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Reactive Atom Plasma (RAP) Figuring Machine for Meter Class Optical Surfaces

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Reactive Atom Plasma (RAP) Figuring Machine for Meter Class Optical Surfaces

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A new surface figuring machine called Helios 1200 is presented in this paper. It is designed for the figuring of meter sized optical surfaces with form accuracy correction capability better than 20nm rms within a reduced number of iterations. Unlike other large figuring facilities using energy beams, Helios 1200 operates a plasma torch at atmospheric pressure, offers a high material removal rate, and a relatively low running cost. This facility is ideal to process large optical components, lightweight optics, silicon based and difficult to machine materials, aspheric, and free form surfaces. Also, the surfaces processed by the Reactive Atom Plasma (RAP) are easy to fine polish through hand conventional sub-aperture polishing techniques. These unique combined features lead to a new capability for the fabrication of optical components opening up novel design possibilities for optical engineers.

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Keywords

RAP; Figuring; Plasma Etching; optical fabrication; Plasma machining; Inductively Coupled Plasma

Abbreviations

California extremely large telescope (CELT)

Capacitively coupled plasma (CCP)

Carbon tetra-fluoride (CF_4)

Continuous phase plate (CPP)

Extreme ultra violet lithography (EUVL)

Extremely large telescopes (ELT)

Full width at half maximum (FWHM)

Ion beam figuring (IBF)

Inductively coupled plasma (ICP)

Nitrogen tri-fluoride (NF_3)

Radio frequency (RF)

Radius of curvature (ROC)

Reactive atom plasma (RAP)

Root Mean Square (RMS)

Standing wave ration (SWR)

Sulfur hexafluoride (SF_6)

Introduction

This paper focuses on the Helios 1200 machine which is a fast surface figuring machine for large scale ultra-precise optical components. The machine is designed around three key points: the Reactive Atom Plasma (RAP) technology, the need for ever larger optical surfaces corrected at nanometer level, produced with high reliability, and production capability offered through a dedicated designed Computer Numerical Controlled (CNC) machine tool.

Embedded technology and dedicated design give a unique capability for the fast surface figure correction of meter class optical components. The specification is to achieve <10nm RMS surface figure accuracy when processing a meter sized optical component with a processing time shorter than 10 hours. This specification presents serious challenges when considering current achievements are obtained within 100 hours [1].

In 2003, driven by a steadily growing and unsatisfied demand for extremely high quality surfaces, a UK based research team undertook a review study about optical fabrication techniques. They subsequently aimed at creating an innovative and cost effective fabrication chain [2] to satisfy this worldwide demand. This production chain reflects the development of deterministic machining technologies to achieve figuring accuracy to 1 part in 10^8 relative to optical surface size. Today, ultra-precise surfaces are developed for the overall society in wide ranging applications and products [3]. In fact, there are three major research programs demanding cost effective optical fabrication supply: high energy laser fusion systems, extreme ultra violet lithography (EUVL) and ground based extremely large telescopes (ELT). These application fields have common requirements and challenges. They can be summarized in two technical specifications: ultra-precise form accuracy and high surface integrity.

For the past 10 years, the main dimension of the primary mirror of telescopes has increased significantly over 10 meters. Consequently the optical designs now favor segmented primary mirrors for numerous reasons and significantly due to that of transportation. Most of the proposed next generation telescopes employ segments having dimensions measured from corner to corner in the order of 1.5 meter. However their aspherical technical specifications require nanometer level form accuracy on non-perfect hexagon shape substrates.

Although the overall size has changed by an order of magnitude, the different fabrication techniques have not made gigantic progress necessary to secure acceptable processing time. Disruptive technology is critical for the viability of these large scientific projects. In the case of fundamental astronomical development, the engineering choice for the telescope design leads to the requirement of nearly a thousand for large segments. In Europe, the major project is the European Extremely Large Telescope (E-ELT), whereas in the US, a strong emphasis is made on the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT).

To meet the current technical demand, surface figuring is facing significant and unprecedented challenges in terms of processing speed, surface integrity and level of form accuracy.

For the purpose of this development, the fabrication chain of optical components (mirrors or lenses) can be presented through three main fabrication steps: grinding, polishing, and figuring.

Across the optical fabrication field, there are numerous competing figuring techniques. The first of them is polishing - sub-aperture polishing - which is well established but has moderate capability to figure large optical components and does not enable the required throughout neither the ability to correct the surface shape near edge regions. The main disadvantages are: moderate determinism of the tool removal function, lack of control at the edge of the workpiece, continuous slurry management demands and long processing times. Secondly, Ion Beam Figuring (IBF) [4-5], which is well proven working at nanometer, is known to suffer from a low material removal rate for a given full width at half maximum (FWHM) of the beam footprint dimension. Also the equipment is expensive to run and to 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, a large IBF system is time consuming as the pressure in the chamber must be below 1.0×10^{-4}Pa. Typically, the pump down takes approximately 5 hours for a $10m^3$ chamber [6].

The other figuring techniques are Magnetorheological Finishing (MRF) [7-8], Chemical Vaporization Machining (CVM) [9-10-11] Atmospheric Pressure Plasma Machining (APPM) [12-13] Plasma Jet Machining (PJM) [14-15] and Reactive Ion Beam Etching (RIBE) [16]. Today, it is clear that there is a trend towards greater use of energy beams: particles, laser, or plasma. Plasma and particle based figuring techniques are gradually becoming mainstream processes in optical fabrication workshop as they offer high removal rate, broad material removal range and ability to tune for given applications.

This paper presents a new generation of energy beam figuring machines. Specially, the Helios 1200, which has the capability to fulfill the aforementioned benchmarks of high technology industries and demanding science projects in a cost effective manner.

2. RAP Process overview

In this research work, the high material removal rate is achieved using the Reactive Atom Plasma (RAP) process whilst the performance of the figuring process is enabled through a purposely built Computer Numerically Controlled (CNC) machine tool. The RAP process was developed to provide a unique rapid surface figuring capability with extreme tool adaptability due to the soft edge of its plasma plume. The RAP technology is well-developed for processing optical surfaces made of fused silica [17-18], silicon, borosilicate, silicon carbide [19-20] and ULE® [21].

Unlike mechanical polishing processes, the RAP process does not induce sub surface damage and unlike capacitively coupled plasma (CCP), the RAP process does not require conductive material. Also it operates at atmospheric pressure and the energy beam footprint is scaled and tuned to process large surfaces with typical mid spatial frequencies superior to $0.2mm^{-1}$. As there is no need for vacuum system, it benefits of a low running cost compared to Ion Beam Figuring (IBF). Additionally since there is no contact between tool and workpiece then there is no clamping mechanism and no post machining distortion. Finally, through the use of sophisticated time dwell algorithm compensating for the heat transfer, the RAP tool has the capability to etch optical components within a minimum number of iterations.

The RAP process is essentially a dry etching process using a Radio Frequency (RF) Inductively Coupled Plasma (ICP) which atomizes the reactive gas to create free radicals. This process is localized in the plasma discharge area, the radical species are created from different reactive precursor gases such as: carbon tetra-fluoride (CF_4), nitrogen tri-fluoride (NF_3) or sulfur hexafluoride (SF_6) [22-23].

Table 1. Properties of reactive gases (at 293K and 1 atmosphere)

	CF_4	NF_3	SF_6
Bond energy (kJ/mol)	485	277.8	285
Boiling point (°C)	-126	-129.1	-50.8
Density* (kg/m^3)	3.63	2.97	6.15
Viscosity* (μPs)	17.0	14.5	26.6

These gases are characterized by low enthalpies of atomization and are preferred to secure a high quality surface with minor surface roughness degradation. In some cases, the choice of reactive gas is carried out on the bi-product which can redeposit on the surface and affect the surface roughness in an undesirable manner.

The RAP process has strong potential for four major types of highly demanded applications: rapid figure correction of large optics, figuring of phase plates, removal of mid spatial, and fabrication of complex aspheric surfaces [24]. Two of these applications are detailed hereafter.

Firstly, in regards large telescopes, it was published in 2000 that the difficulty of figuring large aspheric optics by traditional means is approximately in proportion to the slope of the aspheric departure: 100um and 20um departure from spherical shape for the Keck and the California Extremely Large Telescope (CELT) telescopes respectively. As surfaces depart more and more from a spherical shape, increasingly dexterous tools are required to obtain a good fit between the tool and the optical surface [25].The RAP process can theoretically achieve the figure correction of these highly complex surfaces. Secondly, in regards high laser system it was reported in 2004 that the fabrication of continuous phase plate (CPP), used in the integrated optical module of the final optic assembly of laser fusion programs, is perfectly feasible and cost effective [26].

3. Mathematic development and applied engineering of the RAP process through de-convolution methods

Classically, a figuring process is carried out iteratively by analyzing surface figure error and removing material using a dedicated tool path algorithm [27]. Also, it is necessary to assess accurately the removal beam function of the plasma torch. To do so, the surface topography of a witness sample is measured using an interferometer, the surface is then exposed to the RAP energy beam for a defined amount of time. After this a second interferometric surface topology measurement is carried out and the difference between the two measurements gives the effective beam removal function. Such a procedure is not required systematically prior each processing as it was shown to be particularly consistent.

The tool path velocity of the etching beam travelling on the work surface results from a dwell time proportional to the desired material removal depth. To carry out this task, Fast Fourier Transform (FFT) methods are used to calculate the dwell time distribution for the removing of a specific substrate topology. This is called de-convolution technique. On the other hand, the dwell time map enables modeling of post process surface topology (convolution) [17-28] and the calculation of the process convergence ratio.

At given local speeds, dwell times t and the material removal function r the dwell time procedure can be expressed as follows:

$$h = t \times r + E \quad (1)$$

(h stands for the heights of the removed material and the symbol ‘x’ denotes the convolution operator, and E is certain amount of error)

Figure 1 illustrates the basic de-convolution procedure and presents it in its velocity form more relevant for the CNC machine tool.

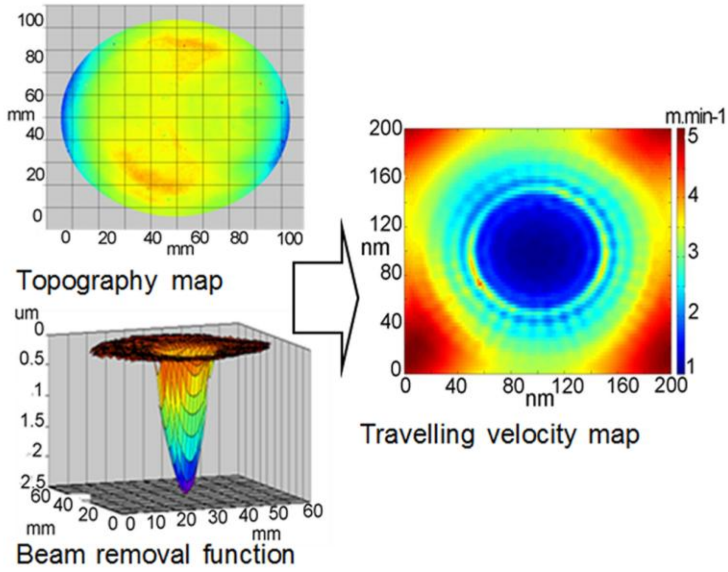

Figure 1.Typical de-convolution process

4. Reactive Atom Plasma Process

The RAP process was developed and patented [29] by a team of engineers in 2001 through a spin-off company of the Lawrence Livermore National Laboratory in California, USA. The technology came from the need for removing subsurface damages of glass components, silicon wafer and silicon carbide optics. Based on plasma processing, the RAP process can be described as a non-contact dry chemical etching process carried out at atmospheric pressure. Since its invention, the main application has shifted towards ultra-precise surface correction of optical components used in astronomy, space, defense, and semiconductor industrial sectors.

The shift in process development came in 2002 where a two axis motion system prototype machine called the RAP 300 was developed to carry out a feasibility study and determine the figuring capability of the RAP energy beam. This work demonstrated the tremendous potential of RAP process on most silicon based optical materials. The prototype machines pioneered fast figuring at nanometer level using RAP energy beams. Following this successful achievement, a 1200 mm processing capability machine was jointly designed and developed by Cranfield machine tool researchers and RAPT Industries engineers. In 2008 a new 1200mm capacity machine was realized and brought into operation at Cranfield. The new facility which is presented in this paper is known as the Helios 1200. But first, we will focus on the torch.

4. 1. RAP torch

The RAP torch of Helios 1200 is equipped with a convergent divergent type nozzle to provide a turbulence free jet at subsonic velocities. Compared to a classic "full bore" Inductively Coupled Plasma (ICP) torch, the Helios torch design increases the performance of the etching footprint by bringing a higher number of reactive species to the process footprint. Both the radio frequency generator, torch coil and torch nozzle are water cooled to maintain optimum and consistent processing conditions over long periods of time. This thermal control is critical in the context of consistent tool footprint stability and consistency.

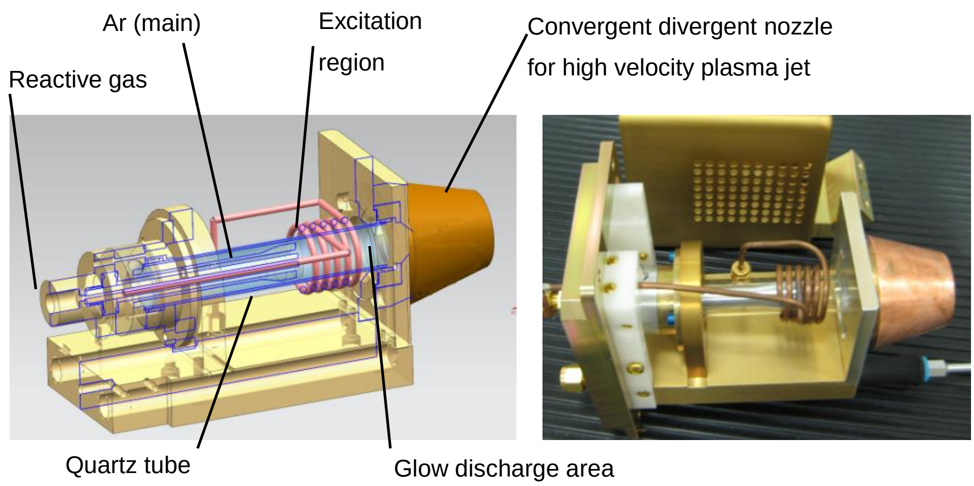

Figure 2. ICP torch of Helios 1200

The Radio Frequency Inductively Couple Plasma is generated by passing an alternating current through a coil which is wound around a dielectric tube. The plasma generated inside the quartz tube forms a closed conducting loop, known as the plasma core, which acts as a single turn secondary coil in a transformer. As the name suggests, the plasma is heated inductively. The electromagnetic (EM) fields, induced by the coil current, penetrate the plasma and through joule heating maintain it.

Typically, the etch characteristics are dependent on numerous parameters such as: tube diameter, gas enthalpy, gas flow, RF power, and EM field frequency [30-31]. Much of the power is dissipated in the so-called ''skin-depth'' This prevents the electric field from penetrating into the core of the plasma. The skin depth of the plasma is defined as:

$$\delta=\sqrt{2/\mu\omega\sigma} \qquad (2)$$

where μ is the permeability, σ is the plasma electrical conductivity and ω is the angular frequency. According to (2) increasing the driving frequency will not necessarily couple more power into the plasma. As the frequency increases, the plasma will tend to shield itself. Overall the I.C.P. torch has numerous advantages over an alternative DC torch such as:

- Impurity-free plasmas
- Better control of heat transfer mechanism
- No fundamental limit on torch power
- Ability to generate plasma with the various types of gases
- Operable to atmospheric and very low pressure

4. 2. Radio frequency (RF) network

Due to the size of the workpiece and consequently the duration of the figuring process, a robust RF network is of primary importance for the deterministic aspect of the RAP tool footprint. It is composed of an ICP plasma torch integrated within an inductive output L type RF network and an RF AC power generator. The RF generator uses agile technology and an algorithm based on Standing Wave Ration (SWR) to determine the optimum RF in a minimum amount of time.

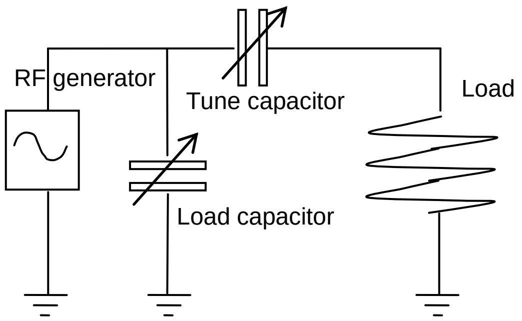

Figure 3. Inductive output L network

A fixed matching inductively output L network delivers power into relatively large output coil (25mm diameter). The typical limitations of this RF network design are mainly due to the voltage rating of the tune variable vacuum capacitors and the self-resonant frequency of the coil. Due to process specifications of the RAP torch the choice of RF technology leads to cost effective frequency tuning methods avoiding expensive automatic matching network solutions.

5. RAP machine design (Helios 1200)

Due to the non-contact nature of the RAP process there are many possible configurations to manufacture precision optics. This feature greatly relaxes the mechanical constraints on clamping of the workpiece and in the Helios 1200 enables the substrates to be held face down which prevents re-deposition of removed material.

In the design considerations for the machine, the following attributes were seen to be desirable: non-contact material removal tool which allows for a force-free workpiece holding system; production capability assured by a high end CNC system, dedicated machine and gas handling control; specialized motion system designed for efficient raster scanning, configured for a small machine footprint for large scale optical components; double fault tolerant monitoring and post treatment of hazardous gases for process output consistency and compliance with all relevant European legislation and machine tool directives.

The CNC motion system, controlled via a Fanuc 30i, is of a three linear axes orthogonal design. The plasma torch is mounted on a vertical Z axis of small stroke and low mass which is mounted onto a low mass high dynamic response X slewing axis. This high response axes being driven via a linear motor. Above and orthogonal to the Z-X axes arrangement is mounted the workpiece which is held within a Y axis carriage. This third axis s driven as a gantry system through twin motor ballscrew drive systems either side of the carriage.

A dedicated software package covering gas handling interacts with the machine programmable logic controller (PLC)’s ladder to ensure machine safety. This is an important feature as both hazardous gases and kilowatt radio frequency power supplier are used.

Gas extraction is monitored and the treatment of volatile bi-product compounds (species) is carried out by a wet gas scrubber with a 720 cubic meter per hour air handling unit. A developed Human Machine Interface (HMI) software package manages the safety features, the radio frequency generator and the motion control system.

Figure 4. Cranfield / RAPT Helios 1200 machine

Due to European legislation, the machine chamber is designed with double skin principle where fresh air flows between the machine's outer and inner skins thus providing efficient extraction of reactive and bi-product gases (fig. 5).

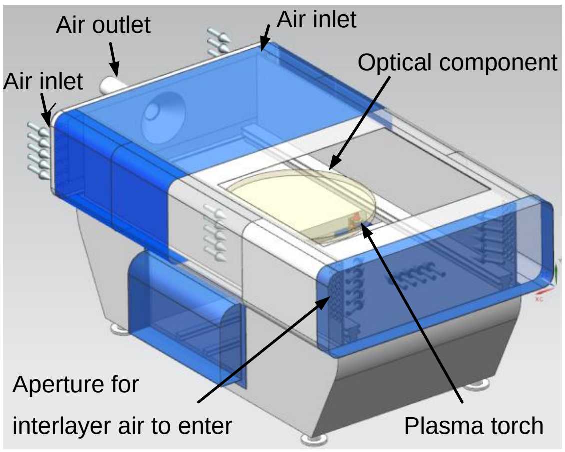

Figure 5. Air flow configuration (double skin design)

From a processing viewpoint, the motion between the torch and workpiece is of the raster scanning type. The optical component moves along the Y axis and the plasma torch moves in the XZ plane (fig. 6). The primary axis, called X, has an acceleration capability equal to 10 m/s2 that enables fine adjustments of the torch velocity in flight. This dynamic ability enables to transfer the time dwell map to the workpiece by adjusting the travelling speed along short distances when rastering [27].

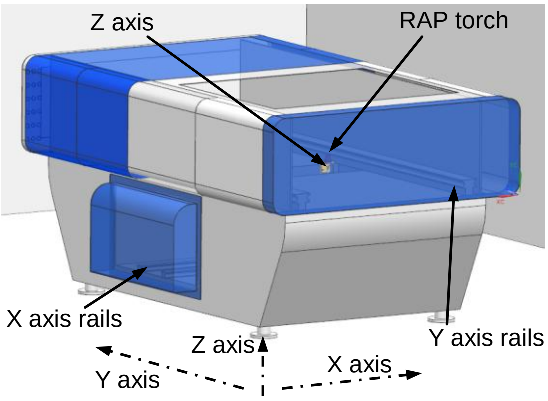

Figure 6. Three (3) axis cinematic configuration

The vertical axis, called Z, enables control of the standoff distance between torch nozzle and workpiece surface enabling figure correction of surfaces with sag up to 50mm. The top-loading carriage holds the component with the surface to be figured facing downwards, and the torch moves across this surface using the 3-axis range of motion.

The machine Y axis is a mechanical ballscrew driven system with twin drive designed to carry over 500Kg moving mass with nominal acceleration of 0.1g’s. The picture below shows the workpiece holder as viewed through the machines top sliding door.

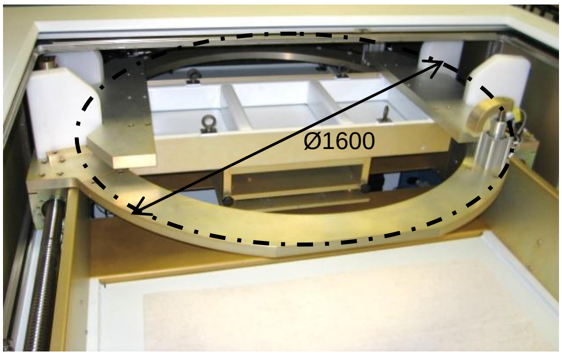

Figure 7. Workpiece holder dimensions

The processing chamber accepts ELT type mirror segments (fig. 7). The general machine design is scalable (up and down) to enable figuring of virtually any size of optical components.

6. Fundamental performance of RAP energy beam

The basic principle of dwell time technique requires a characterized tool footprint which is detailed in this section. But first, here are provided the experimental conditions.

6. 1. Processing conditions

- RF generator nominal power: 1000 W
- RF generator frequency: 40 MHz
- Temperature and humidity controlled room
- SF6/Ar 10% gas mixture (research grade)

All experimental works were performed on fused silica (grade Q1) substrates.

6. 2. Beam footprint characterization

The plasma tool footprint of the cold tip torch mounted in Helios 1200 has a Gaussian shape (FWHM: 11mm). Its determinism factor was assessed through linear tests where the maximum depth of the trench was analyzed (fig. 8). Typical figuring conditions are attained using feed speed values ranging from 1 up to 6m/min that yield material removal rates from 0.5 to 2.5mm^3/min. Profile and straightness of a single scan of the torch is shown in figure 8.

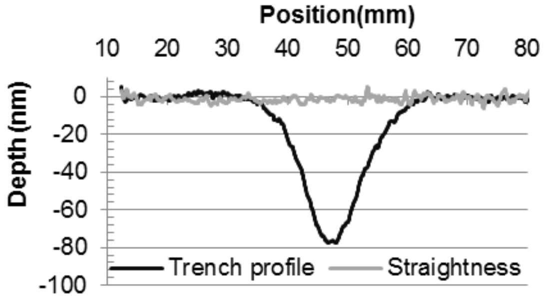

Figure 8. RAP trench cross section (Feed speed: 1m.min-1 / material: fused silica, standoff distance: 6mm)

An important processing parameter is the low sensitivity of the standoff distance variation. The results (fig. 9) present both the maximum depth of the trench versus the standoff distance. The fitted polynomial trendline of the graph shows an interesting optimum value at 6mm which offers both the highest material removal rate and moderate sensibility to standoff distance variation. This is important for a deterministic ultra-precision process.

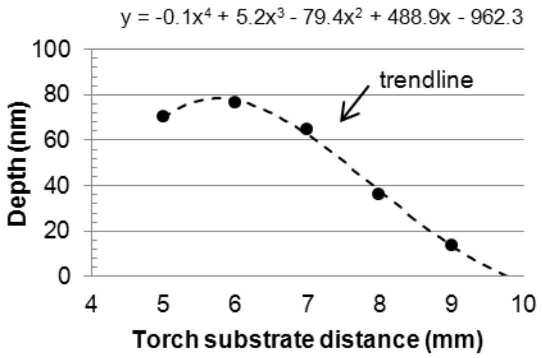

Figure 9. Footprint depth versus standoff distance (Feed speed: 1m/min, material: fused silica)

The characterization of RAP energy beam would not be completed without an assessment of the surface roughness changes. To do so a design of experiment was carried out to highlight both Sa and Sq values through the removal of tens of nanometer of material. The graph below (fig. 10) presents the results after buffer cleaning using aluminum oxide emulsion.

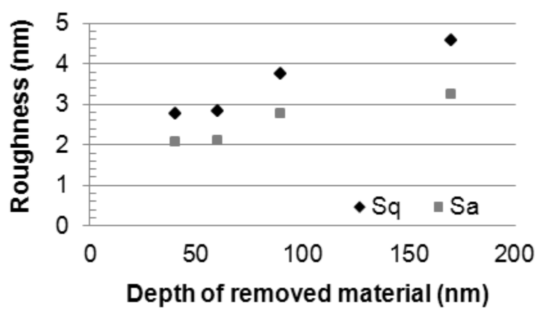

Figure 10. Surface roughness versus material removal depth (material: fused silica polished down to 1.6nm Sa prior experimental test)

7. Application of RAP energy beam for optical fabrication

Based on these fundamental results, a dwell time based figuring process was carried out on a 400mm diameter 3m radius of curvature (ROC) ULE workpiece. After five iterations, the surface figure error was drastically improved (fig. 11). All the measurements of the workpiece surface were carried out using an optical test tower equipped with a vibration insensitive interferometer [32]. The parameters which characterize the surface form were changed from 2260nm PVr 373nm rms down to 250nm PVr 30nm rms.

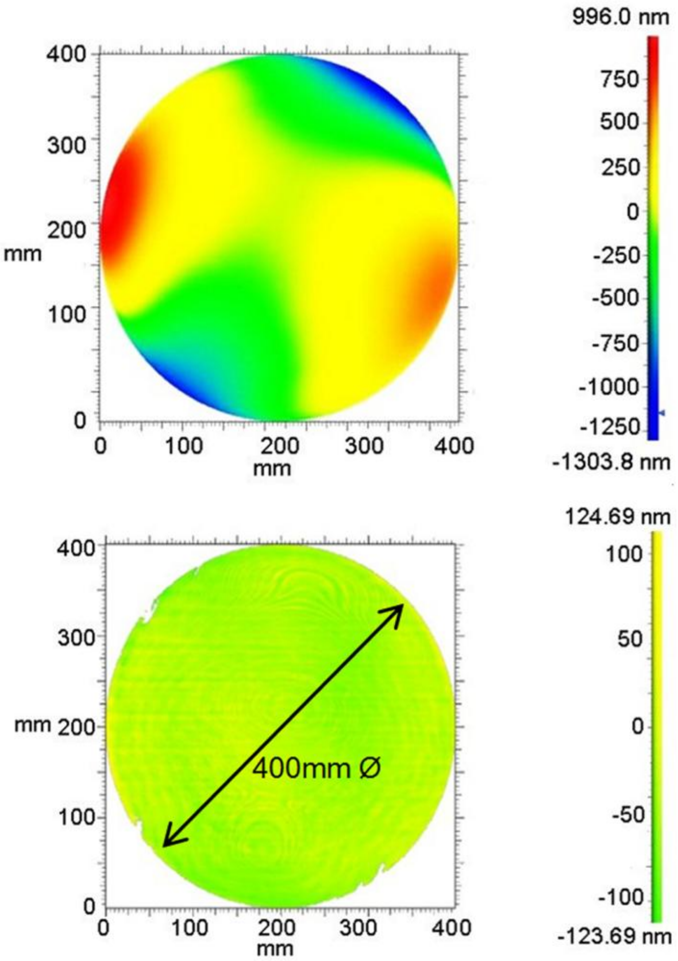

Figure 11. Topography of a pre and post 400mm processed ULE surface.

8. Conclusion

A new production capability for figuring large free form optics has been achieved through the design and fabrication of Helios 1200 machine. In the context of the production of meter size optical components this machine offers an ability to avoid a significant bottleneck in the production process chain.

The Helios 1200 is functional in production environment and the processed surfaces are highly compatible with simple buffing, or neutral sub aperture polishing. The RAP processing capability fits comfortably with grinding and polishing in various combinations. The RAP 1200 machine is highly repeatable and the RAP process itself highly deterministic when applied to a range of glasses and silicon based ceramics. The tool footprint influence function is stable over long durations making it especially applicable to larger optics and longer process cycles. It is also tunable according to the processed material and geometry. For thin section light-weighted optics demanding edge control it is especially appropriate. On-going process development of the RAP process is expected to confirm its advantages for lightweight optical components and continuous phase plates (CPP).

This paper has introduced a new and novel energy beam machine tool which offers a unique optical processing capability where the technology can be easily scale up or down.

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