Rapid fabrication of lightweight silicon carbide mirrors

John S. Johnson, Kevin Grobsky, Zygo Corporation
Donald J Bray, POCO Graphite, Inc.

Keywords: Silicon carbide, MRF, optical fabrication, polishing

ABSTRACT

Silicon carbide (SiC) has long been recognized as an attractive mirror material due to its superior mechanical and thermal properties when compared to conventional optical materials. However, the material properties of SiC which make the material attractive from a design standpoint have often precluded its use when low cost and rapid delivery of an optical mirror were required. This paper describes an approach that was developed by Zygo Corporation, working in conjunction with POCO Graphite Inc. for the rapid fabrication of lightweight silicon carbide optics. This approach utilizes a SiC substrate produced by POCO Graphite Inc. using a non-traditional process coupled with deterministic finishing techniques developed by Zygo. Using this approach, we are now capable of producing high quality prototype components ($\lambda/10$ PV figure, 10 Å rms. micro roughness) of SiC within a few weeks, rather than the traditional period of months. Applications include lightweight scan mirrors, stage mirrors for lithography positioning tools, as well as similar applications where high stiffness and low weight are significant performance parameters. MRF polishing results comparing SiC to conventional optical materials are also presented.

INTRODUCTION

Some of the preferred characteristics for an optical mirror material include low density, high elastic modulus, low coefficient of thermal expansion, and high thermal conductivity. Depending upon the specific use, the fracture toughness and stress corrosion constant, which control slow crack growth and long-term reliability under static or dynamic loads during manufacturing and use, may also be important.

Silicon carbide (SiC) has long been recognized as an excellent material for high performance optical applications because it offers many advantages over other commonly used glasses and metals. Some of the superior attributes of SiC include extremely high specific stiffness (E/ρ), high thermal conductivity and outstanding dimensional stability. A comparison between the properties of SiC (1), (2), (6) and other common optical materials is shown in Table 1.

Because silicon carbide is an extremely hard and strong material, the precision machining required for both shaping and lightweighting is typically performed with diamond tooling on very stiff high quality machine tools (e.g., precision CNC equipment) using slow (comparatively speaking) material removal profiles. Conventional finishing processes (lapping, polishing) of SiC substrates also proceed much more slowly when compared to conventional optical materials due to the hardness and fracture toughness of the material. Even with the necessary use of diamond abrasive, the material removal rate for SiC is approximately 1/35th that of fused silica and less than 1/50th that of Zerodur. Compounding these issues, any lightweighting of the substrate can induce additional difficulties for achieving high quality optical surface profiles ($< \lambda/10$). Achieving such a high level of surface profile accuracy is often problematic, as the skilled optician requires multiple iterations of the polishing process to overcome such difficulties as print-through, accommodate unusual component geometries, etc. As a result, it is normally expensive to produce a lightweighted, super-polished SiC substrate, and the lead-time for obtaining a finished substrate can be several months. Thus, although SiC appears to be an ideal optical material from a material properties standpoint, the cost and lead-time associated with the preliminary shaping, lightweighting, and optical finishing of the SiC substrate have heretofore been major impediments to the widespread use of the material in optical systems.

Conventional optical materials have substantial drawbacks as well. Glasses and glass-ceramics like ULE and Zerodur are supplied in rough form only. These materials are fragile when lightweighted. Intricate machining can take many days or even weeks to perform since low feedrates are required to prevent deep fracture formation. Residual stresses have to be considered and relief steps should be done to halt fracture propagation. Mistakes in processing are many times catastrophic, costing weeks of schedule time as well as the loss of material and labor.

Optomechanical Design and Engineering 2002, Alson E. Hatheway, Editor,
Proceedings of SPIE Vol. 4771 (2002) © 2002 SPIE · 0277-786X/02/$15.00

Zygo Corporation, working in conjunction with POCO Graphite Inc., has developed an approach for the rapid fabrication of lightweight silicon carbide optics. This approach utilizes a SiC substrate produced by POCO Graphite Inc. using a non-traditional process (6) coupled with deterministic finishing techniques resident at Zygo. Using this approach, we are now capable of producing high quality, lightweight prototype components (λ/10 PV figure, 10 Å rms. micro roughness) of SiC within a few weeks. This approach may have significant ramifications for applications such as the fabrication of lightweight scan mirrors and stage mirrors for lithography positioning tools where lead-time is essential.

MATERIAL BACKGROUND

The available methods of producing optical-grade silicon carbide substrates include green forming by slip-casting or dry pressing(3, 5), chemical vapor deposition (CVD), hot-pressed SiC (4) and chemical conversion of graphite (6). A summary is presented in Table 2 of some of the advantages and disadvantages of the various processing techniques for producing a SiC substrate. A quick synopsis of the various techniques is described below.

PM SiC processing utilizes SiC powder that has been sintered or reaction bonded. Although the volume-driven production costs of this method are lower than for some of the alternate techniques, the tooling requirements associated with producing a “one-off” substrate are extensive and time-consuming. Therefore, obtaining a prototype mirror in low quantities using the PM process can be a cost-prohibitive and lengthy process. Another issue arises because the PM technique uses a traditional powder consolidation process that produces two-phase material. The “impurity” material acts to compromise the performance of the silicon carbide and can lead to adverse effects during subsequent optical surface processing. For example, it is not uncommon for the surface roughness achieved during polishing to be detrimentally affected because the wear characteristics and chemical reactivity of the silicon phase are different than for the silicon carbide phase of the material.

Hot-pressed SiC is formed by the application of pressure and heat to powdered material. Only rough and simple shapes can be formed by this process. Machining for complex features or lightweighting are done at great expense after pressing when the material is at full hardness.

The CVD SiC process produces high purity and near-zero porosity material. CVD SiC is an excellent reflective optics material exhibiting superior polishability with low scatter, exceptional thermal and cryogenic stability and high resistance to atomic oxygen and electron beam degradation. Unfortunately, because the deposition process for monolithic substrates is lengthy, there are cost and lead-time issues. Although substrates with large surface area can be formed, thickness is limited to less than 2.5-cm. Furthermore, in order to achieve a lightweight structure using a monolithic substrate produced using the CVD process, diamond tool based machining must be used. As with hot-pressed SiC, this is a lengthy and costly process.

To address some of the issues associated with producing a lightweighted SiC substrate, POCO developed (6) a new process for rapidly producing SiC mirror substrates. The basis of this process relies upon the chemical conversion of graphite to SiC. POCO overcame process issues experienced by other manufacturers of distortion, cracking and incomplete conversion by developing a special grade of graphite with extraordinarily uniform microstructural properties as the basis material. The POCO-supplied SiC substrate is then overcoated with a thin layer of CVD SiC to improve the optical finishing properties of the surface.

Material	Density (ρ)	Elastic modulus (E)	Thermal expansion (α)	Thermal conductivity (κ)	Mechanical Figure of Merit (E/ρ)	Thermal Figure of Merit (κ/α)
Units	g/cm^3	GPa	$\times 10^{-6}$/K	W/m K	(LARGE)	(LARGE)
RBO SiC	2.89	391	2.4	155	135	65
CVD SiC	3.21	466	2.2	280	145	127
HP SiC	3.20	455	2.0	130	142	65
POCO SiC	2.93	232	2.0	170	91	85
Beryllium	1.85	287	11.3	190	155	17
Zerodur ® (7)	2.53	91	-0.09	1.64	36	18
BK7 (glass)	2.53	80.7	7.1	1.12	32	0.2
SXA	2.91	117	13.0	125	40	10
Aluminum	2.7	68	23.6	170	25	7

Table 1
A comparison of room temperature performance parameters of selected optical materials

Process	Description	Remarks
• Pressureless sintering - "green" parts are prepared using two methods.	• Chemically formulated slurry is slip cast into molds, dried, and fired; or • Dry SiC powder is mixed with sintering additives, cold pressed, machined and fired.	• High density & good mechanical properties • High pattern and tooling costs so low volume needs are costly to satisfy • Low purity due to chemical additives • Significant processing after firing (e.g., grinding) is required
• Hot pressing and hot isostatic pressing	• Dry SiC powder is mixed with sintering additives and pressed at high temperatures	• High density & good mechanical properties • Significant processing after firing (e.g., grinding) is required • Shape and size limits
• CVD process	• Organo-metallic vapor is decomposed at moderate temperatures and low pressure to deposit SiC on either graphite or SiC substrate • Machining required to achieve desired shape and light-weighting in base substrate	• Excellent mechanical and thermal properties • Size and shape limits • Expensive due to length of deposition process • Extremely costly machining processes
• POCO conversion process	• Net shape substrate machined from graphite, then chemically converted to SiC, followed by CVD deposition	• High purity and excellent properties • Cost effective in low volume • Suitable for production volumes • Part thickness limited by infiltration depth • Size and shape limits dictated by CVD process

Table 2 (6)
Brief Descriptions of Various SiC Component Manufacturing Techniques

SURFACING BACKGROUND

Of the optical finishing firms that process SiC, most utilize classical finishing techniques to achieve material removal and precise surface contour. Loose or fixed abrasive processes are used for initial surfacing. For finishing, precisely shaped, viscoelastic pitch or polyurethane foam-faced tools are employed to transfer pressure and velocity through an abrasive slurry to the workpiece surface. With traditional optical glasses, material is removed by both chemical and mechanical interactions between the abrasive (typically micron to sub-micron sized), the carrier fluid (water), and the workpiece. Such conventional optical finishing processing can take weeks of effort from highly skilled opticians to complete the polishing of a single, super-polished substrate even in traditional materials. The material hardness and the special lightweight geometries desired of SiC structures make processing using these traditional methods difficult and slow. A high level of effort is typically required due to several factors. These factors include:

- The polishing process is purely mechanical for CVD SiC, so diamond-based slurries must be employed in place of the usual ceria or zirconia based slurries used for conventional optical materials,
- The material removal rates for SiC are less than < 5% that of conventional optical materials (e.g., glasses, simple metals),
- Convergence to high figure accuracy (λ/10 or better) is an iterative, time-consuming process when using conventional polishing techniques and is dependent upon the skill level of the optician,
- Many SiC optics are extremely lightweighted (75-90% weight reduction) and subject to geometry-specific surface form errors (e.g. quilting),
- Mechanical loading and stress relaxation during the process can induce surface form errors that are not easily removed using conventional polishing techniques.

Zygo recognized that in order to overcome most of these polishing related issues, a solution would have to:

- Offer high material removal rates,
- Achieve rapid optical figure convergence ,
- Give computer-driven, deterministic results based on metrology data,
- Have the flexibility and resolution to address quilting and other localized figure errors,
- Be insensitive to substrate geometry and mechanical loading effects.

To address these issues in both traditional optical and high-performance ceramic materials, Zygo recently brought on-line a number of unique magneto-rheological (MR) (8) polishing machines. These CNC-based platforms are capable of polishing workpieces from as small as 10 mm square to a maximum of 500 mm x 1000 mm in a deterministic manner. Coupled with Zygo's extensive and world-renowned metrology capability, the use of data-driven, deterministic polishing means that Zygo can achieve rapid convergence to high precision surface requirements.

COMBINED APPROACH FOR SiC FABRICATION

POCO Graphite can produce a near-net or net shaped complex SiC structure without the need for mold-making or long machining cycles in hard ceramic material. To complement this, Zygo Corporation's unique resources are applied to achieve final optical performance. Thus, our solution for rapidly finishing complex and lightweighted SiC substrates is to:

- Utilize POCO's capability for rapid graphite machining and SiC conversion and plating,
- Employ conventional polishing techniques to obtain a specular, polished substrate with limited convergence to figure (i.e. within the magnetorhelogical finishing (MRF) process "target zone" figure) (Zygo),
- Finish the optical surfaces with MRF platforms to achieve the required high precision surfaces (Zygo)
- Coat, integrate remaining hardware (if required) and perform final metrology to assure conformance to specification (Zygo)

This approach makes it possible to deliver a finished SiC optical structure, ready for final integration within weeks of specification of the requirements. Details of the fabrication cycle are outlined below.

SUBSTRATE SPECIFICATION AND FORMING

A design for manufacture (DFM) effort begins with collection of the optical and mechanical performance requirements. Geometry considerations relative to the application need to be addressed early. For lithography stage mirrors there may be a desire to integrate the wafer chuck, incorporate threaded inserts within the structure and specify highly planar mounting locations. In the case of a scan mirror, issues like gimbal attachment and natural resonant frequencies may be considerations. Although usually in line with low weight requirements, the conversion of graphite to SiC is limited to approximately 3-mm depth (6-mm total thickness), so this is a key design constraint for facesheet and rib thickness. Traditional optical manufacturing concerns such as clear aperture and surface quality are addressed, as are material dimensional and finish requirements. Full specification including tolerancing of the optical structure follows the DFM effort and the material forming process can begin.

To apply the POCO process to the rapid deployment of a lightweighted SiC mirror substrate, the base substrate, a graphite block, possessing the appropriate starting material microstructural properties (e.g., porosity, particle size distribution) is rapidly machined using conventional multi-axis CNC machine tools to achieve the desired level of complexity and light-weighting required for the specific application. Because the machining rates for graphite are much faster than for SiC (comparable to Al), a lightweighted substrate can be fabricated in a much shorter period of time (typically a few days instead of several weeks). The structure can be machined to tolerances of 5-10μm, if required. Following this, the machined graphite component is converted to SiC via a proprietary process developed by POCO. Post conversion densification can be done using either SiC or silicon infiltration. After the substrate is fully formed, converted and densified, the optical surfaces are coated with very fine grain CVD silicon carbide, nominally 150-300 μm thick. Application of the CVD SiC layer allows the surface to be polished to low surface micro roughness.

OPTICAL SURFACING

In the fall of 2000, Zygo brought a large platform MRF machine online for the production of stage mirror type optics and for experimentation with large optics fabrication using MRF. Zygo is a world leader in the production of half-meter class plano optical components. We believed that the determinism of the MRF process would be effective in expanding our ability to produce large aperture surfaces to the precision required in high-end applications such as interferometry, microlithography, reconnaissance and high energy laser systems. MRF has been found to be highly complementary to the resident large plano polishing and large aperture metrology capability.

MR polishing utilizes a suspension consisting of magnetic particles (carbonyl iron), nonmagnetic abrasive particles, water, and stabilizing agents. Under the influence of a magnetic field, the fluid stiffens and becomes a Bingham medium. In this reversible state, the MR fluid passes between a rotating wheel and the substrate surface causing wear. Characterization of the wear profile and rate prior to workpiece processing are inputs (along with the surface error) to the software creating the CNC code governing the relative motion between part and “spot”.

Zygo’s platform has the largest MRF work envelope in existence. The machine has the capacity to polish optics with surface dimensions of up to approximately 500-mm x 1000-mm. The workpiece (i.e. optic) is held above the MRF wheel, which is QED Technologies’® (QED) standard 150-mm size. The machine operates only in raster mode. The workpiece is stationary during processing, so the wheel is translated in the plane of the workpiece surface to accomplish material removal. See photographs in Figure 1 and Figure 2. This machine has been employed in production for well over a year and routinely finishes optical reference surfaces to less than 25-nm flatness with peak gradient less than 4 μrad (at1-μm resolution).

In the summer of 2001, Zygo added a second large MRF platform. This platform has approximately the same work envelope as the former machine. It has a similar CNC base, but was configured to allow the workpiece to rest on the machine bed during polishing. The MR fluid is passed over a 500-mm polishing wheel rotating above the workpiece. The magnetic field is located at the bottom of the wheel where the magnetorheological fluid stiffens and forms the polishing zone or ‘ribbon’. In this configuration, the wheel is stationary in X and Y during polishing and the workpiece surface is translated. The wheel is translated in Z to maintain a constant insertion depth into the MR fluid (See Figures 3 and 4).

The motivation for specifying a 500-mm diameter wheel was to achieve an increase in MR fluid “ribbon” surface dimensions and thereby volumetric removal rate. A 1.75-liter capacity fluid delivery system is employed, with flow rates in the range of 2.5–3.5 liters/min. The desired increase in removal rate is indeed realized with the large wheel as shown in Table 3.

MR Platform Wheel Size	MR Fluid “Ribbon” Height	Insertion Depth	Removal Rate (Fused Silica)	Removal Rate (CVD SiC)
150 mm	1.90	1.00	0.145 mm^3 / min	0.006 mm^3 / min
500 mm	1.72	0.50	0.312 mm^3 / min	0.0149 mm^3 / min

Table 3. Removal rate for MRF wheels under typical run parameters

While the volumetric removal rate for SiC may at first glance appear too low to be effective, the use of a deterministic process makes the process efficient because wear is programmed only where necessary to correct figure (plus a small uniform removal component).

Prior to MR finishing the substrate must be polished conventionally to achieve low microroughness. Goals for figure are established by considering the volumetric departure from prescription and the comparative efficiencies of the MR and conventional processes to improve figure. On a PV basis, MRF has demonstrated a 70 – 90 % figure convergence rate (per iteration) over a variety of optical materials.

MR finishing is ideal for lightweight structures. Since polishing occurs over only over a subaperture of the surface and since removal changes only marginally with insertion depth of the part into the polishing “ribbon”, the effects of gravity and mounting are inconsequential to the polishing result.

RESULTS

Figures 5 and 6 show an example SiC mirror. This POCO-made scan mirror has a “racetrack” or oval shaped surface with dimensions of 300-mm by 205-mm. The facesheet is 3-mm thick and the overall height is 44.5-mm. The mirror weighs approximately 24% that of a SiC solid of the same overall dimensions. Figure 7 shows the surface figure attained using conventional (continuous planetary) polishing with no special provisions made for close figuring. During polishing lead weights were placed on the back to increase removal. After polish-out the PV departure was 87-nm over a 95% clear aperture with the errors having primarily low order form as well as some “print-through” due to loading through the ribs. The cycle time required to surface this mirror to this state (grind and polish) was about 3 weeks. Using a removal profile at the rate from Table 3 for the 500-mm wheel, the QED software created CNC polishing program had a process time of 7.5 hrs. Assuming a 70% convergence rate we can expect that the PV error of the part after one run will be approximately 25-nm PV. Since further employment of the conventional process would require special tooling and even then proceed at a low rate of convergence on figure, the comparative efficiency of using the MR process is obvious.

Estimation can be made for larger mirrors. Consider, for instance, a mirror that is twice as large as the one above. This would be a 600-mm x 410-mm oval surface. Assuming similar equipment is used to prepolish the mirror surface, we may estimate that the surface error resulting from the process would be of similar shape but at perhaps greater magnitude. Figure 8 is a synthetic representation of such a mirror having the same surface form at 3X magnitude (261-nm PV). The QED software, given the same wear profile as input, calculates a process time for working this imagined mirror of 82 hours. Using the convergence rate previously mentioned, we may estimate that a total of two runs taking 82 hours and 25 hours respectively would yield a PV result at the 30-nm level.

CONCLUSIONS

POCO Graphite has developed a process to fabricate complex and lightweight SiC substrates with short lead time when compared to other SiC material processes. The primary advantage is that there is no need for tooling and that machining to lightweight or complex form is done on pre-conversion graphite. The converted SiC material is clad with CVD SiC to yield low surface roughness values after final polishing. Zygo Corporation has two unique computer controlled, large work envelope, MR polishing platforms that can be used to process CVD-clad substrates deterministically. We have demonstrated that, with the material removal rates obtained on CVD SiC using these machines, processing even large mirrors is possible and practical.

REFERENCES

1. D. Vukobratovich, Course notes from SPIE short course SC26, “Introduction to Optomechanical Design for Mechanical Engineers”, (1990), p 77
2. Takashi Onaka, Hideo Kaneda, Haruyuki Okuda, Hiroshi Murakami, Tsuguo Kohno, Shinji Miura, Ryoji Yamashiro, and Yoshikazu Sugiyama, “The development of lightweight silicon carbide mirrors for the Japanese infrared space mission”, http://origins.jpl.nasa.gov/meetings/ulsoc/papers/onaka.pdf
3. Tobin, E., et al., “Design, fabrication, and test of meter-class reaction-bonded SiC mirror blank", Proc. Of SPIE, Vol. 2543, p. 12
4. Shi, J, and Ezis, A., “Application of hot-pressed silicon carbide to large high-precision optical structures", Proc. of SPIE, Vol. 2543, p. 24.
5. Robb, P., et al., “Interferometric measurements of silicon carbide mirrors at liquid helium temperature", Proc. of SPIE, Vol. 2543, p. 196.
6. J. Casstevens, A. Rashed, R. Plummer, D. Bray, R. Gates, “Silicon Carbide High Performance Optics: A Cost effective, Flexible Fabrication Process”, SPIE Proceedings, Vol. 4451 (2001), p. 458.
7. Zerodur ® is a registered trademark of Schott Glass Co.
8. D. Golini, W. Kordonski, P. Dumas, S. Hogan, “Magnetorheological finishing (MRF) in commercial precision optics manufacturing”, SPIE Proceedings, Vol 3782 (1999), pgs. 80-91

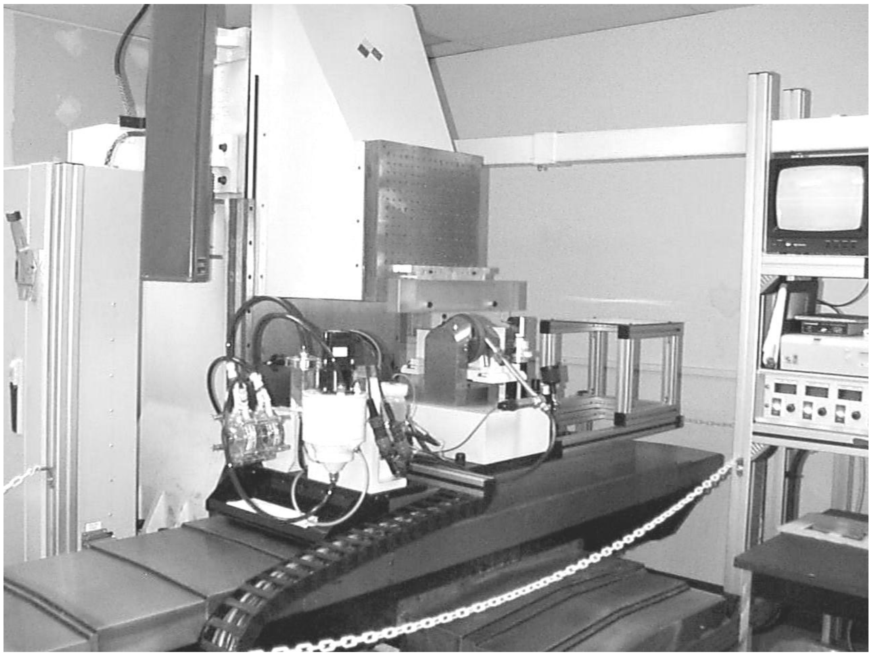


Figure 1. 150-mm wheel raster MRF machine (side view)

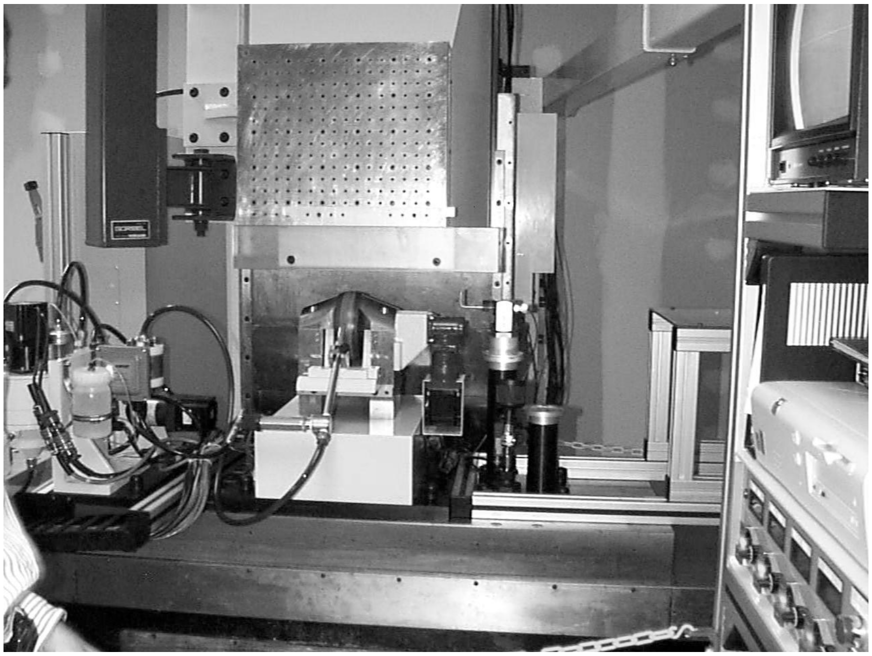


Figure 2. 150-mm wheel raster MRF machine (front view)

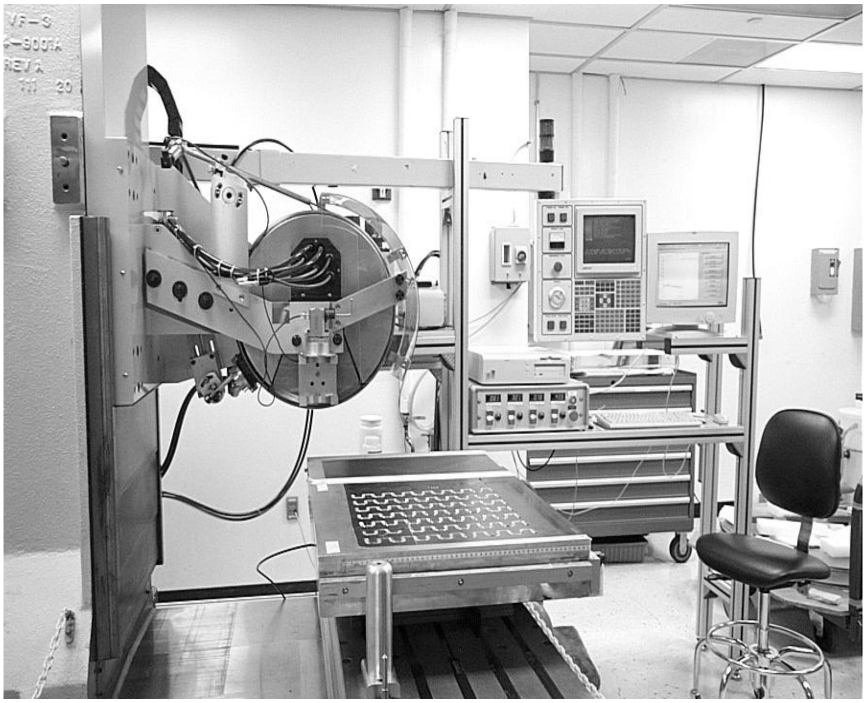


Figure 3. 500-mm wheel raster MRF machine (side view)

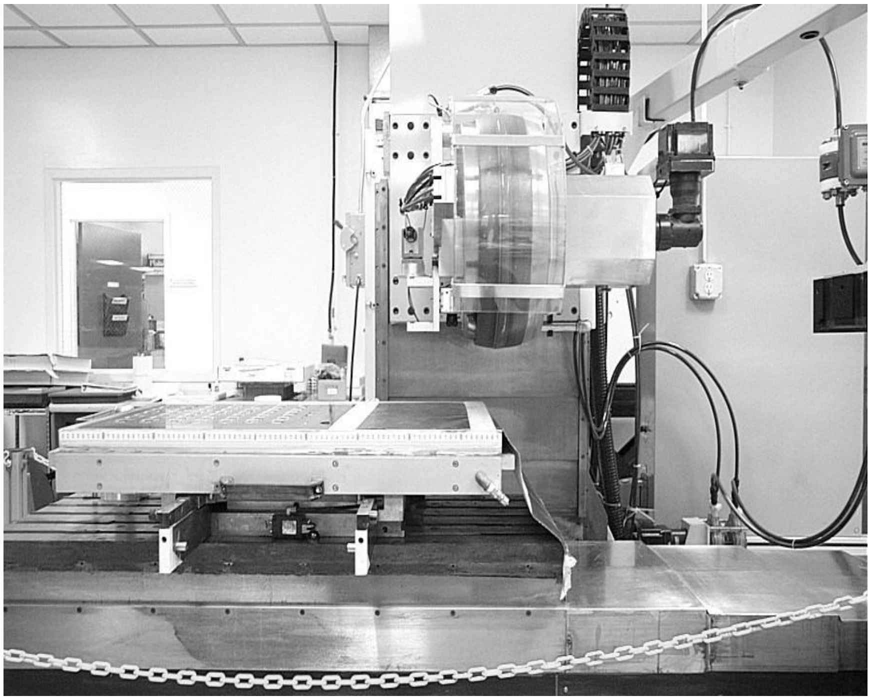


Figure 4. 500-mm wheel raster MRF machine (front view)

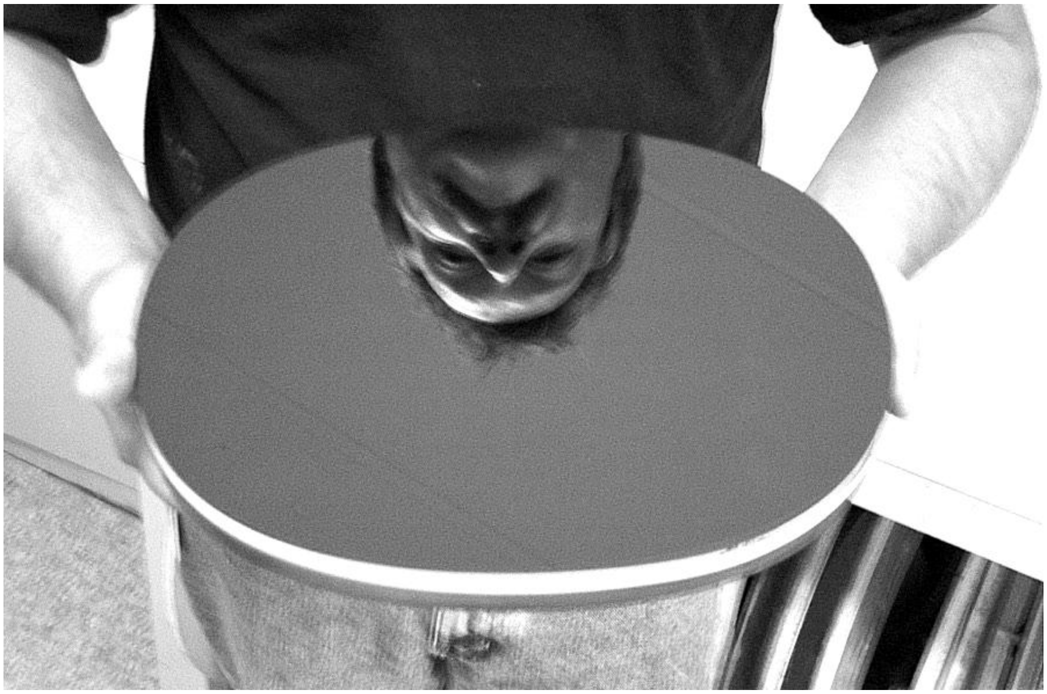


Figure 5. POCO SiC mirror (front)

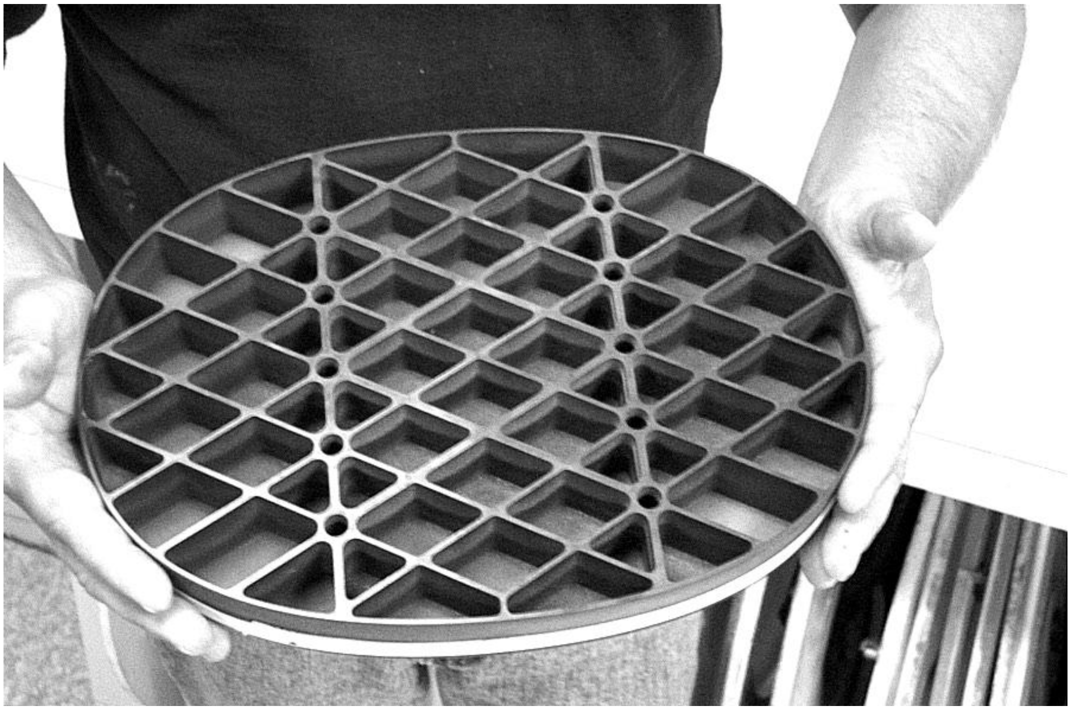
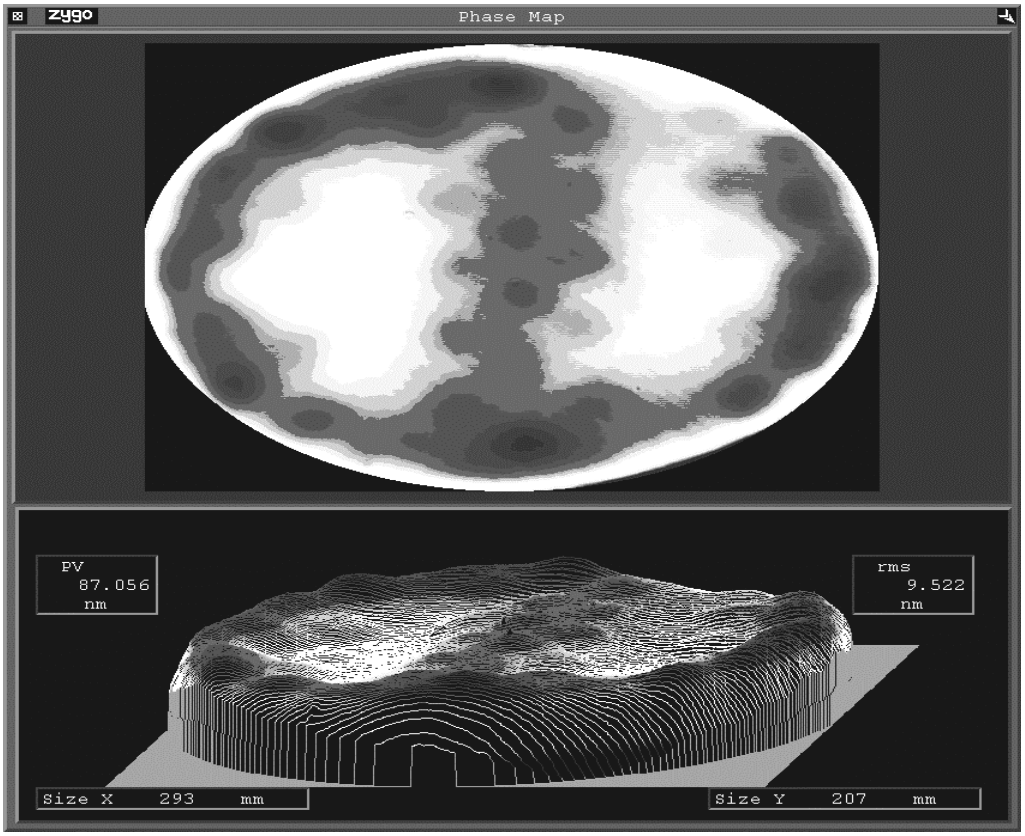


Figure 6. POCO SiC mirror (back)



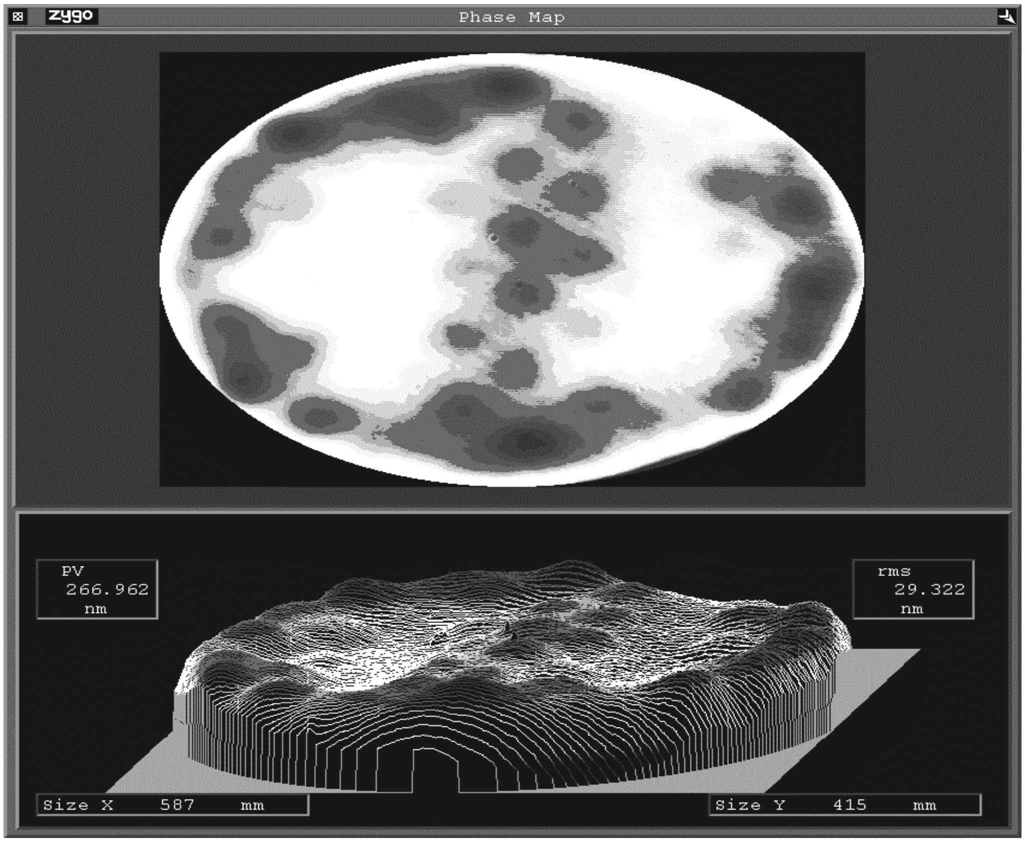
PV 87.056 nm

rms 9.522 nm

Size X 293 mm

Size Y 207 mm

Figure 7. Mirror surface figure after conventional polishing



PV 266.962 nm

rms 29.322 nm

Size X 587 mm

Size Y 415 mm

Figure 8. Synthetic representation of large mirror surface error used to estimate MRF time