Fast Figure Correction of 400 mm Diameter ULE Mirror by Reactive Atom Plasma

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Abstract

In the last decade, major international projects have generated a growing demand of metre-scale optics and this has increased the required throughput of optical fabrication chains. Such a demand is today only partially satisfied. In particular, the final figuring stage still constitutes the bottleneck step for large optics manufacturing. In this context, rapid plasma processes at atmospheric pressure have become an attractive solution to speed up the surface figuring at nanometre level. Reactive Atom Plasma (RAP) is a figuring method based on dry chemical etching by means of an inductively coupled plasma torch. RAP combines high material removal rates and nanometre level repeatability, thus providing an ideal tool for processing of large ultra-precise surfaces. In the work presented in this paper, the rapid figure correction capability of the Reactive Atom Plasma process is applied onto a large optical surface. For this purpose, a 400 mm diameter mirror made of ULE is processed on the Helios 1200 RAP machine, at Cranfield University Precision Engineering. The surface geometry is a 3 m radius of curvature concave spherical shape. An initial form error of ~2.3 µm PVr, measured by means of a spatial carrier interferometer, is corrected within three iterations, for a total processing time of 2.5 hours. A final residual figure error of ~43 nm RMS is achieved. The result is attained by applying an in-house developed iterative figuring procedure that combines adapted dwell-time techniques with a dedicated tool-motion path to assure rapid convergence of the process. Considerations about the number of iterations, the respective processing times, the residual figure error and the rate of convergence highlight the process speed and allow rapid fabrication of metre-scale optics. In particular, for a surface characterised by a figure error of ~1 µm PV the figuring is expected to last ~10 hours.

1 Introduction

The need for mass production of large scale ultra-precise optical surfaces is today a reality. Ultra-precision optics, sized between 400 mm and 2 m diameter, are already a necessity for construction and maintenance of major international research projects. Noteworthy examples comprise meter-class mirror segments for extremely large telescopes, medium sized reflective optics for the new generation Extreme Ultraviolet Lithography and 400x400 mm transmission optics for laser fusion energy programmes like the National Ignition Facility (NIF). Optical fabrications chains suffer of slow production times due to a bottleneck at the final figure correction stage. State of the art figuring technologies like CNC polishing, Ion Beam Figuring and Magnetorheological Finishing still cannot meet the cost and time requirements of the emerging large optics market. Indeed, these techniques may need tens to hundreds of hours to converge to a λ/20 RMS residual over metre-scale surfaces. In this context, the Reactive Atom Plasma (RAP) process constitutes an ideal alternative since it combines figuring accuracy at nanometre level with high process speed. RAP is an atmospheric pressure figuring technology based on dry chemical etching by means of an inductively coupled plasma torch. Its efficiency has already been proven on surfaces up to 140 mm diameter [1,2]. In this paper, the figure correction work performed on a 400 mm diameter optical surface is presented, thus demonstrating the large scale capability of the RAP process.

1.1 Experimental results and discussion

The work described in this paper is carried out using the Helios 1200 figuring facility, at Cranfield University Precision Engineering (Figure 1 left). On a 420x420x40 mm substrate made of Corning ULE®, a concave spherical geometry with 3 m radius of curvature was ground and polished in the centre of one of the 420x420 mm surfaces. The resulting clear aperture is 400 mm diameter (Figure 1, right). The surface figure after polishing is then measured on an optical test-tower by means of a vibration insensitive interferometer based on the spatial carrier method (Zygo DynaFiz). This is equipped with a 4'' transmission sphere (λ/20 PV). The initial figure error after focus correction (Figure 2, left) shows an near-astigmatic term of ~2.3 µm PVr [3] (373 nm RMS). This error map was utilized for the computation of the torch travel speed map for the first iteration tool-path algorithm. Such computation is based on adapted dwell-time techniques that account for the non-linear nature of the removal rates. In the machine, the substrate is scanned face-down by the plasma torch that moves along free-form paths following the part geometry at tangential speeds defined by the velocity map. A staggered meander-type motion sequence, purposely designed to achieve

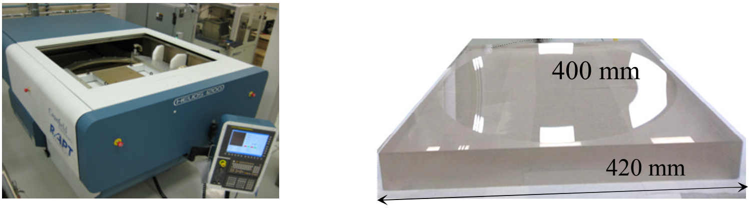

Figure 1: The Helios 1200 figuring facility (left) and the ULE substrate (right).

a homogeneous surface temperature distribution, constitutes the tool-path [1,2]. The figure correction is completed after the third iteration. In Figure 2 (right), a 3D-plot of the final surface is shown. A residual figure error of 43 nm (λ/15) RMS, and 280 nm PVr, is achieved within 2.5 hours, for an overall convergence of 89% (see also Table 1). The residual error topography is characterised by a moderate waviness due to the RAP raster-scanning pattern, as well as by higher spatial frequency patterns. These are attributed to roughness increase and sub-surface damage from previous contact machining. Such features are considered to have a relevant effect on the residual error parameters, but could be significantly improved by a simple "flash" post-RAP polishing method.

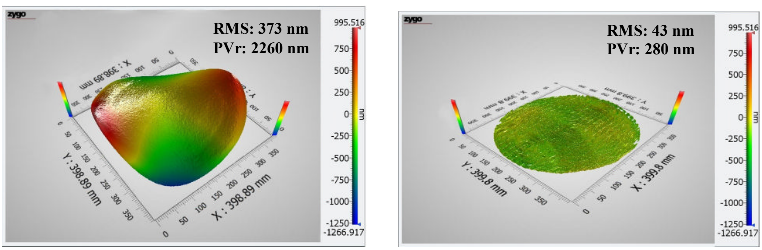

Figure 2: *left*: Initial figure error map; *right*: residual error after third iteration.

Table 1: Figuring process summary table

Evaluated aspect		
Mean figuring time [min/iteration]		51
Total figuring time		2 h 32 min.
Convergence [%]		89
Figure error in RMS [nm]	Initial	373
	Final	43
Figure error in PVr [nm]	Initial	2260
	Final	280

2 Conclusions

The presented result demonstrates the rapid large scale figuring capability of the RAP process. The figuring procedure previously devised and applied on small areas is successfully scaled up. A 400 mm diameter spherical surface with an initial figure error of ~2.3 µm PVr is corrected to λ/15 RMS within three iterations (89% convergence). The mean processing time per iteration is 51 min. for ~2 µm effective figure error removal, which highlights the unrivalled process speed. For a meter-scale substrate with a characteristic figure error of ~1 µm PV, a total processing time of less than ten hours can already be confidently predicted. Surface roughness deterioration and residual sub-surface damage from previous abrasive processes are present. These can be removed by a post-RAP flash polishing process, which is currently at the research stage at Cranfield University Precision Engineering. Combination of RAP figuring and flash polishing will constitute a rapid and cost-effective finishing methodology that can be implemented into a novel kind of large optics fabrication chain.

References:

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