Plasma Surface Figuring of Large Optical Components

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ABSTRACT

Fast figuring of large optical components is well known as a highly challenging manufacturing issue. Different manufacturing technologies including: magnetorheological finishing, loose abrasive polishing, ion beam figuring are presently employed. Yet, these technologies are slow and lead to expensive optics. This explains why plasma-based processes operating at atmospheric pressure have been researched as a cost effective means for figure correction of metre scale optical surfaces. In this paper, fast figure correction of a large optical surface is reported using the Reactive Atom Plasma (RAP) process. Achievements are shown following the scaling-up of the RAP figuring process to a 400 mm diameter area of a substrate made of Corning ULE®. The pre-processing spherical surface is characterized by a 3 metres radius of curvature, 2.3 µm PVr (373nm RMS), and 1.2 nm S_q nanometre roughness. The nanometre scale correction figuring system used for this research work is named the HELIOS 1200, and it is equipped with a unique plasma torch which is driven by a dedicated tool path algorithm. Topography map measurements were carried out using a vertical work station instrumented by a Zygo DynaFiz interferometer. Figuring results, together with the processing times, convergence levels and number of iterations, are reported. The results illustrate the significant potential and advantage of plasma processing for figuring correction of large silicon based optical components.

Keywords: Fast figuring, RAP, Rective Atom Plasma, Large optic fabrication

1. INTRODUCTION

This paper is about the latest figuring results of the Reactive Atom Plasma (RAP) project using the large RAP machine called HELIOS 1200. The surface figuring machine, designed for large scale ultra precise optical components, was used to figure correct a 400mm diameter spherical concave area characterized by a 3m radius of curvature. The key achievement of this work relied on three pivotal technologies: Reactive Atom Plasma (RAP), the vibration insensitive interferometric measurement and Computer Numerical Controlled (CNC) machine tool. It will be shown how a high material removal rate and the determinism of the RAP torch enable robust prediction of the processing time for metre scale optical components. The RAP process provides a unique rapid surface figuring capability with tool size flexibility due to the “soft edge” of the plasma plume.

1.1. Motivation for cost effective optical fabrication chain

In 2003, driven by a steadily growing demand for extremely high quality surfaces, a team of British researchers undertook a review study about the various optical fabrication techniques and their ultimate capability. Through this study, they aimed to offer an innovative and cost effective fabrication chain[1] reflecting the latest development of deterministic machining technologies to achieve figuring accuracy to 1 part in 10^8mm. At this early stage, they were addressing the needs of three major research programs: high energy laser fusion plants[2], extreme ultra violet lithography (EUVL) systems[3] and large telescope mirrors[4]. They had observed that these application fields have common requirements and challenges: high form accuracy and high surface integrity. Indeed, both form and surface integrity require the designation *fault free*.

In the past ten years, all the well-known optical fabrication techniques have moderately evolved to achieve higher quality roughness and form accuracy. Over that period, the overall sizes of newly designed ground based telescopes changed by an order of magnitude. At the same time, lightweight optical components have become more and more demanding in terms of machining constraints. Both size and quantity have increased at the same pace. It is now common to speak about thousands of off-axis aspheric mirrors for extremely large telescopes. In Europe, the major project is the E-ELT, whereas in the US, a strong emphasis is made on the Giant Magellan Telescope and the Thirty Meter Telescope.

To meet the current technical demand in terms of processing speed, surface integrity, and level of form accuracy, the surface figuring is facing significant challenges. For the purpose of this article, the fabrication chain of optical components (primary mirror or lenses) will be presented through three straightforward fabrication steps: grinding, polishing, and figuring.

This article is about the performance of the RAP figuring process, however it is important to present the competitive techniques. Across the optical fabrication field, there are numerous competing figuring techniques such as: polishing, Ion Beam Figuring (IBF), and Magnetorheological Finishing (MRF; RAP should be considered in the context of their performance.

Polishing[5] is well established but has moderate capability to figure correct large optical components and does not enable the required throughput. The main disadvantages are: poor determinism of the tool removal function, lack of control at the edge of the workpiece, and a demanding need for slurry management.

IBF[6] is known to suffer from a low material removal rate and is expensive to run and maintain due to the use of high cost components: molecular turbo-pump (required to vacuum the processing chamber), ion gun and electron beam neutralizer. From a processing viewpoint, IBF is time consuming as the pressure in the chamber must be below $1.0x10^{-4}$Pa. Typically, the pump down takes approximately 5 hours for a 10 m^3 chamber.

MRF[7] is time consuming and the cost of the solution is significant for industrial scale processing.

1.2. Reactive Atom Plasma (RAP) technology

RAP is an emergent technology for figuring optical surfaces made of silicon based materials such as ULE®[8], fused silica[9], silicon[10], silicon carbide[11] and borosilicate. The RAP figuring process benefits from high material removal rate (1-10mm^3.min^{-1}) using a non-contact plasma tool which operates at atmospheric pressure. Its unique energy beam enables many possible configurations to manufacture large and precision optics. Consequently, the mechanical constraints on the workpiece are minimised. The clamping mechanism is made very simple and post machining distortion is rendered unimportant due to the negligible mechanical stress imposed by the process. Helios 1200 (Fig. 1) is designed so that the substrate is held face down, which reduces potential surface contamination. Loading and un-loading can be carried out manually via a dedicated drawer, or using a crane which lifts the main frame of the sample holder and brings the carrier unit to an external location more easily to accommodate the handling of metre-scale optics.

To ensure production capability, the RAP 1200 figuring machine is fitted with a FANUC CNC system (30*i* series) that controls two rotary and one linear motors. The axis used to support the sample carrier can bear a 500Kg moving mass with a nominal acceleration of 0.01g. The axis used to move the plasma torch unit across the substrate surface is designed to have a better dynamic capability and has been satisfactorily tested to comply with the most demanding travelling velocity map issued from the deconvolution algorithm.

Figure 1. RAP machine at Cranfield University Precision Engineering (left), Sample holder (right)

The RAP 1200 machine is CE marked and conforms to European electromagnetism and machinery directives. The dedicated human machine interface controls and monitors the mass flow gas controller, motion system, fluoride detection sensors, chamber environment condition and the radio frequency (RF) generator. Different types of fluoride gases such as CF_4, SF_6 and NF_3 have been successfully tested using a standard gas extraction unit. Currently, the neutralisation of reactive species is carried out by a conventional caustic wet scrubber. It is also designed to maintain a constant air flow in the machine processing chamber and extract SiF_4 and other by-product gases.

2. EXPERIMENTAL WORK

1.1. Grinding

A 420x420x40 mm ULE workpiece was ground[12] from a flat surface using the Cranfield Box machine (Fig. 2).The surface was formed by consecutive 100µm deep cuts. After grinding, the substrate was measured using a Leitz PMMF coordinate measurement machine. The acquired data set was interpolated through an in-house developed method which compensates for probe radius, thermal drift and measurement noise. The results (Fig. 2) showed a 400nm RMS, 2.2 microns PV surface form error whilst the substrate was bonded to the grinding fixture and resting on three point supports. Detailed measurements highlight fine features on the surface such as cusps which were 200 nm high and 100 µm wide, as a consequence of the grinding tool path. Such a surface was suitable for inexpensive simple polishing in order to obtain a specular reflection for interferometric measurement proposes.

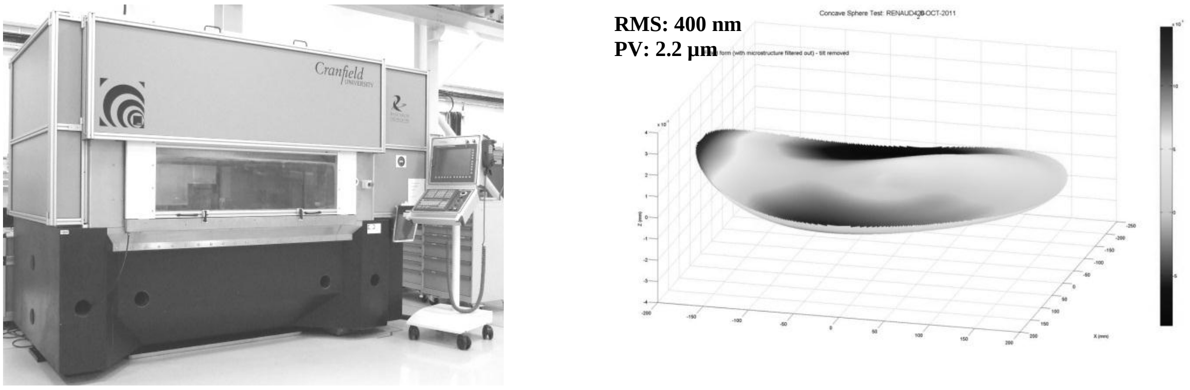

Figure 2.Box machine used for grinding process (left), Surface topography map after grinding (right)

1.2. Polishing

After grinding, the 420 mm ULE workpiece was hand polished using a 4µm grit size cerium oxide solution. For this task, a conformal sub-aperture tool was fabricated and used on the surface still mounted on the grinding fixture. The polishing duration was reduced to the minimum necessary to obtain an interferometric measurement. The surface form was measured using a 4D Phasecam 4000 interferometer with f/6 diverger lens. Results were de-rotated and averaged over the full aperture to null major asymmetric aberrations from the test system. The form result shows a 335 nm RMS and 1.69 µm $PV_{99\%}$ values. The radius of curvature was measured using a Taylor Hobson Form Talysurf over a central 314.9 mm aperture. The ROC result is 3.003 m. Finally, the surface roughness was measured using a 4D W/L interferometer and the result shows 1.22 nm S_q.

1.3. Interferometric measurement

After polishing, the workpiece was released from the grinding fixture and the surface form error was measured using a dedicated optical test tower recently installed at Cranfield University Precision Engineering (CUPE) (fig. 3). The design and fabrication was undertaken after reviewing the different possible field of view axis and direction configurations such as horizontal, vertical facing downwards, vertical facing upwards, and the use of a fold mirror. The main focus was to ensure a repeatable measurement, easy adjustment, and a minimum surface aberration due to the sample holder. After these overall considerations, the measurement work station has a vertical configuration where the normal to the surface is pointing upwards. The substrate is positioned onto the lower platen which enables fine and precise (tip/tilt/power) adjustment necessary for the 4 steps measurement procedure specific to the vibration insensitive interferometer whose uses a spatial carrier (Zygo DynaFiz). This was equipped with a 4'' transmission sphere f/3.3 assessed for form accuracy better than $\lambda/50$ PVr[13]. The optical test tower was used systematically for all RAP figuring work presented in the following section.

Figure 3. Optical test tower overview (left), Optical test tower lower platen (tip/tilt/power correction) (right)

1.4. RAP processing

The substrate was loaded face-down (fig. 4) and raster scanned by the plasma torch using a self-derived toolpath routine. Unlike in a previous published work[9], the plasma torch was constantly controlled in the 3 spatial dimensions. This is required by the spherical shape of the surface which has a maximum sag of 6.7 mm. This strategy enables to maintain a constant standoff distance while following the part geometry. Thus the nominal tangential speeds defined by the velocity map were applied. Whatever the sag and the slope of this free form surface, this work showed it is possible to apply the in-house developed staggered meander-type raster scanning which has the specificity to reduce temperature changes.

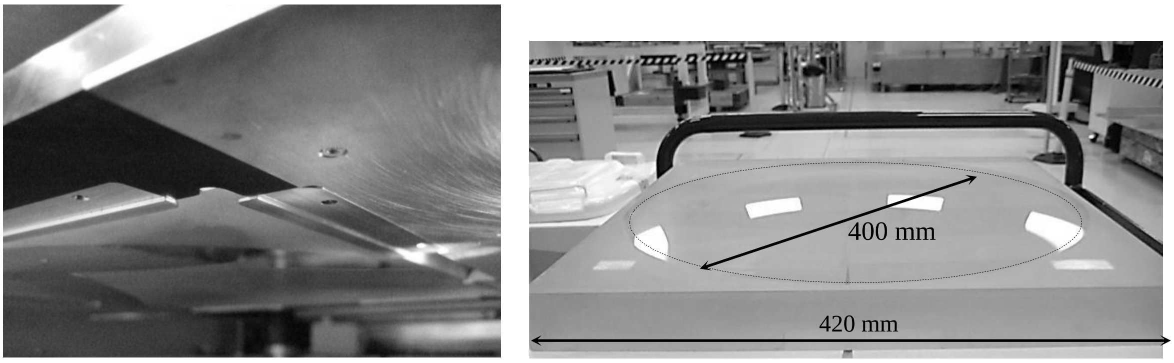

Figure 4. Sample holder for large optical components (left), 420x420mm ULE substrate after RAP processing (right)

3. RESULTS AND DISCUSSION

The initial figure error (Fig. 5), after power correction, shows third-order spherical aberration, the surface figure error is ~2.3 µm PVr, and 373 nm RMS. This error map is utilised for the computation of the torch travel speed map for the first iteration tool-path algorithm. The process was repeated for further iterations. Each iterative step used the dwell-time computational method which uniquely accounts for the non-linear nature of the removal rates.

The achieved final figure error was obtained after three iterations. Figure 5 (right) shows a two dimensional plot of the final surface. A residual figure error of 43 nm (>λ/15) RMS, and 280 nm PVr, is obtained with a total processing time of 2.5 hours. More details about the procedure steps are given in Table 1. The overall convergence is 89%. The residual error topography is characterised by a moderate waviness (~100 nm PV) due to the RAP plume footprint, as well as by higher spatial frequency patterns. These are attributed to a roughness increase and sub-surface damage caused by previous contact machining. Such features are considered to have a relevant effect on the residual error parameters, but could be significantly improved by an inexpensive “flash” hand polishing.

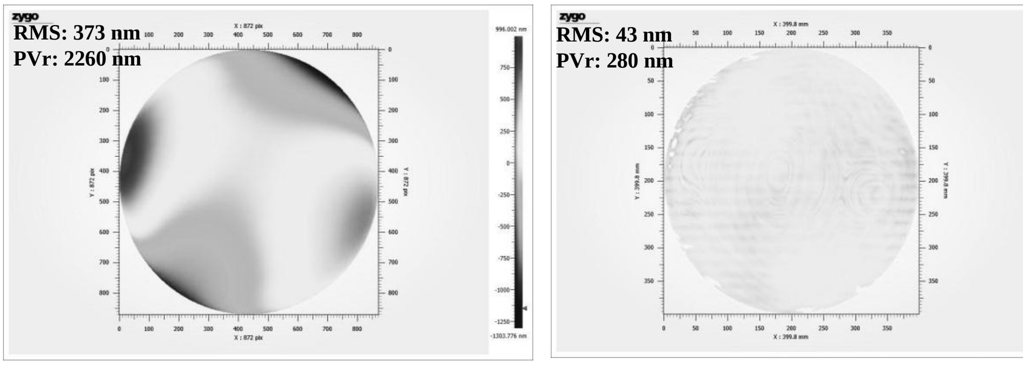

Figure 5. Initial figure error map (left); residual figure error after third iteration (right)

Table1: Figuring process summary

Total figuring time		2 h 32 min. (total duration for the three iterations)
Convergence [%]		89
Figure error in rms [nm]	Initial	373
	Final	**43 ~ λ/15** (λ=633nm)
Figure error in PVr [nm]	Initial	2260
	Final	**280**

The spatial frequencies are scrutinised to analyse the residual footprint of the RAP plume and further improve the overall figuring technique performance. To do so, the topography map of the third iteration is displayed. Horizontal and vertical directions are chosen, profile cross sections are plotted, and power spectral density computation is carried out (Fig. 6). A 'swirly' pattern can be seen but it is believed to be due to birefringence due to the quality of the workpiece. The analysis focuses on the residual waviness due to the tool footprint pattern. As expected, it matches the main raster scanning pitch length. Its amplitude is 100 nm PV which is much reduced compared with the previous iteration. This confirms the benefit of introducing a controlled and alternated main and secondary pitch parameter from one iteration to the next. It reduces the presence of undesirable mid-spatial frequencies and the number of iterations.

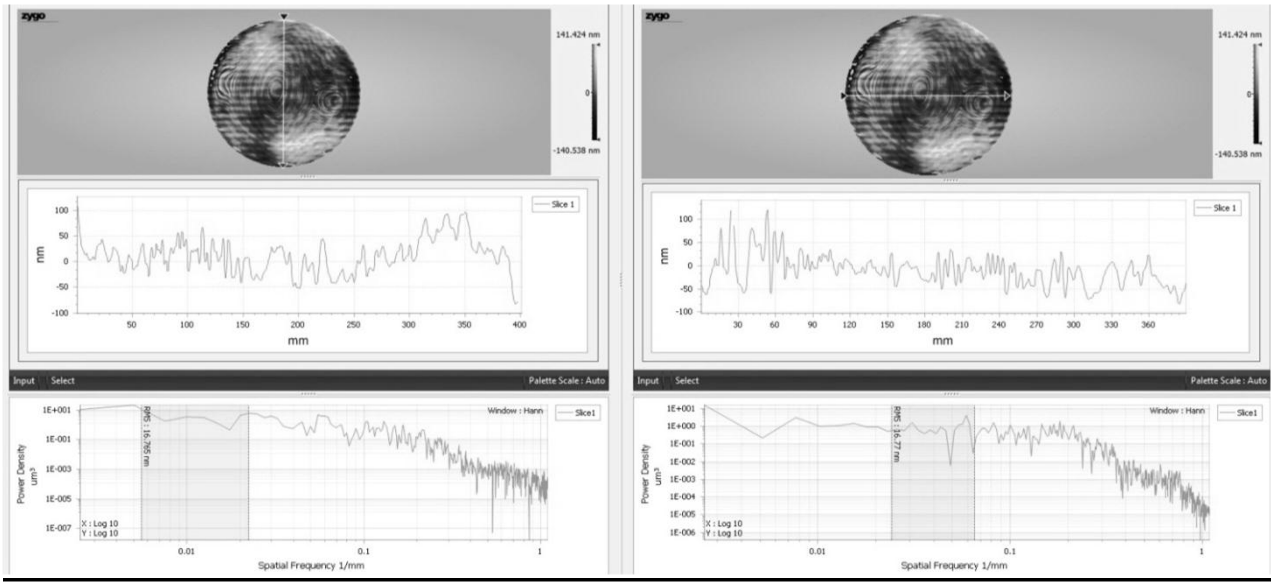

Figure 6. Power spectral density line graph for a direction perpendicular to scanning pattern (left), along to the scanning pattern (right).

4. CONCLUSIONS

The result of the experimental work demonstrates the rapid large scale figuring capability of the RAP process. A 400 mm diameter spherical surface with an initial figure error of ~2.3 µm PVr is corrected to λ/15 RMS 280 nm PVr (Lambda =633 nm) within 2.5 hours. The outcome of this work shows mainly high convergence rates and no edge effect which is highly important for cost effective manufacturing. Overall, this highlights the unrivalled RAP processing speed compared with other figuring techniques. Also, this result documents a possible optical fabrication chain through grinding, polishing and RAP figuring steps. The achievement is of significant interest for fusion laser programmes, large telescopes and deep ultraviolet lithography systems. On the basis of this result, a total figuring time of less than ten hours can be confidently predicted for metre-scale substrates with a characteristic input figure error of <1 µm RMS.

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