}$); T_s is the surface temperature (K); k_B is the Boltzmann constant ($m^2\ kg\ s^{-2}\ K^{-1}$); and, E_A is the activation energy (J) [24].

Material Removal Calculations

The stable reactive plasma jet, moving over the surface of an optic, results in a trench with a Gaussian cross section. The Material Removal Rate, $MRR_{Dynamic}$, for a single trench is given by

$$MRR_{Dynamic} = \int_{-\infty}^{\infty} f(y)\, dy\, .L\ \div t_T = \sqrt{2} D_{Max} \sigma_y \sqrt{\pi} . L \div t_T \tag{4}$$

Where D_{Max} is the maximum depth of the trench (nm); L is the length of the trench (mm); t_T is the time taken to etch the trench (s); and, σ_y = the Full Width Half Maximum of the trench cross section divided by $2\sqrt{2\ln 2}$ [25].

Satisloh Plasma ADAPT

The interferometric results from the trench material removal experiments were inserted into the Satisloh Plasma ADAPT (Satisloh Plasma Advanced Deterministic Adaptive Polishing Technology) software program. The program is a deterministic process simulator, which is based on Finite Element Modelling that calculates the optimised tool path rates based on the plasma torch, surface geometry, measurement data, and process kinematics. A dwell time algorithm was used to calculate the varying velocity that was required at different points in the raster pattern that was conducted over the surface of the optics.

Results

Reproducibility

Repeatability defines the variance in a process and is the corner stone of precision engineering; however, repeatability only describes the precision in a given system. Reproducibility describes the variance across different systems in different organisations and is an important metric for technology commercialisation. The results in this section show how the SPP systems generate consistent results in Satisloh GmbH and Corning Advanced Optics, Corning Incorporated.

Figure 3 and Figure 4 shows plasma figuring results on a HPFS® ConCave Sphere with a 53 mm Clear Aperture, undertaken on an SPP in Satisloh. The starting surface form was 152 nm PV with 28 nm RMS and the final surface form was 76 nm PV with 10 nm RMS, which was achieved in a single iteration. The surface roughness stayed constant throughout the process.

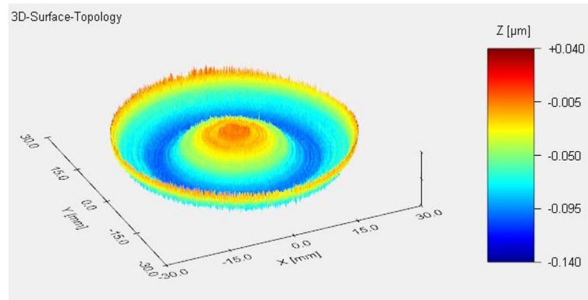

Figure 3. Sphere HPFS 7980 ConCave 53mm CA - Before

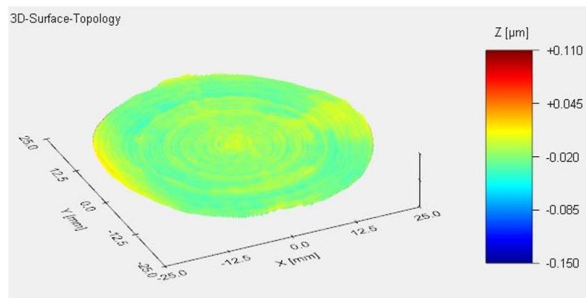

Figure 4. Sphere HPFS 7980 ConCave 53mm CA - After

Figure 5 shows plasma figuring results on a HPFS® ConCave A-Sphere with a 92 mm Clear Aperture and a 250 µm departure from Best Fit Sphere, which was undertaken on an SPP in Corning. The starting surface form was 299 nm PV with 51.5 nm RMS and the final surface form was 51 nm PV with 9.5 nm RMS. The surface form error reduction was achieved in only two steps.

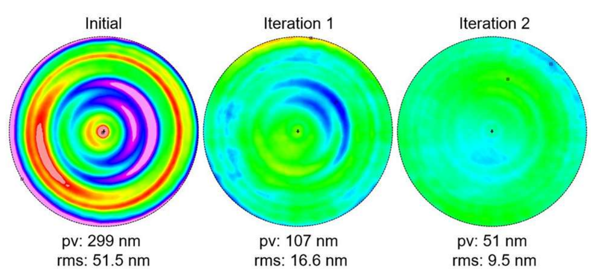

Figure 5. ASphere HPFS 7980 ConCave 92mm CA 250µm BFS

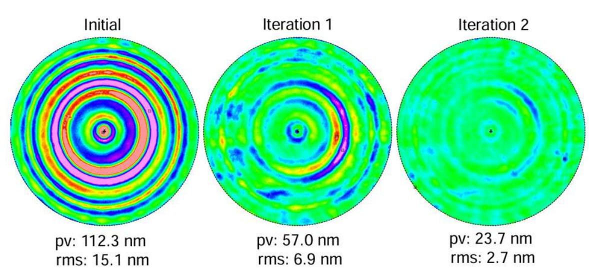

Figure 6. ASphere HPFS 7980 ConCave 92mm CA 250µm BFS Mid Spatial Frequency (MSF) Error Reduction

Figure 6 shows the same data as Figure 5, but with 36 Zernikes removed, which enables a deeper analysis of the Mid Spatial Frequency (MSF) error reduction by subtracting low and mid order wavefront aberrations.

The surface roughness on the HPFS® 7980 stayed constant, throughout the plasma figuring iterations, with a value of circa 2 Å RMS.

Technology Comparison – Optic Processing Times

The cycle time to figure correct optics depends on the starting surface topography and the required surface topography. Different optics will, therefore, have different processing times. Work conducted in Satisloh and during the Beta Test shows that the SPP has processing times that are comparable to MRF. [22]

Future Work

The SPP has demonstrated figuring capability on different materials that are shown in Table 1. Further materials are under development.

Table 1. SPP Figuring Materials Capability

Standard Parameters	Enhanced Parameters
Fused Silica	BK7
Crystalline Quartz	Zerodur
Amorphous Silicon	ULE
Crystalline Silicon	
Germanium	
Silicon Oxide Coatings	

Conclusion

The Satisloh Plasma Polisher (SPP) Plasma Figuring technology corrects Mid Spatial Frequency (MSF) errors at the same speeds as Magneto Rheological Finishing (MRF). The SPP targets MSF errors in the 1 mm to 2 mm range, which are corrected without changing the surface roughness of the optics.

The SPP has both lower capital and operational expenditures compared to both MRF and IBF technology; furthermore, it is an environmentally friendly, clean, low energy process that uses no slurry and has no emissions.

The SPP is a compelling new technology for the sub-aperture figuring toolbox and is an enabler of future strategic capability.

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