



Advanced Manufacturing Technologies for Light-Weight, Post Polished, Snap-together Reflective Optical System Designs

Michael N. Sweeney

CMM Optic
2909 Waterview Drive
Rochester Hills, MI 48309-4600

ABSTRACT:

Fast, light weight, off-axis, aspheric, reflective optical designs are increasingly being designed and built for space-based remote sensing, fire control systems, aerial reconnaissance, cryovac instrumentation and laser scanning. Diamond point turning (DPT) is the technology of first resort for many of these applications. In many cases the best diamond machining technologies available cannot meet the desired requirements for system wavefront error and scatter. Aluminum, beryllium, AlBeMet and silicon carbide mirrors, layered with thin films of electroless nickel, silicon, or CVD SiC can be first diamond machined or precision ground and then post polished to achieve greatly enhanced performance levels for surface scatter, wavefront error (WFE), and alignment registration. By application of manual or computer controlled post polishing, and by using precise null testing techniques, the objectives of snap-together, or limited compensation alignment of aggressive reflective optical systems can be achieved that are well beyond the performance envelope achievable by diamond machining alone. This paper discusses the tradeoffs among materials and processes selection for post polished reflective systems and illustrates actual applications including telescopes for earth and Mars orbit, and a commercial, high speed, flat field scan engine.

Keywords: diamond point turning (DPT), null test, snap-together optics, f-theta, optical bench, interferometer, wavefront error (WFE), spectrometer, beryllium, ALBeMet, Silicon Carbide, chemical vapor deposition (CVD).

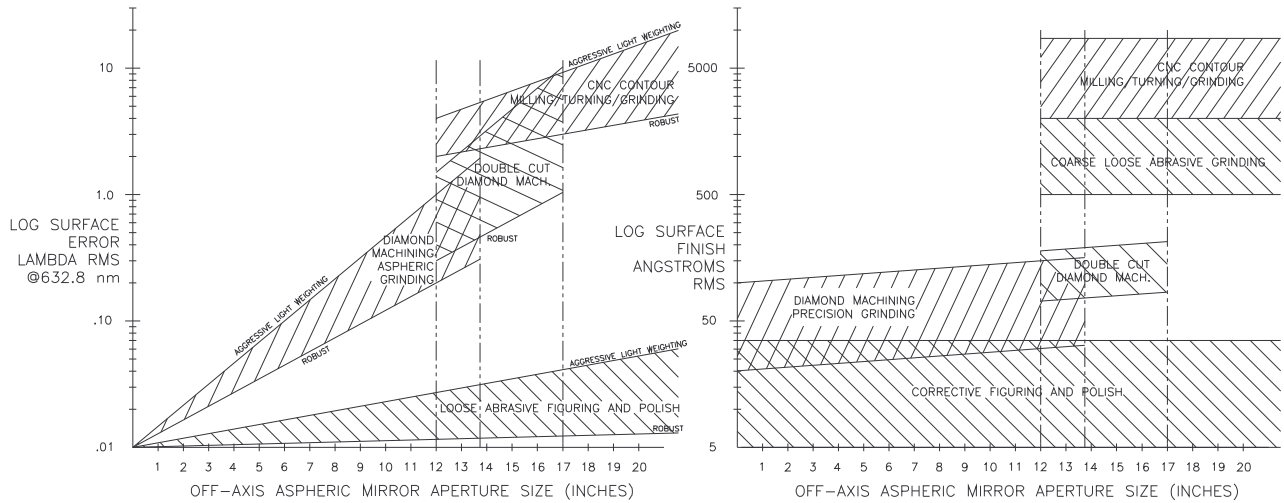
INTRODUCTION:

Diamond point turning (DPT) has emerged as the technology of choice to produce optical surfaces for a wide variety of reflective optical systems. Recent advances in ultra-precision hard wheel grinding also produces form and finish accuracy approaching that of DPT on hard surfaces such as glass or SiC. It is a commonly held belief within industry that post polishing of such surfaces will degrade the base radius, aspheric coefficients, and registration to the mounting surfaces. In reality, centrifugal forces from diamond machining often cause a variety of mounting registration and surface figure errors, particularly for large, off-axis, or light-weighted mirrors. It can be shown that these errors are readily corrected in the post polishing process by application of interferometric null tests precisely calibrated under static conditions to mounting datums generated during the diamond machining process. In effect, a metrology template for a near-perfect aspheric surface, near-perfectly aligned to target mechanical datums is established. The mirror surface and mounting datums are then corrected to conform to the established template. In addition, mirrors that are outside the capabilities of diamond machining can be generated by high precision CNC contour milling and grinding and likewise tested and slaved to a null test fixture to achieve the similar results.

DISCUSSION:

Every optical element or system should be carefully evaluated for application of the most practical manufacturing technologies prior to finalizing the design. The focus of this discussion is concentrated on light-weight, metal and ceramic substrate materials that are generally diamond point machined or otherwise "rough" generated and then post polished to achieve demanding optical surface and alignment requirements in the context of high performance military, space, astronomical and photographic imaging applications. The graphs shown below outline a general performance envelope for a number of manufacturing processes available for the creation of aspheric mirrors excluding molding and

replication. Aluminum may be directly diamond machined into an effective mirror while an expanded repertoire of mirror substrate materials including aluminum, beryllium, and silicon carbide may be clad with a diamond machineable layer of copper, pure aluminum, electroless nickel plating, or silicon. Application of electroless nickel or silicon results in a surface that is both readily diamond machined and greatly improvable in terms of figure and finish by post polishing while preserving the respective properties of the selected substrate material. Also diamond machined aluminum can be post polished to enhance both figure and finish.



Figures 1: The above graphs show the general performance envelopes among fabrication technologies, achievable surface figure and surface finish and the effects of light weighting as applicable to off-axis aspheric mirrors ranging to about 0.50+ meter in aperture. A significantly light-weighted beryllium or silicon carbide mirror may be considered robust due to exceptional properties of specific stiffness. Surfaces clad with silicon, CVD SiC and electroless nickel may be improved to within the indicated regimes for polishing regardless whether initially diamond machined or otherwise rough generated. Also diamond machined aluminum surfaces can be enhanced for both figure and finish by post polishing. The resulting optical figure is highly dependent on how robust the substrate is while the surface finish is nearly independent except for moderate effects on the diamond turning process.



Figures 2: Left photo shows a state-of-the-art diamond turning and grinding machine. The right photo shows a 290 mm light weight CVD SiC clad SiC mirror undergoing hard wheel aspheric grinding prior to computer polishing. The optical figure from grinding was about 2.0 waves P-V @632.8nm and less than 50 Angstroms RMS surface finish; ideal initial conditions from which to commence computer polishing. “Slow tool servo” capability and on-machine profilometric measurement technologies also provide the means to fabricate and measure complex aspheric surfaces including those not having rotational symmetry with the machine axis.

Diamond machining advantages and limitations: As discussed and illustrated in the figures above, diamond machining has limitations that are greatly influenced by the size, design, and material selected. Small on-axis or nearly on-axis surfaces can be generated to impressive accuracies and finishes. Larger surfaces that are cut further off-axis introduce tool wear, aerodynamic buffeting, large centrifugal forces, and much longer cutting times more prone to drift. Many of these problems can be reduced by optimizing the mirror design for the diamond machining process and by applying on-machine profilometry to define compensation parameters for re-cutting the part. Optimizing the mirror structure for diamond machining forces can be done but may run counter to the structural goals for an instrument that is unlikely to experience a similar load case. There is a point of diminishing returns when pushing the diamond turning process too hard. This decision point is reached very quickly on a limited quantity specialty applications that often require component level interferometric testing anyway. The decision point is less well defined for production programs which are pushed very hard to eliminate the need for post polishing. In this event, significant engineering, process tuning, incremental design improvements and the development of correction algorithms for radial and circumferential errors can be justified. The following table compares many of the associated tradeoffs.

Manufacturing Tradeoff	Net diamond point turned (DPT)	DPT/post polished
Aggressive light weighting	May result in significant fling distortions, that will require reiterative measurement and re-cutting	Errors readily corrected with null test
Thermal cycling after final finishing	May result in figure change that cannot be corrected without re-cutting	Errors readily corrected with null test
Mount print-through on diamond machining fixture	May result in figure change that cannot be corrected without re-cutting	Errors readily corrected with null test
Mounting registration to optical Surface	Can be excellent for axis symmetric Parts or small off-axis surfaces close to spin axis. Errors can be corrected with null test with attendant risk of distorting the optical figure.	Errors readily corrected with null test
Interferometric null testing	Often bypassed in favor of on-machine profilometry and assembly level test	Mandatory to exploit full range of post polishing potential
Bare aluminum and copper finishes	Excellent results obtainable	Can't be polished readily
Electroless nickel plating	Good to excellent results	Readily polished for finish and figure
Silicon and CVD SiC cladding	Good to excellent results depending on material quality	Can be polished well depending on material quality
Optical tolerancing	RSS budget may be unreliable. Figure errors can add or subtract directly from mirror to mirror	RSS budget reliable due to random nature of surface errors resulting from post polishing.
Prototype cost	Less costly without null testing. Extensive optimization of process combined with use of null testing expensive with diminishing returns	Reasonable compared to net DPT if null tests are used in both cases. Much lower risk to meet performance objectives
Production cost	Extensive optimization of design and process to suit DPT technology is justifiable. Aggressive goals for finish and figure may result in low yield	Relegating DPT process to roughing operation and use of on-process metrology will result in high yield. Aggressive to impossible goals for net DPT easily achieved by polish.
Risk factors	Aggressive goals for surface finish or surface figure may not be attained no matter what.	Reasonable figure and finish goals will be attained. Differential CTE risk must be managed particularly over large temperature swings

Table 1: Net diamond machining verses post polishing

Post polishing Null Test Technologies: Null tests typically consist of interferometric templates of the ideal aspheric optical surface that is desired. Diamond machining is highly complimentary to null testing of aspheric optics. Diamond machined reference surfaces for tilt, decenter and airspace can be readily diamond machined into a master plate or into auxiliary test optics to aid in the set-up and calibration of the null test. The photos below illustrate a variety of vertical axis null test set-ups that are calibrated to high precision to reference datums and provide the optician with a real time, computer aided surface figure measurement template. In this manner, vast improvements to optical figure and finish can often be accomplished in a matter of hours and days depending on the size and nature of the surface. In many cases, post polishing represents less than a 10% cost premium in the context of the whole product cost. This is particularly true if the part is to be null tested anyway, if the null test cost is amortized over many pieces or if the manufacturing cost of material and machining is comparatively high such as for a large aperture light weight beryllium telescope.

Conic sections, consisting of parabolas, ellipses and hyperbolas, are very common to diamond machined optical assemblies. Each of these surfaces can be tested to calculated conjugate focal points. The conjugate points can be registered for alignment to the mirror under test by association to diamond machined reference datums designed into a master tooling plate. Generally conic sections are easier and less costly to null test than higher order aspheric surfaces. Fast, convex hyperbolic mirrors are generally the most difficult and expensive conic surfaces to null test and post polish and are also typically the most alignment sensitive elements to consider for snap-together design philosophy.

General case aspheric mirrors may be tested by use of computer generated holograms (CGH) or null lenses to construct the desired interferometric reference template. CGH's are particularly complimentary to diamond machining since fiduciary reference surfaces can be established within the design of the CGH that can be registered to the diamond turning reference datums with appropriate advanced planning. As discussed for the conic surfaces, fast, convex, high order aspheric surfaces pose the greatest cost and manufacturing challenges to the optical fabricator.



Figures 3: The photo at left depicts a large, off-axis, general aspheric, nickel plated and post polished aluminum mirror tested in the presence of a computer generated hologram (CGH) and phase measuring interferometer. The optical axis of the null test is precisely registered to diamond machined reference surfaces cut into the master plate on which the mirror is registered. The photo at right illustrates hand polish corrections being made to a nickel plated beryllium hyperbolic secondary mirror that will be used in an aerial reconnaissance telescope. Alignment techniques are developed to ensure that the center of curvature of the Hindle sphere and the focus of the interferometer are registered to create an optimal test template in terms of mounting registration and conjugate placement during polishing.



Figure 4: This photo shows a 15" aperture, light-weighted, nickel plated aluminum mirror that is an off-axis segment of a 38" diameter general case aspheric surface of revolution. This mirror is the tertiary mirror for a four-mirror, off-axis variable zoom system. The iso-grid light-weighting structure typical of all of the mirrors can be seen in the primary mirror in the background. The tertiary mirror is null tested for optical polishing utilizing a CGH and on-process, vertical axis, phase measuring interferometry. Since the mirror exceeded the 12" radial tool travel of the diamond turning machine, it's surface was blended with two cuts both before and after nickel plating to produce a near-net optical figure of about 2.0 waves RMS @632.8 nm and 150 Angstroms RMS surface finish. Electroless nickel plating was also held to less than 0.0015" to minimize the potential for bi-metallic distortion over the operational temperature range. The mounting geometry was thrown off in tilt by centrifugal turning forces and unsymmetrical mounting by 0.001" in the circumferential direction and 0.0025" in the radial direction. Mounting geometry is then corrected to within 0.0002" tilt over the mirror overall dimensions, figure is corrected to less than 0.10 wave RMS @632.8 nm, and surface roughness is improved to less than 30 Angstroms RMS with all artifacts of diamond machining periodic structure erased.

Mirror Design issues: The design of the mirror substrate is critical to achieving the goal of a snap-together optical system. Generally, outboard mounting tangs or flanges with three raised pads on both sides can be used successfully to transition from diamond machining into post polishing and then seamlessly into a precision optical bench. This approach is used on the two space telescopes discussed below. Auxiliary mounting features at the back of the mirror can also be established to reduce surface figure and mounting geometry errors induced by centrifugal forces. As mirrors become increasingly larger in aperture, starting at about 150-250 mm, outboard mounting flanges become less practical and back mounted approaches are more commonly used. It is prudent to exploit axial symmetry for diamond turning and polishing whenever possible. Axis symmetric mirrors should have an accessible precision rotational reference datum that is diamond machined or precision ground. Off axis surfaces often can accommodate one locating hole along the optical axis. Far off axis mirrors generally rely upon two widely spaced dowel pins to control off axis distance and clocking registration. A precision ground hole and slot with minimized engagement length is highly effective at

minimizing the clearance tolerance and also to prevent “hang up” on the pins and damage to the locating features upon repeated assembly/disassembly.

Localized strain isolation at each three point mount is critical and can be accomplished by keeping mounting pad area down to 5-8 times the area of the fastener attachment hole and using deep oversized counterbores to reduce elastic deformation under the fastener head. Radial differential expansion between the mirror and the structure can be compensated by integrally machined or detachable radial compliant blade flexures.

Mirror Structure Design issues: The design and manufacturing of the optical bench to house a snap-together mirror assembly is also very critical. Ideally the mirrors and the structure are fabricated from the same material. By the use of aluminum, beryllium, or AlBeMet (aluminum beryllium alloy) this goal is readily achieved. Silicon carbide and glass mirrors are typically integrated to metal or composite structures so appropriate measures to compensate for differential expansion, such as the use of flexures, must be incorporated. Mirror designs with outboard mounting tangs or flanges in combination with one piece machined optical benches with exterior mounting features for the mirrors to plug into, results in a compact, accurate and structurally efficient design. Since the surfaces of the optical bench are accessible, raised pads can be created to locate the mirrors and excellent geometry for coplanarity and parallelism from one side of the structure to the other is readily established. Dowel pins are typically imbedded 2-3 pin diameters in length into the optical bench with minimized engagement length into the mirrors.

Lapping verses diamond machining of mounting surfaces: Sometimes specifications require that interface mounting surfaces on mirrors and structures be diamond machined rather than ground or lapped. The diamond turning or flycut process is very effective at conditioning interface mounting surfaces on mirrors and housings to achieve excellent geometry. A limitation of this process is that the finish can be too good and can gall very easily. Diamond machining of pads also requires that the part be fastened to a fixture to hold it in place thus causing spring-back errors. It is often the case that repeated conditioning of mounting pads is required as parts change upon iterations of material removal and thermal cycling. It is impractical to schedule repeated diamond machining operations to fine tune mounting surfaces. Hand lapping results in mounting surfaces that are rough enough not to stick and gall while sustaining sub-micron precision. Mounting features may also be re-conditioned by lapping on a continuous basis throughout the manufacturing process in a virtually free state without clamping fixture stresses. It is best to allow the optical fabricator to select the appropriate process to meet interface accuracy requirements.

Snap Together Example #1: Telescope for Earth Orbiting Spectrometer

The MAESTRO instrument, developed by EMS Technologies for the Canadian Space Agency, required a set of two identical telescopes to service two spectrometers in the visible and near infrared spectrums, respectively. These three mirror off-axis telescopes required small aspheric surfaces that were not far off axis. Net diamond machining of aluminum surfaces could have possibly achieved the requirement for 0.12 wave RMS wavefront error @632.8 nm, however the requirements for low scatter in the visible and near infrared spectrums necessitated post polishing. Post polishing also removed all doubts about meeting the WFE requirement.

The mechanical design undertaken at CMM Optic was focused on optimizing the design of the mirrors to achieve a compact light weight package while at the same time optimizing the aspheric surfaces for generation by diamond machining. The mass budget was generous so the mirrors and structure could be made robust and all aluminum. By making the outline and mounting surfaces of the primary, secondary, and tertiary mirrors, along with the housing and air space compensator spacer, the same dimensions with three raised pads on the front and back of each, the parts could be diamond machined to great accuracy and assembled together like a stack of pancakes. A single pair of dowel pins extending through both sides of the mirror housing located all of the mirrors, thus mechanical stack-up errors were minimized. The required flat fold mirror was integrated to the primary mirror substrate as a further refinement to the efficiency of the design. An air space compensator spacer was necessary to achieve an afocal condition with 7X magnification.

Each of the three conic aspheric surfaces were tested and polished via on-process interferometric null tests controlling separation and concentricity of conjugate points to the master tooling used to diamond machine the mirrors. Minor

corrections in mounting geometry were initiated as required prior to refining the surface figure and finish. At assembly, fine tuning of the decenter and despace of the primary and secondary mirrors relative to each other on the order of ± 2.0 microns ± 0.50 micron was required to achieve the required wavefront performance for irregularity and residual power. All other mirrors and degrees of freedom relied on snap together precision. The final wavefront error for both telescopes was 0.08-0.09 wave RMS @632.8 nm over the required field of view resulting in a significant performance margin under the basic requirement.

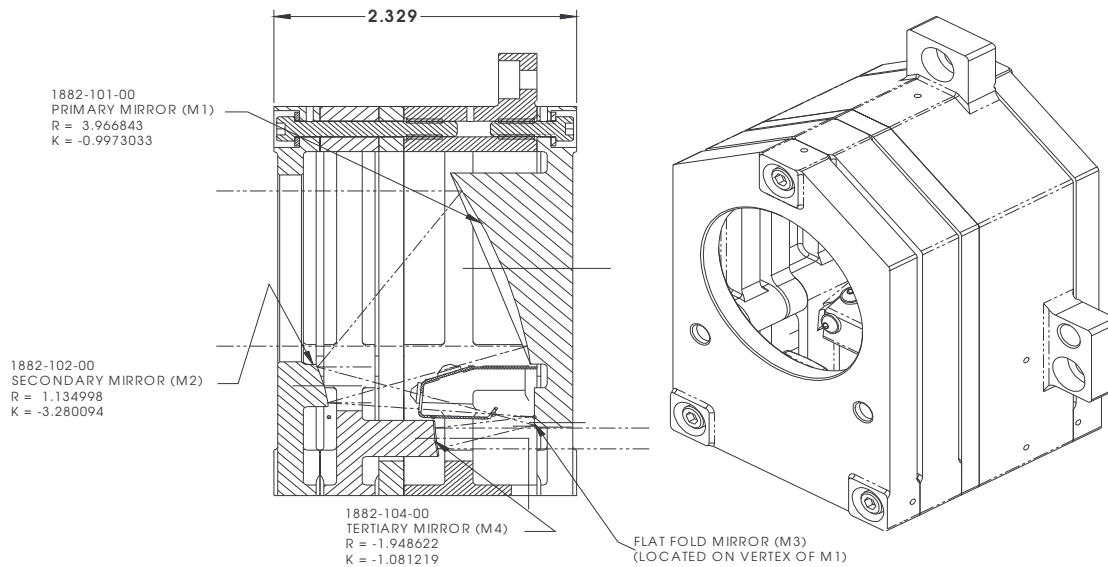


Figure 5: The cross sectional view at left and isometric drawing at right illustrate a compact snap-together, diamond machined and post polished telescope designed and manufactured for the MAESTRO spectrometer now being built by EMS Technologies for the Canadian Space Agency. The best possible features for diamond machining were incorporated into the design. Post polishing in the presence of interferometric null tests for each aspheric surface resulted in surface finishes less than 25 Angstroms RMS and surface figures of less than 0.020 RMS @632.8 nm while still maintaining accurate mounting registration.

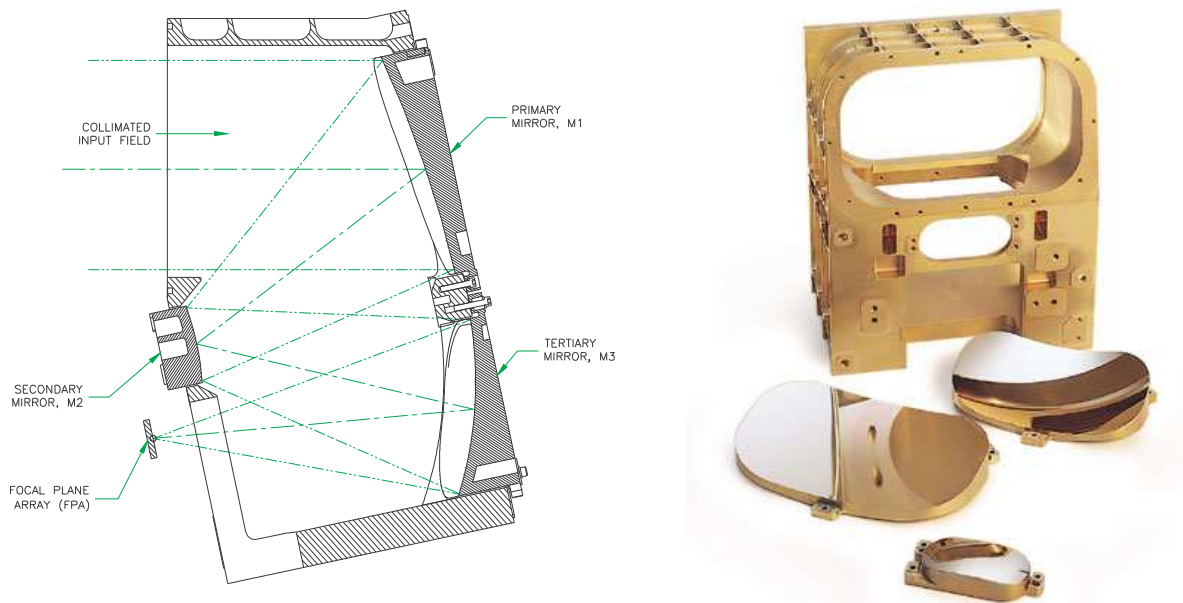
Snap Together Example #2: Mars Odyssey 2001 Orbiting Camera Telescope

The telescope that was designed by Raytheon SBRS and built by CMM Optic for the THEMIS instrument on the Mars Odyssey 2001 spacecraft involved a carefully considered and executed tradeoff between net diamond machining and post polishing manufacturing technologies. The telescope design was exceptionally fast (F/1.5), consisted of off-axis, high order, aspheric surfaces, was of moderate aperture size (175 mm), with a stingy mass allocation for inter-planetary space flight. On-orbit operational temperatures were predicted to be significantly lower than room temperature (-10 to 0°C) so uniform contraction of the mirrors and structure was imperative. Although the primary mission of the THEMIS instrument was imaging in the infrared spectrum, visible wavelength performance for scatter and wavefront error was highly desirable by NASA to resolve finer surface details on Mars and to generate broader participation by scientists and students via regular posting of images on NASA websites.

Initially, the manufacturing goal was a snap together aligned telescope with net diamond machined aluminum surfaces. Since it was considered doubtful that surface figure and surface finish goals could be met with the large, off-axis and light-weighted primary and tertiary mirrors, Raytheon and CMM agreed that two telescopes would be built: one with net diamond machined aluminum optics and one with nickel plated and post polished optics. Null tests were required so the added cost to post polish one set of optics was not large in the context of the total project cost. Every reasonable effort would be made to ensure that both telescopes were fabricated to the limits of the respective manufacturing performance envelopes. Each mirror for both telescopes would be tested via CGH's to assess mounting and figure

errors, and, in the case of the post polished telescope, provide the means to improve the figure, finish, and alignment registration..

Initially a best-fit sphere was diamond machined into each of the three aspheric mirror substrates with stock allowance for finish processing. The best-fit sphere could be easily tested interferometrically and provided an excellent indication of the figure distortion and finish degradation that would occur when the actual aspheric contours were cut. Not surprisingly the figure changes were large and were mostly non-axis symmetric, so could not be corrected without the use of a fast tool servo technology. Reduction of the spindle rotation rate resulted in a marked improvement in surface figure at the expense of an increase in surface roughness. It was also discovered at the same time that a specially forged block of Aluminum 6061-T651 procured by Raytheon for the project had traces of uniformly distributed impurities which further limited the achievable surface finish result on bare aluminum.



Figures 6: The figure at left shows a cross section view of the three mirror off-axis $f/1.5$ telescope designed by Raytheon Corporation and manufactured by Axsys Technologies for the THEMIS instrument on the Mars Odyssey 2001 spacecraft. A one piece optical bench finished to sub-micron geometry for local surface coplanarity and surface to surface parallelism was critical to the success of the snap-together alignment philosophy incorporated for the THEMIS project. The photo at left illustrates the actual THEMIS optical bench and the three outboard tang mounted aspheric mirrors.

The results on the best fit spheres strongly favored the scenario for nickel plated and post polished mirrors. Since the parts would be post polished, spindle turning rates could be significantly reduced to favor surface figure over surface finish. Each mirror was then set up within its respective null test using CGH's and evaluated for surface figure and mounting geometry errors to the established master template. Each mirror was diamond machined both before and after electroless nickel plating in order to achieve a finished nickel plating thickness of 0.0004-0.0006" with a uniformity of 0.0002". Thin and uniform nickel plating thickness was paramount to minimizing the risk of bi-metallic stresses in the thin light weighted mirrors as the telescope was cooled to the required operational temperature.

Finishing of the optical bench was also essential to the success of the THEMIS telescope. The telescope housing was precision ground and lapped for sub-micron coplanarity of mirror mounting pads and end to end parallelism with accurately located and sized jig ground dowel holes for locating the three mirrors and IR/VIS focal plane sub-assembly. Dowel holes were jig ground after the structure was thermal stabilized and lapped. Dowel pins were standardized in size to much tighter tolerances than the typical off-shelf 0.0002" range to further reduce stack-up errors.

In the end result, the nickel plated and post polished mirrors tested about 5X better in terms of both surface figure and finish compared to the net diamond machined optics set. The post polished mirrors were successfully integrated into the optical bench using strictly snap-together precision. The telescope was shown to be stable after being subjected to the rigors of vibration and thermal challenges. The design residual error for the telescope over the field of view was 0.31 wave RMS WFE and was well balanced over the field of view. The as-built performance was less than 0.40 wave RMS over the field of view. The telescope exhibited a slight amount of defocus when cooled from room temperature. The focal plane array was set for best focus at the average expected equilibrium temperature on-orbit around Mars and this telescope is currently conducting an unprecedented mineralogical and topographical survey of the planet Mars.

Surprisingly, the back up net diamond machined THEMIS telescope tested much better at assembly than was predicted by test of the individual mirrors. Statistical methods for assigning error budgets for optical systems such as square root sum of the square (RSS) of RMS figure errors apply very well for post polished optics but can be erroneous for structured and potentially directly additive or subtractive errors such as those exhibited by the net diamond machined THEMIS telescope mirrors. The pronounced astigmatic surface errors in the primary and tertiary mirrors were very similar in shape and largely cancelled each other out at assembly. As a result, the net diamond machined THEMIS telescope was within a factor of 2.0 in terms of RMS WFE (0.80 versus 0.40) while an RSS calculation would have predicted a factor of 5.0 compared to the telescope with polished mirrors.



Figures 7: Other examples of beryllium and aluminum telescopes manufactured by Axsys for space-borne remote sensing applications and which employed post polished nickel plated optical surfaces and “snap-together” design and fabrication practices.

Snap Together #3: Flat Field Scanning System

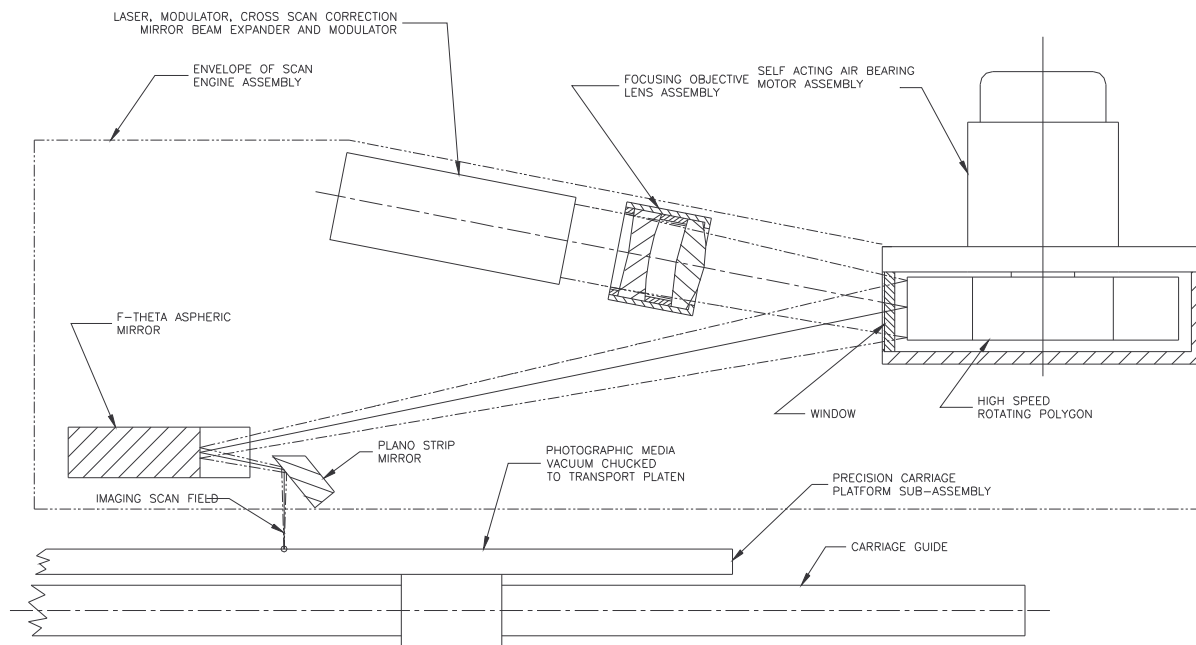
CMM Optic has applied a snap together post polished design approach to the use of aspheric mirrors for a family of flat field scanning systems. Such devices are used to expose photographic media for the graphic arts and publishing industries and also for surface defect inspection. Such systems can generate scan rates of 2000+ Hz, modulate at 100+ MHz, expose less than 10 microns diameter pixels, and have scan widths in excess of 26”.

The most common approach to designing flat field systems of this nature is to use an F-theta lens assembly to flatten the curved field inherently produced by the rotating scanner into a flat field. Alternatively, a diamond machined and post polished aspheric f-theta mirror having nearly the same width as the scan field can be used. The optical engineer is then able to optimize a large solution space consisting of base radius, aspheric coefficients, and off-axis distance to the mirror prescription to simultaneously achieve near-telecentricity of the scanned beams, minimized scan line bow, maximized depth of focus, and controlled spot quality, spot size, scan linearity.

The f-theta mirror is typically placed fairly close to the scan line image so is highly scatter sensitive. This requirement necessitated the application of electroless nickel to the aluminum mirror substrate and post polishing after diamond

point machining. Since the instantaneous clear aperture on the f-theta mirror surface was very small in comparison to the overall aperture of the mirror, global figure requirements are quite loose. It is extremely important, however, that the incremental surface slope error along the scan track aperture is closely controlled to prevent the introduction of streak artifacts on the photographic media caused by subtle pixel spacing errors in the fast scan direction.

It was the objective of the design team to develop an f-theta mirror design that optimized the diamond machining process while at the same time accommodating post polishing to improve optical finish. It was unnecessary to improve the optical figure from that generated on the diamond machining operation. The resulting mechanical design included three widely spaced raised pads, integrally machined strain isolation features, and two dowel holes for accurate registration of the mirror during diamond machining and to allow an accurate transfer to a large aluminum casting that formed the chassis for the scan engine assembly. The mechanical design also accommodated a tapered profile in two dimensions to maximize the natural frequency of the mirror during the diamond turning process. The resulting mirror design and a schematic of a production flat field scanning system using the f-theta mirror design approach can be seen in the figures below:



FLAT FIELD COMPUTER TO PLATE (CTP) PHOTOGRAPHIC SCANNING SYSTEM

Figures 8: The photo at the top illustrates the nickel plated, diamond machined and post polished aspheric aluminum f-theta mirror used in a computer to plate (CTP) photographic scan engine. The lower figure illustrates the f-theta mirror used in the context of a complete flat field scanning system.

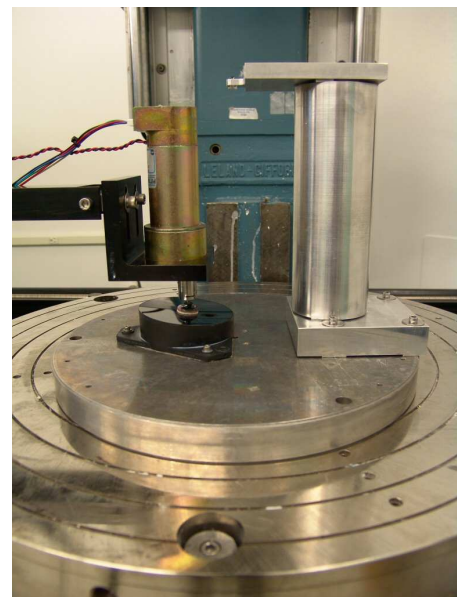
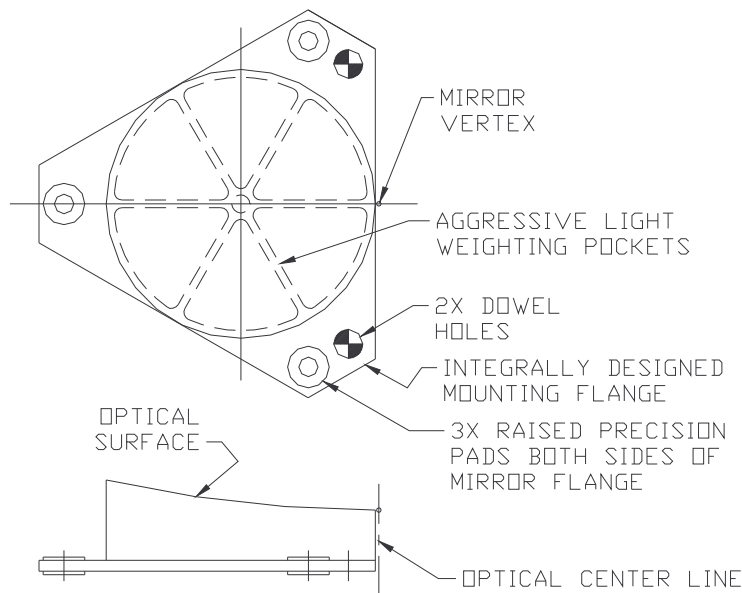
Snap Together #4: Off-axis Aspheric Silicon Carbide Mirror

Silicon Carbide continues to advance as a viable alternative to beryllium for light-weight, high performance mirrors. Silicon carbide is similar in density to aluminum with a modulus of elasticity greater than beryllium. The table below illustrates the relative properties of various common mirror substrate materials to silicon carbide produced by Poco Graphite. Many formulations and methods of manufacture exist within industry for silicon carbide mirror substrates. The Poco Graphite process entails machining of intricate mirror substrates with integral mounting features into a near net form from soft and inexpensive graphite material. The graphite is then converted into Silicon Carbide upon infusion of Silicon gas. The initial converted material, SiC-1, is highly porous but is satisfactory as a mirror substrate. Additional conversion processes can be used to fully densify the material to SiC-5, SiC-7 as well as refine many of the material properties.

Material	Density g/cm ³ (lb/in ³)	Elastic Modulus GPa(Msi)	Thermal Expansion ppm/K(ppm/F)	Thermal Conductivity (W/m·K)	Tensile Strength (MPa/ksi)	Specific Stiffness (Modulus/density)
Beryllium I70H	1.9 (0.067)	287 (43)	11.4 (6.3)	190	310 (45)	6.0
Al 6061-T6	2.7 (0.098)	68 (10)	23.6 (13.0)	170	380 (55)	1.0
Zerodur	2.5 (0.090)	92 (13.8)	0.0 (0.0)	1.6	N/A low	1.46
Fused Silica	2.1 (0.075)	72 (10.8)	0.5 (0.28)	1.5	N/A low	1.36
Silicon	2.3 (0.083)	110 (16.5)	3.8 (2.1)	125	N/A low	1.90
Poco SiC-1	2.55 (0.092)	218 (32.7)	4.6 (2.5)	170	129 (18.7)	3.4
Poco SiC-5	2.93 (0.106)	354 (53)	4.6 (2.5)	170	116 (16.8)	4.8
Poco SiC-7	3.05 (0.110)	340 (51)	4.6 (2.5)	170	137 (19.8)	4.4

Table 2: Relative properties of common mirror materials

The intended optical surface of Silicon Carbide mirror substrates must be cladded with a dense, uniform layer for final processing. Chemical vapor deposited (CVD) Silicon Carbide and Silicon are most commonly applied. These materials can be polished to outstanding finishes and range from near-perfect to good match in thermal expansion, respectively, to the substrate material. CVD SiC cannot be diamond point machined but is highly conducive to hard wheel and loose abrasive material removal and optical finishing approaches. Silicon cladding can be diamond point machined as well as hard grinding and loose abrasive techniques.



Figures 9: The figure at left illustrates the design of an off-axis aspheric silicon carbide mirror utilizing a CVD SiC cladded Poco Graphite SiC-1 process. The SiC optical surface is first generated by hard wheel aspheric grinding and then finished with loose abrasive on a computer polishing machine in the presence of on process interferometric metrology as shown in the photo at right.

SiC mirror substrate designs that are essentially “drop-in” replacements for “snap-together” beryllium or aluminum designs are readily developed. As discussed above, an optimal mechanical design for an off-axis aspheric mirror consists of three outboard mounting pads and either two dowel holes, or if practical, one dowel hole on the optical axis. In this manner the mirror surface profile can be accurately located to its interface mounting datums during manufacture while simultaneously isolating the optical figure from fastening stresses. An example of a SiC off axis aspheric mirror recently manufactured at CMM can be seen in the figure above. This mirror substrate is aggressively light-weighted CVD SiC cladded Poco Graphite SiC-1. The mirror surface was first precision hard wheel ground to a figure accuracy of about 0.60 wave RMS @632.8nm and a surface roughness less than 30-40 Angstroms RMS. The hard wheel grinding process can be used to control interface mounting accuracy, vertex height, and tight tolerances on base radius and aspheric coefficients similar to diamond point machining. Free form, raster pattern, computer polishing was then applied in the context of on-process interferometric metrology, to smooth, figure, and finish the surface to less than 0.10 wave RMS @632.8nm and less than 15 Angstroms RMS. The null test was calibrated so that a template of the desired aspheric surface was available for final figuring and for correcting mounting pad registration as required.

SUMMARY:

Aluminum, beryllium, AlBeMet and silicon carbide mirrors that are coated with a surface that may be polished can often be improved for both surface figure and finish by a factor of 5X or more over that possible with the best possible net diamond machining and ultra-precision grinding processes. It is also possible to measure and correct for mounting surface registration errors resulting from diamond machining and hard wheel grinding “fling effects” at the post polishing stage. The key to success is the development of an interferometric null test that is calibrated to sub-micron precision as the master template for all figure, finish, and mounting geometry corrections. Snap-together alignment or near net alignment significantly reduces the risk in the procurement of fast, off-axis, three and four mirror aspheric reflective optical system designs.

The design of the mirrors and structure are also essential to snap together mirror systems. Three pad mounting, local strain isolation at fastening points, and locating features such as dowel holes are critical for seamless transfer of controlled surfaces from diamond machining, through post polishing, and into final assembly. Thermal stabilization techniques and the ability to test and correct the figure of the mirror until the optical figure does not exhibit change is also critical and a key advantage over net diamond machined optics.

Silicon carbide mirrors cladded with either CVD SiC or Silicon can be designed and fabricated similar to metal mirrors including aggressive light-weighting, integral mounting and locating holes, and outboard flanges to enable isolation of fastener strain from the optical surface. SiC has respectable tensile strength and integral mounting features are feasible so long as care is taken to avoid stress concentration and to spread out fastening forces. The capability to fabricate aggressively light weighted designs with integral mounting features into soft and relatively inexpensive graphite prior to investment in conversion to SiC is also very attractive. CVD SiC cladded SiC mirrors have also been shown to have exceptional isotropic contraction when cooled to cryogenic temperatures. SiC structures to house aspheric mirrors can also be designed and fabricated using similar technologies as those commonly applied for beryllium and aluminum.

Multiple cut diamond machining, slow tool servo turning and grinding, and conventional CNC contour machining may be used as a rough figuring operation for large or far off axis mirrors. In these instances interim measurement technologies such as coordinate measurement machines are often used to track figuring correction iterations until interferometric approaches can be applied. These optics also can be slaved to a master interferometric null test to achieve snap together alignment or at least to minimize the alignment solution space by use of compensators.

Several examples of demanding and highly successful optical assemblies with snap together, diamond machined and post polished surfaces are presented herein along with a discussion of design tradeoffs. In the first example, four small and closely packed nickel plated and post polished aluminum mirror surfaces are designed to stack together in “pancake” fashion by sharing common alignment dowel pins and fastening hole patterns for an earth orbiting spectrometer system. In the second example, a comparatively larger 175 mm f/1.5 off-axis telescope is manufactured in both nickel plated and post polished and net diamond point machined versions for a Mars orbiting camera system. The

post polished version resulted in significant performance advantages. In the third example, a large, narrow, diamond machined, and post polished mirror is used in the context of a high performance, large format flat field imaging system. In the fourth and final example, a light-weight, off-axis silicon carbide mirror, with “snap-together” mounting design is profiled.

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