Surface morphology in plasma jet polishing: theoretical description and application

H. Müller¹, Th. Arnold¹,²

¹ Leibniz Institute of Surface Engineering (IOM), Permoserstraße 15, 04318 Leipzig, Germany.
² Institute of Manufacturing Science and Engineering, TU Dresden, 01062 Dresden, Germany.

Abstract

Atmospheric pressure plasma jets are effective for generating optical freeform surfaces and correcting figure errors. They can also reduce high spatial frequency surface roughness, potentially replacing mechanical-abrasive polishing. Plasma jet polishing involves thermally driven material redistribution. Current research aims to predict surface topography and roughness by analyzing initial surface topography and the local effect of the plasma jet tool. The tool interaction function was mathematically described by evaluating a microstructure pattern before and after plasma jet polishing, revealing a 2D Gaussian convolution function. This function can be applied to areal topography measurements of lapped and mechanically ground surfaces to predict the polishing performance with respect to reduction of tool marks originating from pre-machining processes. Additionally, the convolution function can be used to predict the dimensions of an initial surface structure in order to produce a defined smooth microstructure using plasma jet polishing. Evaluating the smoothing capability of plasma jet polishing helps identify suitable pre-machining conditions in optics manufacturing, such as grinding or laser micromachining, enabling a more efficient process chain for freeform optics fabrication.

Keywords: atmospheric pressure plasma jet, plasma jet polishing, convolution function, thermal induced polishing
The increasing demand for precision optics and optical systems requires continuous development and optimization of manufacturing processes for optical components. Today, optical system designers are increasingly considering the use of freeform surfaces as they offer more compact optical systems designs, higher levels of functionality, and improved optical performance in illumination and imaging systems [1-4].

Precise fabrication of freeform surfaces made of glass can be challenging, especially when large gradients, concave structures, or inflection points are present. Conventional full-aperture processes for shape generation and polishing are usually not applicable. Over the past few decades, several techniques based on CNC machining using the point-shaped tool contact of sub-aperture tools have been developed and brought to industrial maturity, such as abrasive methods like freeform grinding or diamond turning [5-10]. However, smoothing and finishing of the rough surface is often a challenging task because CNC sub-aperture tools must also be used. To minimize subsurface damage (SSD) and achieve an optically smooth surface, a significant amount of material must be removed, while avoiding the creation of unintended mid-spatial frequency structures and figure errors. Bonnet polishing and magnetorheological polishing are proven deterministic abrasive finishing methods for freeform surfaces although their tool function depends on the size of the tool-sample contact zone. The local geometry can be planar, convex or concave, which may influence the dimension of the tool function [11, 12] and thus the material removal rate (MRR). Knowledge of the local MRR can be used to reduce figure error[13].

In contrast to mechanical-abrasive techniques, beam-based methods such as laser machining or atmospheric pressure plasma jet (PJ) machining are predestined for such tasks. Here, the tool-surface interaction is not based on mechanical forces, but on atomistic physical and chemical principles. Due to the tool characteristics, energy or particle beams are wear-free, long term stable and offer a high degree of geometric flexibility with regard to surface design (e.g. slopes, workpiece edge contour, etc.).

Besides laser machining, which has been extensively investigated [14-16], PJ machining technology has been continuously developed in recent years [17-22]. Its application in the field of precision freeform surface generation and figure error correction employing chemically reactive PJs has been widely demonstrated. In addition, the feasibility of its application for surface polishing and SSD removal using
non-reactive PJs has already been demonstrated [23-25], thus providing an alternative for polishing freeform optics using a beam-based tool. Although the plasma-surface interactions at the micro- and nanoscopic level are not yet fully understood, it is known that the polishing effect is due to the convective local heating of the substrate by the PJ. Local heating near the softening point $T_s$ of the substrate leads to melting of the glass surface. A thermally induced redistribution of the material at the surface due to the reduced viscosity on the one hand and a simultaneous minimization of the surface tension on the other hand leads to a reduction in the surface roughness similar to the laser beam polishing effect [26-30].

When plasma jet polishing (PJP) is used as one step in a process chain for the manufacture of freeform optics, it is necessary to define the optimal hand-over surface conditions in order to optimize the entire process sequence in terms of cost and time efficiency as well as the final surface quality. As an example, a process chain comprising mechanical freeform grinding, ultra-fine grinding, and PJP is investigated. By combining these processes, the potential for time savings is high compared to other freeform production chains. However, in order to optimally link these processes, the question arises as to which grinding marks can be tolerated, as they are removed by PJP, and which structures should be avoided. Mathematical descriptions of the tool action help to reduce the number of test samples if the models are able to predict the outcome of the surface state. The present work aims to establish a quantitative description of the polishing capability of the PJ applied to fused silica surfaces by identifying the local action of the tool. It is shown that smoothing can be understood as a convolution of a rough initial surface with a 2D low-pass filter function. A method for determining the filter function is presented and the successful application of surface morphology prediction is demonstrated for several examples.

**Experimental**

The PJ source consists of a coaxial conductor system, where the inner conductor is also used as a gas delivery system ending in a nozzle. A working gas mixture is fed to the PJ source and excited by microwaves at 2.45 GHz and a power of approx. 90W provided by a generator (PlasMas PCU-L 200.4, Heuermann HF-Technik GmbH). The gas discharge ignites at the nozzle tip as soon as at least one free electron is present, and the electric field strength exceeds the breakdown field strength. An argon/helium
gas mixture was fed to the PJ source at a total gas flow rate of 350 sccm to maintain a stable PJ. Since only inert noble gases are used, no chemical reactions occur on the glass substrate.

Surface temperature measurements were performed with a pyrometer (PYROSPOT DT 44G, DIAS Infrared GmbH) attached to the body of the PJ source to ensure that the measurement spot was always in the contact area of the PJ on the surface. Both the source and the pyrometer are mounted on a 3-axis CNC motion system. A meandering tool path was applied for surface polishing. The scan speed scan velocity in the x-direction was 1 mm/s and the line feed in y-direction was set to 0.2 mm.

**Material and measurements**

All experiments were performed on fused silica, a common material for optical applications in the IR to UV wavelength range. Due to its chemical purity and low thermal expansion (0.48 – 0.57·10⁻⁶ l/K) with high thermal shock resistance [31], it is the first choice material for a thermally induced process, and thus also for fundamental experiments on PJP. The softening point of the selected glass is Tₛ =1585 °C [31].

To investigate the PJP effect, a binary grating microstructure with a depth of 25 µm and a structure width of 100 µm and a second crossed grating structure with several steps up to 50 µm depth and widths of approximately 100 µm were created by USP laser micromachining on planar polished fused silica windows (50 mm diameter, 3 mm thickness). In addition, lapped (40 x 40 mm², 4 mm thickness) and ground planar samples (15 x 15 mm², sample #A: 4.5 mm thickness and sample #B: 5.3 mm thickness) were produced by project partners at the University of Applied Sciences, Jena, Germany. The lapped samples exhibited a uniform roughness distribution due to the full aperture manufacturing process. In contrast, the samples ground with a spherical grinding tool showed some wavy overstructures due to the meandering grinding path. These samples were used to compare the surface morphology and roughness before and after PJP. Finally, a laser-machined binary grating pattern with structure period of 225 µm and a depth of 13 µm was prepared on a conventionally polished sample (30 mm diameter, 10 mm thickness) to investigate the predictability of smooth microstructure generation applying the PJP.
A constant surface temperature on the sample in the contact zone of the PJ was ensured by a PID-based closed loop control to adjust the microwave power of the PJ source based on the pyrometer temperature measurement. A setpoint of 1600°C, which is slightly above $T_S$, was fixed for all experiments.

A white light interferometer (WLI; NPFLEx, Bruker Corporation) was used to determine the dimensions of the lasered structures and the surface roughness of the rough and plasma polished surfaces. By using different objectives ($2.5 \times 5 \times 10 \times 50 \times$), the surface roughness can be observed over a spatial wavelength range from about $1 \, \mu m$ to $1000 \, \mu m$.

MATLAB (The MathWorks, Inc.) was employed for the mathematical calculations. Home-made routines allow the calculation of power spectral density (PSD) functions of the individual topography measurements, which were combined into an isotropic mean PSD exhibiting an extended spatial wavelength range according to the different fields of view and resolutions. A fitting routine was written to determine the parameters of the convolution function describing the smoothing effect based on the respective pre- and post-PJP measurements.

Results and Discussion

Determination of PJP function

First, PJP was applied to two defined laser generated structures which are shown in Figure 1(a, d). A rounding of the sharp edges after PJP is clearly visible in Figure 1(b, e). A 2D Gaussian function was chosen as the convolution function for PJP. Besides an approach using the sum of two rotationally symmetric Gaussians, the convolution function described by an asymmetric elliptical Gaussian proved to be the best fitting description of the polishing function, taking into account a slight asymmetry of the thermal hotspot on the surface as the PJ source is moved. The best-fit function for the two laser structures is given by equation (1) where $s_1$ and $s_2$ are the standard deviations belonging to x and y directions, respectively:

$$G(x, y) = \frac{1}{2\pi s_1 s_2} \cdot e^{\left(-\frac{x^2}{2 s_1^2} - \frac{y^2}{2 s_2^2}\right)} \tag{1}$$

The standard deviations $s_1$ and $s_2$ were determined by solving the minimization problem given in equation (2)
where \( f_{\text{PJP}} \) is the experimentally obtained topography after PJP, and \( f_{\text{laser}} \) is the initial laser machined topography. The asterisk denotes a convolution operation. For the applied PJ parameters and considering the values obtained from fitting the two structure types (a) and (d), respectively, the standard deviations yield \( s_1 = 0.0401 \) mm and \( s_2 = 0.0355 \) mm for the grating structure \( (G_1: \text{Figure 1}(a)) \) and \( s_1 = 0.0309 \) mm and \( s_2 = 0.0331 \) mm for the cross grating structure \( (G_2: \text{Figure 1}(d)) \). The resulting topography of the laser structures filtered with \( G_{1/2} \) is shown in Figure 1(c, f). As expected, both sets of values are similar. The small deviations may originate from slightly deviating experimental or measurement conditions, as the experiments on the respective structures were carried out subsequently on separate samples. It is important to note that the function parameters always depend on the process parameters such as gas flow, surface temperature, and PJ source working distance, since these parameters determine the PJ footprint.
Figure 1: Determination of a 2D convolution function for PJP: (a, d) initial laser generated structures, (b, e) topographies after PJP, (c, f) Gaussian filtered topographies.
Roughness prediction for lapped and ground surfaces

The predictability of the PJP result was first investigated on lapped samples. Defined positions on the samples were measured before and after PJP. The filtering operation emulating the PJP effect was performed using the previously determined convolution functions $G_1$ and $G_2$ and topography measurements exhibiting different resolution and field of view. A comparison of the areal representation of theoretical and experimental PJP is given in Figure 2 for the same position measured with 2.5x, 5x and 10x WLI objectives. As can be seen, the surface formation resulting from PJP of the lapped surface (Figure 2(a-c)) can be well predicted by the filtering operation (see Figure 2(d-f)). The distribution of significant hills and valleys can already be seen by applying the convolution function to the rough initial surface. The occurrence of those structures is confirmed in the experiment (Figure 2(g-i)). A direct comparison of the horizontal cross sections in Figure 2(k-m) shows the general agreement between filtered and PJP treated structures. The slight differences due to the different sets of standard deviation values can be neglected as the difference to the experimental results is slightly higher. Especially, in the long wavelength range (2.5x) higher departures from the measured topography occur, indicating that the filtering underestimates the actual smoothing capability of the PJ.
Figure 2: (a-c) Surface topography of lapped surface measured with WLI magnifications (2.5x, 5x, 10x), (d-f) Calculated surface topography applying the convolution function $G_1$ to lapped surface, (g-i) measured surface topography after PJP. The depicted data are measured at the same position of the sample. The cross sections (k-m) compare the PJP topography to the filtered topography using both convolution functions $G_{1,2}$.

A more comprehensive picture can be obtained by comparing the respective PSD functions. Figure 3 compares the mean isotropic PSD function and the mean square height (Sq) of the PJP treated surface with a calculated PSD function obtained from filtered WLI measurements. Additionally, the PSD function of the lapped surface is shown. The smoothing effect is evident and most efficient in the spatial wavelength range between 1 and 100 µm. The PSD function of the PJP surface can already be predicted by theoretical considerations (see Figure 3(a)). Furthermore, it is evident from Figure 3(b) that the experimental Sq can also be estimated with good accuracy from the theoretical approach. Only the measurement with the 50x WLI objective cannot be verified theoretically, because the image size with
an extension of 90 µm in y-direction is too small for the lateral extension of the 2D Gaussian convolution function.

Figure 3: Analysis of WLI measurements of lapped and PJ polished surfaces compared to theoretical polishing using the determined convolution function $G_{1/2}$ for (a) mean isotropic PSD function and (b) $Sq$. The depicted data are measured at the same position of the sample.

Finally, the applicability of the convolution function to ground surfaces is demonstrated. For this purpose, two different initial surfaces were used and re-measured with several WLI objectives. The results for the center position of the samples are discussed below. The surface measurements with the 5x WLI objective are shown in Figure 4. Due to the different infeed angles of the grinding tools, both samples show a different distribution of grinding marks. By using two different initial surfaces, the influence on the polishing result and its predictability was investigated.

Figure 4: Surface topography (5x WLI objective) of two differently ground surfaces (#A / #B). Processing with different grinding parameters results in deviating roughness distributions.
The mean isotropic PSD functions depicted in Figure 5 of the initial surfaces (black lines) show more pronounced peaks caused by the grinding process, mainly for sample #B (Figure 5(b)). A much stronger preferred direction of the grinding marks was already observed for this in the surface measurements. For sample #A, shown in Figure 5(a), the grinding marks are less pronounced. The mathematical description of the PJP from equation (1) is used to predict, at best, the extent of feature leveling. The PSD functions for both samples after PJP and after filtering using the convolution function $G_1$ show that the PJP surface can be well predicted (Figure 5: red lines vs. blue lines). It emphasizes that the extent of PJP can also be well predetermined for ground surfaces. Especially for sample #B, it can be seen that the extent of the leveling of the prominent peaks by PJP can be theoretically estimated by the filtering operation.

Looking at the areal topography measurements in Figure 6(a, b), it is obvious that the surface after PJP shows typical height distributions as they also occur after theoretical determination (see Figure 6(c, d)). This once again emphasizes the good predictability of the polishing result based on the mathematical description initially determined on the lasered structures using a 2D Gaussian function.
Figure 6: Surface measurements (5x WLI objective) for sample #A and #B: (a, b) after PJP compared to (c, d) theoretically determined PJP result by applying the convolution function to the initial sample surface measurement and (e) individual Sq for all WLI objectives.

Even for the ground initial surfaces, the Sq resulting from the measurements with the various WLI objectives, shown in Figure 6(e), can be estimated based on convolution function applied to the initial sample surface measurement.

In addition to predicting roughness, the application of the convolution function $G_I$ to the initial surface can also be used to provide an understanding of the explanation of imperfections after PJP. Figure 7(a-c) shows the areal topography measurements of sample #C. Here, after PJP, some holes appear whose origin cannot be explained at the first sight. However, if the convolution function is applied to the ground initial surface, it is obvious that their origin can already be found in the initial surface.
Figure 7: Application of the convolution function to the ground surface shown in (a). The filtered topography (b) can explain the holes which appear after PJP (c). The comparison of x-profiles (d) shows the prediction of positions and extent of the holes, but also their origin in the initial surface.

Comparing the x-profiles in Figure 7(d), it is obvious that the depth and position of holes can also be predicted by applying the convolution function.
Generation of a predefined microstructure

In the process of determining the 2D convolution function to describe the PJP effect the rounding of sharp edges by the PJP has already been demonstrated. This effect can be used for the generation of defined smooth microstructures. In the present case, a sinusoidal structure is to be generated by PJP. The cross section profile of a target structure is represented by the black line in Figure 8(a) which exhibit PV values of 8.9 µm and a period of 225 µm. A fit routine involving the Gaussian filter function was employed to determine a rectangular grating structure of a certain amplitude that corresponds to the sinusoidal target structure after PJP. This results in an initial pattern having an amplitude of 13 µm (see red curve in Figure 8(a)), which was then generated by ultra-short pulse laser micromachining.

(a) target: PV = 8.9 µm / ω = 225 µm

(b) laser-machined: PV = 13 µm / ω = 225 µm

Figure 8: Generation of predefined microstructures: (a) profile cross sections of the target structure (black curve) and calculated initial pattern (red curve) over a length of n = 5ω and (b) the areal measurement of the laser-machined initial pattern.

The areal topography measurement shown in Figure 8(b) was filtered by the convolution function $G_1$.

The cross section profile of the filtered structure and the predefined target is shown in Figure 9 (red and
black curves). Here, the PV$_{\text{filter}}$ value is also given. A slight PV difference of 0.3 µm is observed. This may be due to irregularities found in the valleys of the machined structure.

![Figure 9: Cross section profiles of the structures after PJP (blue curve) and the filtered laser-structured topography (red curve) compared to the target profiles (black curve) measured over a length of n = 5ω. The PV values are given in addition.](image)

The profile obtained after PJP is also included in Figure 9 for comparison (blue curve). It can be clearly seen that the PV$_{\text{PJP}}$ value obtained experimentally is 0.8 µm larger than the predicted value. A reason for this effect might be instabilities of experimental parameters connected to the in-process temperature measurement and microwave power setting. An improved closed-loop control algorithm could result in an even better matching of the targeted and resulting sinusoidal structure amplitude.

**Conclusion**

It was shown that the polishing effect in PJP can be described by a 2D Gaussian function. Starting from a defined pattern, the mathematical description can be applied to rough initial surfaces to predict the result of the PJP process sufficiently accurate. The convolution function itself depends on the process parameters of the PJP and must always be redetermined when they are changed. First, the predictability of the PJP results on rough surfaces has been shown. Practical PJP tests have clearly demonstrated that it is possible to estimate the PSD function and Sq roughness for uniformly rough surfaces, such as those obtained after lapping, but also for ground samples, which often exhibit
stronger textures due to the manufacturing process. The aim of further investigations is to optimize the initial surfaces based on the theoretical approach to achieve uniformly polished optical surfaces and to transfer the results to freeform lens designs.

Another application of the convolution function of the PJP process was presented. Smooth microstructures can theoretically be generated. By deconvolution of the target structure and the convolution function, an initial pattern can be calculated, which after PJP should yield in the target structure. The extent of feasibility depends on stability of the experimental parameters. Further experiments are necessary to improve machining stability and to investigate the macroscopic and microscopic effects in PJP, such as material flow, and thus to determine more precisely the initial patterns for the requested microstructures as a function of the describing parameters (PV, ω).

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**Availability of data and materials**

All data generated or analyzed during this study are included in this published article.

**Competing interests**

The authors declare that they have no competing interests.
Authors’ contribution

HM conducted the PJ experiments and measurements, performed analysis of the results as well as the theoretical calculations, and handled the paper documentation. TA wrote the MATLAB fitting routines, offered valuable advice for the interpretation of the data and took extensive care of correction of the manuscript to present the data more clearly. The authors have read and approved the final manuscript.

References


Figure captions

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