REACTIVE ATOM PLASMA (RAP^{TM}) PROCESSING OF OPTICAL SURFACES

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INTRODUCTION

Increasing demands are being made on optical surfaces, these being driven by shorter wavelengths, increased precision and the need for faster, smaller optics demanding complex aspherical surfaces to replace multiple spherical surfaces. Lately, there have been multiple innovations in final finishing (with sub-aperture, deterministic polishing steps) and metrology (stitching interferometry, computer generated holograms) of such optics. Issues such as sub-surface damage, mid-spatial frequencies, and cost and lead time of manufacturing still plague the development and deployment of precision optics.

A novel integrated manufacturing process comprising a split chemical mechanical polishing technique has been developed that addresses the issues with current modern optical manufacturing techniques.

INTEGRATED MANUFACTURING PROCESS

The conventional approach to the manufacture of precision optics relies on some form of a Chemical Mechanical Polishing (CMP) step. CMP involves pushing down mechanically on the precision surface in the presence of chemical abrasives, and invariably introduces a certain amount of damage to the surface [1]. This damage is heavily dependent on the abrasives used (mostly grit size), relative velocity between the tool and the surface, and the normal pressure applied. This damage is usually removed through a laborious process of using finer and finer grit and reduced polishing pressures over a series of iterations. Additionally, a damage mitigation step could be added to the loop and this invariably takes the form of an etching step as illustrated in *FIGURE 1*. This sequence of steps is repeated many times, until the desired precision on the surface is achieved. Surface metrology is performed in between cycles to guide the following iteration(s).

The conventional approach has been applied with great success to optics manufacturing. One of the key advances that has permitted the continued application of conventional techniques has been the advent of sub-aperture deterministic polishing techniques. However, two factors are causing the continued application of the conventional approach to break down. These are:

1. Increasingly complex geometries

   This is due to either very high aspect ratios (caused by very lightweight or thin substrates), or difficult free form geometries (caused by low f/#s in the case of aspherical optics).

2. Advent of advanced materials such as ceramics

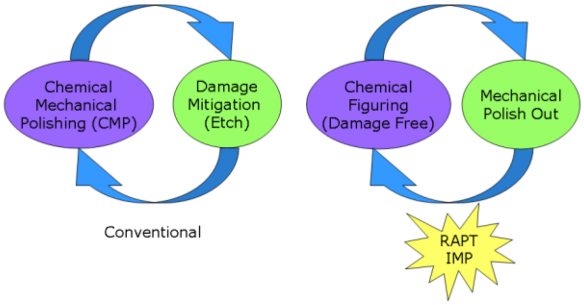

FIGURE 1. Comparison of Conventional and RAP approaches

This is because the CMP process imparts an unknown amount of stress to the surface layer. The metrology between iterations measures only the deviation from the desired geometry and there are no established techniques today to determine the state of stress/strain underneath the surface. As these substrates get thinner, this unknown surface stress causes uncontrolled deformation in the surface, either over a period of time, or worse in between and during process cycles. During subsequent cycles with finer grit and lower normal pressures, the damaged surface is removed, causing the state of stress to relax – this causes additional deformation that is uncontrolled by the process. This then leads to a very slow (undeterministic) convergence to the desired surface geometry and leads to serious disruptions in the manufacturing process.

In this paper, we discuss a radically different approach which enables rapid, reliable, low-cost damage-free manufacturing of these precision surfaces. Our Integrated Manufacturing Process (IMP) involves serializing the chemical and mechanical steps rather than doing them in parallel as in CMP. In our process, the chemical figuring (shaping) step is responsible for imparting the desired geometry to the surface in a non-contact manner. Given the non-contact manner of the figuring step, the cycles become deterministic, as the substrate is essentially stress-free. A metrology step is used as before to determine the deviation from the desired geometry at each iteration. A mechanical buffing or polish-out step is also required as part of the cycle since the chemical etching step, by its very nature increases roughness due to selective etching at damage sites, grain boundaries, etc., which are widely prevalent on the surface being figured. The mechanical buffing step is designed to be conformal to the geometry being manufactured and uses low contact pressures to essentially provide a roughness mitigation step without altering the figure of the surface.

RAP^{TM} Processing

Reactive Atom Plasma (RAP^{TM}) processing is a non-contact, sub-aperture, deterministic material removal technology operating at atmospheric pressure. The process involves the delivery of reactive radicals to the surface being machined. This is typically done by creating a plasma into which a reactive precursor chemical is injected and broken down into reactive radicals which are then delivered to the surface. The appropriate precursor chemistry is chosen so that the by-products of reaction with the substrate are volatile and removed in the gas phase from the substrate without redeposition or debris forming back on the surface. As a result, the surface left behind is damage and contaminant-free. One embodiment of the RAP^{TM} technology is illustrated in *FIGURE 2*. Here, an argon plasma is created (typically by using inductively coupled RF power to excite the plasma) and a reactive precursor such as CF_4 introduced into the plasma. Other chloro or fluoro-carbons could be used just as well depending on the chemistry requirements. This gets broken down into individual carbon atoms and highly reactive fluorine radicals as illustrated in *FIGURE 2*. The stream of reactive atoms is directed onto the surface of the glass (in the example) substrate and the volatile by-products of reaction are SiF_4 and CO_2, both of which are exhausted in the gaseous form. The chemical reaction rate with the substrate is dependent on the concentration of the radicals, the chemistry of the substrate itself, and the temperature of processing. The reaction follows the Arrhenius law, and the etch rate "*Rate*" using the RAP process is given by the Arrhenius law:

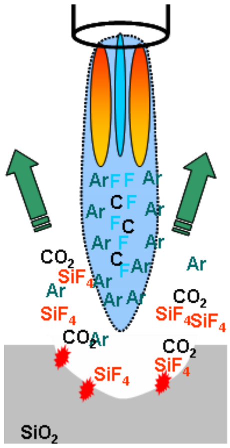

FIGURE 2. RAPT Processing

$$Rate \qquad Ae^{\;E_a/RT} \qquad (1)$$

where A is a phenomenological rate constant, E_a is the activation energy, R the universal gas constant[1] and T is the absolute temperature of the reaction. It is easily seen that the etch rate varies exponentially with temperature. Practical issues however limit processing temperatures.

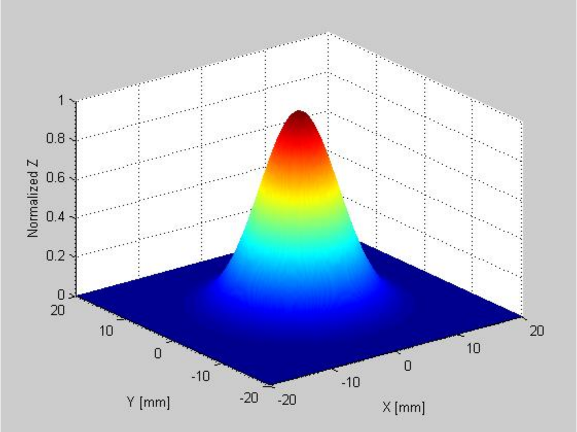

FIGURE 3. Gaussian tool footprint

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[1] R has the value of 8.314×10^{-3} kJ $mol^{-1}K^{-1}$

Unlike traditional sub-aperture polishing techniques which have a static footprint, the RAP$^{\text{TM}}$ process has a footprint that is dynamic due to the exponential temperature dependence. While this complicates the tool path algorithm, the footprint also has a smooth, symmetric Gaussian shape as illustrated in *FIGURE 3*. The Gaussian shape minimizes ringing due to high-frequency artifacts and minimizes and in certain cases eliminates mid-spatial frequency errors.

As with any other sub-aperture technique, the surface being machined is measured using metrology techniques such as interferometry or profilometry and an error map is determined by subtracting this surface map from the desired geometry. This error map is used to compute an iterative material removal map and a tool-path algorithm computes the dwell time of the plasma over the surface to be machined, by deconvolving the tool footprint from the material removal map.

Conformal Polishing

As noted before, the RAP$^{\text{TM}}$ process corrects the low and mid spatial frequency errors. A conformal polishing step is then used to polish out the high-frequency artifacts, without influencing the low-frequency errors

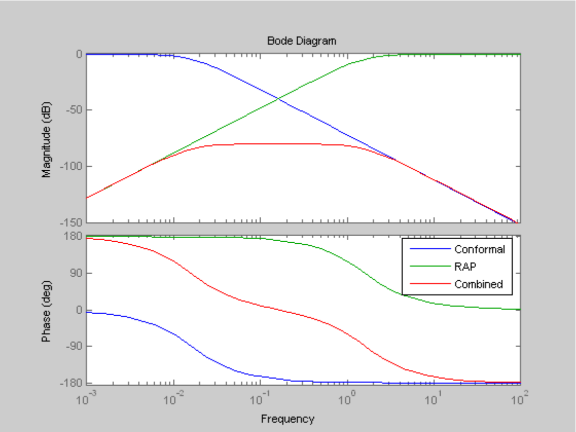


FIGURE 4. Notional frequency response of the Integrated Manufacturing Process

FIGURE 4 illustrates the RAP$^{\text{TM}}$ process and the conformal polishing step on a notional 1-dimensional frequency axis (chosen for ease of visualization). The RAP$^{\text{TM}}$ step can be modeled as a high-pass filter as discussed earlier, and the conformal polishing step is designed with the spatial frequency characteristics designed such that the combination of the two processes results in the desired attenuation of errors in the surface over the desired frequency range.

A combination of feed-forward and feedback control techniques as discussed in [2] can then be applied to ensure desired convergence. This, along with the lack of significant stress in the substrate, leads to truly deterministic and rapidly convergent manufacturing of precision optics.

RESULTS

As discussed earlier, RAP$^{\text{TM}}$ processing can be done with a variety of tool sizes depending on the spectral content of the error map. A range of tool sizes from 0.5mm to 50mm full-width half max have been demonstrated.

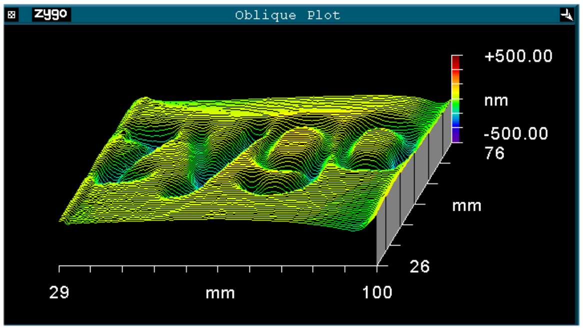
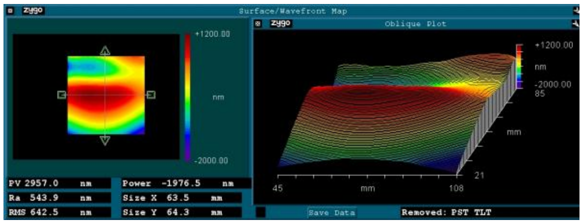


FIGURE 5. Nano-graffiti lettering. "Zygo" on fused silica

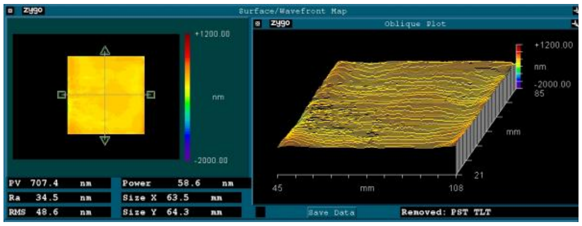
FIGURE 5 illustrates some nano-graffiti on fused silica – this is meant to demonstrate the tool-size and the control over the etching, and is not terribly useful. *FIGURE 6* illustrates a flat fused silica substrate that has a P-V error of 5 waves while *FIGURE 7* illustrates the same surface after 2 RAP$^{\text{TM}}$ iterations.



PV 2957.0 nm
Ra 543.9 nm
RMS 642.5 nm
Power -1976.5 nm
Size X 63.5 mm
Size Y 64.3 mm
Removed: PST TLT

FIGURE 6. Flat surface prior to IMP (5 waves P-V)

The P-V surface error has been reduced to 1 wave P-V in less than a half hour in this example. Even more important, especially with lightweight optics is the damage removal during the figuring process itself [1].



PV 707.4 nm
Ra 34.5 nm
RMS 48.6 nm
Power 58.6 nm
Size X 63.5 mm
Size Y 64.3 mm
Removed: PST TLT

FIGURE 7. Flat surface post IMP (1 wave P-V)

The integrated manufacturing process has also been applied to the figuring of powered aspherical optics and has been shown to be a rapid cost-effective technique to fabricate damage-free precision surfaces.

CONCLUSIONS

Conventional approaches to the fabrication of high-aspect ratio precision surfaces are limited due to the damage imparted to the substrates and the resulting stress. An Integrated Manufacturing Process has been demonstrated to provide rapid and predetermined convergence to the desired shape. This IMP is being deployed to manufacture optics to about 0.25 waves P-V at which point in time, existing final finishing approaches can take over to obtain a surface with relatively little damage and with minimal mid-spatial frequency errors.

The IMP, and more specifically RAP^{TM} process cast the manufacturing of precise optical surfaces in an entirely new light, *i.e.*, the creation of very precise surfaces with fairly imprecise tools. Given the non-contact and deterministic nature of the RAP^{TM} process, the tool is easily implemented on a dexterous robotic manipulator. With relatively low sensitivity of the process to the height of the plasma above the surface, requirements on the impedance (stiffness) of the precision machine implementing the RAP^{TM} process are significantly reduced. This permits the implementation of the RAP^{TM} process on a tool with varying impedance over the workspace such as a dexterous robotic manipulator. Such a dexterous design also permits in-situ machining of pads for assembly of precision optics thus accelerating the assembly cycles and reducing the cost.

ACKNOWLEDGEMENTS

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