Rapid fabrication of lightweight SiC aspheres using reactive atom plasma (RAP™) processing

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ABSTRACT

Polishing has traditionally been a process of mechanical abrasion with each iteration removing the damage from the previous iteration. Modern sub-aperture techniques such as CCOS, MRF polishing etc. have added a considerable amount of determinism to this iterative approach. However, such approaches suffer from one significant flaw, i.e., the algorithms are completely guided by figure error. This approach fails when there is a considerable amount of strain energy stored in the substrate and becomes very evident when the aspect ratio of the mirror increases significantly causing relaxation of strain energy to have deleterious and unpredictable effects on figure between iterations. This is particularly pronounced when the substrate is made of a hard ceramic such as silicon carbide requiring a considerable amount of pressure to obtain any appreciable material removal rate. This paper presents an alternate approach involving a stress-free figuring step and a buffing step intended to recover the surface roughness.

Keywords: reactive atom plasma, silicon carbide, RAP, sub-surface damage, asphere fabrication

1. INTRODUCTION

Rapid fabrication of lightweight mirrors is a key requirement for the success of various space-based and terrestrial programs. Rapid fabrication leads to significant cost savings, by directly reducing the optician "touch-time" and by minimizing risk due to longer schedules. However, rapid fabrication requires a rethinking of the optics fabrication paradigm. Despite the advances made in the last few years in sub-aperture polishing, the fundamental concept of mechanical polishing has not really changed radically. Although it can be argued that polishing is primarily a chemical mechanical process, in many cases, the chemistry is primarily meant to render the substrate suitable for mechanical abrasion. Other techniques such as single point diamond turning and ion beam figuring are also mechanical in nature. The biggest drawback with such mechanical means of polishing stems from the fact that they introduce significant amounts of stress (as a result of strain energy buildup) in the substrate. This state of stress is unknown for the most part and subsequent figuring iterations cause this state of stress to change. This stress can be used to one's benefit as is done with techniques such as stress-lapping, but in many cases the stress or rather the change in stress between iterations causes unpredictable and deleterious changes in figure. This gets compounded as the aspect ratio of the substrates increases causing significantly increased changes in figure as a result.

1.1. Sub-surface damage (SSD) and resulting stress

Silicon Carbide (SiC) is an attractive candidate for making optical mirrors due to its excellent thermo-mechanical properties[3]. It has a specific stiffness that is second only to Beryllium (without the accompanying toxicity issues) and a thermal stability that is better than ULE or Zerodur. It is also a ceramic and is rad-hard. However, these very properties make it a hard material to process. Typically, diamond is the only material that is used to grind/polish SiC, and even using such hard materials for tools, appreciable material removal rates require a significant amount of normal pressure. This additional normal pressure from conventional finishing techniques has many deleterious effects. However, two of them require special mention:

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- First, the additional normal force leads to a predominantly quilted mirror in cases where lightweighted substrates are used.
- Second, a significant amount of strain energy is stored in the face sheet of the mirrors and relaxes between iterations causing significant changes in figure further leading to slow and non-deterministic convergence. This is again compounded in lightweight mirrors with thin face sheets since the damage layer is an appreciable part of the face sheet.

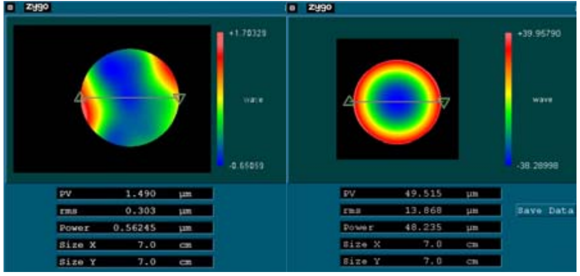
It is well known that grinding/polishing causes sub-surface damage that extends below the surface of the optic. During these mechanically abrasive processes, the surface of the optic is sheared either in a brittle fracture mode or a ductile shear mode leading to a surface with a high density of microscopic cracks and/or plastic deformation. Subsequent processing is done with this in mind, and opticians typically as a rule of thumb, remove 2-3x more material than the grit size used in the previous grinding/lapping step. The micro-cracks and fractures introduced in the surface lead to a compressive stress in the damage layer causing it to bend into a convex shape[1]. The amount of this shape change can be measured accurately to give a quantitative measure of the SSD introduced during a particular abrasive operation. The Stoney equation which is used to quantify stress from thin film coatings can be used to compute the surface stress assuming uniform stress distribution and by modeling the damage layer as a thin film. Accordingly, the stress is given by the biaxial form of the Stoney equation that is valid for high aspect ratios (>1:50) between the depth of the damage layer and the thickness of the substrate[2].

$$\sigma = \frac{4\delta E d^2}{3(1-\upsilon)t_{ssd} D^2} \tag{1}$$

where,

σ = Twyman stress (MPa)
ν = Poisson’s ratio
E = Young’s Modulus (MPa)
t_{ssd} = Damage layer thickness (nm)
δ = Circular plate deflection (nm)
d = Substrate thickness (mm)
D = Substrate diameter (mm)

To obtain an understanding of SSD and its effects on resultant figure error, 3-inch round, 1.5mm thick coupons of SiC were subjected to conventional processes. The dimensions of the disks were chosen to be representative of the inscribed circle on a lightweighted mirror thus leading to a good extrapolation of results from coupons to finished mirrors. The disks were first ground on a fixed abrasive diamond lap to remove about 250mm of material per side. This was done to ensure that any earlier mechanical damage was replaced by a known amount of damage from the fixed abrasive process. After that the RAP process was used to strip off about 20um of material uniformly on both sides in order to remove the damage introduced in the previous lapping step [2]. This was considered the baseline ‘stress-free’ state of the disks. One surface was used for metrology while the other was milled using a process proprietary to a SiC manufacturer. A peak deflection of almost 50μm was observed after the milling operation illustrating the sensitivity of figure error to sub-surface damage.



PV 1.490 µm
rms 0.303 µm
Power 0.56245 µm
Size X 7.0 cm
Size Y 7.0 cm

PV 49.515 µm
rms 13.868 µm
Power 48.235 µm
Size X 7.0 cm
Size Y 7.0 cm

Fig. 1. Figure error prior (1.4 µm PV) to and post (49.5 µm PV) milling on a 3" sample representing the inscribed circle on a lightweighted optic. Notice the convex bow indicative of the compressive stress on the damage layer.

1.2. Damage mitigation using RAP

A series of RAP etching steps were then performed to both relieve the stress and return it to the original damage-free state. The depth of the damage layer was also carefully calibrated during this sequence of RAP iterations by carefully measuring the thickness of the material etched away during each iteration until the substrate was returned to its original state. The change in sag is illustrated in Figure 2. The Stoney equation reveals a peak stress of about 0.9 GPa – it should be noted that this number is conservative at best given that it assumes a uniform state of stress throughout the entire damage layer which ranges between 15-25 μm for SiC processed with conventional methods. These numbers confirm the big issue with change in figure between polishing iterations using conventional approaches and the difficulty in separating quilting issues on lightweighted mirrors from errors due to SSD.

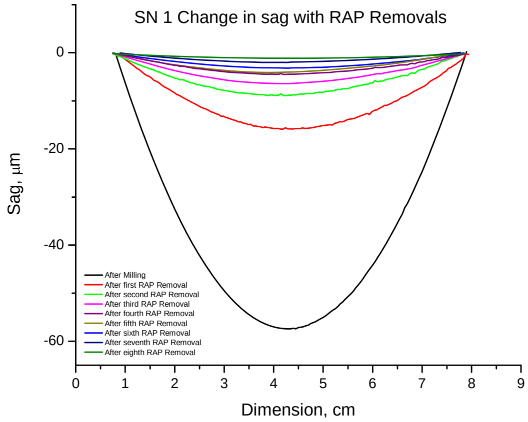


Fig. 2. Change in sag with RAP removal steps

2. ASPHERE FABRICATION

The first step in applying the integrated manufacturing process to the fabrication of aspheres is damage removal to avoid the aforementioned issues with figure changes between iteration due to the relaxation of strain energy stored in the substrate. A layer of 15-25 μm which is the damage layer left by most grinding/generating operations is etched away. Due to the fact that SiC is a polycrystalline substrate, application of the RAP step can lead to increased roughness of the substrate. This increase in roughness is primarily due to the following 2 mechanisms:

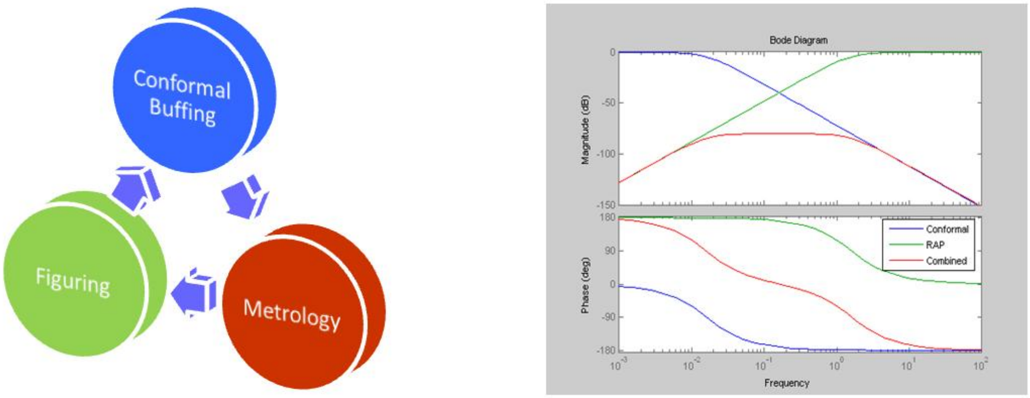


Fig. 3. Notional representation of the Integrated Manufacturing Process as spatial filters applied to the error spectrum

a. Increased surface energy at damage sites
b. Contrast in etch rates at grain boundaries

As such, application of the RAP step typically involves an integrated manufacturing process (IMP) as illustrated in Figure 3. The RAP step is used to converge on the desired figure in a damage-free manner and acts like a high pass spatial filter on the error spectrum. The resulting increase in roughness is compensated for by using a conformal buffing step to recover surface roughness. Flexible laps with pitch buttons are used primarily to knock off asperities resulting from the RAP figuring step. Given that there are no requirements for material removal from this process, low normal loads are used and result in negligible damage to the underlying substrate. The conformal buffing process acts like a low pass spatial filter on the error spectrum as illustrate in Figure 3. By suitable control of the corner frequencies of both spatial filters (lap stiffness and torch footprint), one can directly control the amount of mid-spatial power left in the error spectrum.

3. RESULTS

An on-axis parabola with the following specifications was fabricated using the integrated manufacturing process:

Clear aperture: 200mm
Conic Constant: -1 (parabola)
f/#: 2.25
Figure error < 0.050 λ RMS
Roughness < 1nm RMS

Such an optic was figured and finished achieving a roughness of about 0.33nm RMS in less than 3 weeks. Results from the processing are illustrated in Figure 4. Further improvements in processing will allow the extension of the process to figure errors as low as 0.010 λ RMS.

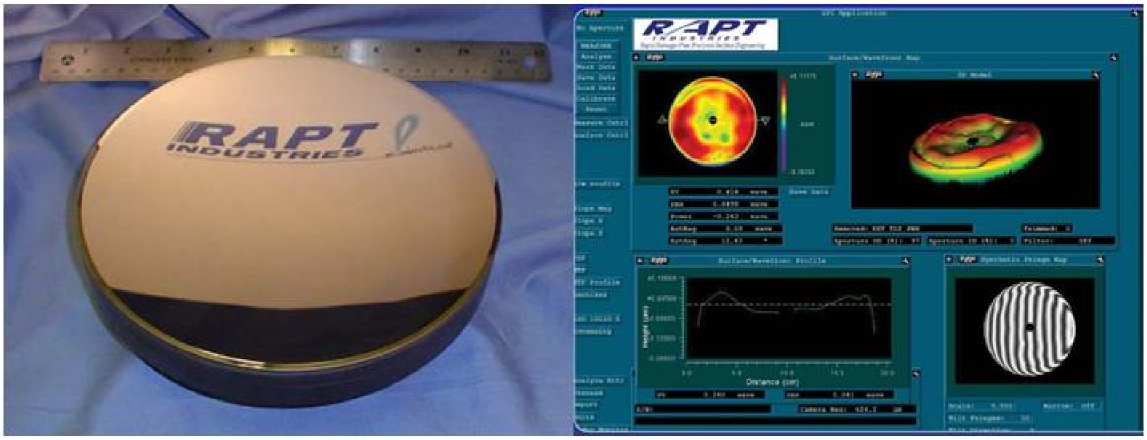


Fig. 4. On-axis parabola and figure error data

4. CONCLUSIONS

Lightweight mirrors pose special fabrication issues due to the amplified effects of SSD on the figure error. The problem gets even more compounded with ceramic substrates such as SiC. We have demonstrated a novel approach to the fabrication of such mirrors leading to significant gains in lead time, cost, precision and reliability of the finished mirrors.

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REFERENCES

1. Preston, F. W., 1921, The structure of abraded glass surfaces, *Trans. Opt. Soc. v. 23*, 141-164.
2. Verma, Y., Fiske, P.S., Chang, A. K., Barrett, J. W., Futtere, K., Gardopee, G. J., Kelly, J., Kyler, T., Lee, J., Lyford, N., Proscia, D., Sommer, P. S., and Subrahmanyan, P. K., 2006, *Proceedings of SPIE, Astronomical Telescopes and Instrumentation, 2006.*
3. Johnson, J. S., Grobsky, K., and Bray, D. J., 2002, Rapid fabrication of lightweight silicon carbide mirrors, *in Optomechanical Design and Engineering 2002 (A. E. Hathaway, ed.), Proceedings of SPIE v. 4771*, p. 243-253.