N92-22449

ULTRA-PRECISION PROCESSES FOR OPTICS MANUFACTURING

William R. Martin
Oak Ridge National Laboratory
Oak Ridge, TN 37831

ABSTRACT

The Optics MODIL (Manufacturing Operations Development and Integration Laboratory) is developing advanced manufacturing technologies for fabrication of ultra-precision optical components, aiming for a ten-fold improvement in precision and a shortening of the scheduled lead time. Current work focuses on diamond single point turning, ductile grinding, ion milling, and in/on process metrology.

INTRODUCTION

Industry in this country does manufacture sophisticated optics. For now the process is laborious, time consuming and the results are difficult to predict. But the opticans are artists and accomplish much. For the next century, there will be better methods.

Technology emerging today may be able to impact the market place in the Year 2001. As the market pulls the technology into industrial applications, that emerging technology will be modified to enable a profitable application. In our country, more and more cooperative and collaborative R&D efforts are in effect between the tripartite, industry, universities, and federal laboratories. We are beginning to better leverage our technological assets to provide the citizens of our country the opportunity to work in high value-added industries that are globally competitive. There are a number of important on-going efforts to improve the producibility of optics. Several Optics Science Centers at our major universities are involved in outstanding efforts. Fortune 500 companies and small entrepreneurial firms are involved in ingenious new approaches. Federal funding is supporting the effort of the Center for Optics Manufacture and the Optics MODIL.

The Optics MODIL, funded by the Strategic Defense Initiative Organization, is integrating the emerging and enabling technology to manufacture ultra precision optics that will be affordable. The size of the ultra precision optics market is currently both small and volatile. There is a lack of current market incentives for industry to accelerate the deployment of ultra precision technology. While one can debate what application will expand this ultra precision market segment, it is important to recognize that the Europeans, especially the Germans, and the Japanese have very strong manufacturing development programs for Nanolevel Finishing Technology. It's probable that those foreign efforts are not just for the pursuit of technology for technologies sake. Commercial application and markets include: analyzers - environmental monitors, air quality; diagnostics - process monitors, scanners; laboratory equipment - spectrometers; IR imagers; satellites - high cost, low quantity; diffractive optical elements; contact lenses, aspheric corrector; precision molds - plastic, optics (fresnel optics), contact lenses; precision machined components for precision machines. While we have mentioned a number of applications, there may be even more important ones that we have missed.

MIRROR MANUFACTURE

The approach of the Optics MODIL is to develop manufacturing processes for ultra precision work that is: deterministic, affordable investment for small and large business, adaptable for in/on process metrology, applicable to a range of materials, and flexible with regard to shape and size.

A desirable feature of this new capability would be the ability to provide custom designs at prices we currently reserve for off-the-shelf procurements. Another view would be to offer the product in low quantities (i.e. 5 to 10) that currently are reserved for total buys of 500 to 1,000. The new business, must be able to take a few designer optical characteristics and build the product. Tooling and fixturing costs must be low and readily available. The customer must be willing to reduce the specification to a minimum without providing the manufacturing business with stacks of documents.

Current finishing processes being developed with industry are single point turning, ductile grinding and ion milling with strong metrology development to provide inspection in- or on-process. These efforts are evolving within the umbrella operation of a Producibility and Validation Test Bed where joint industrial programs can be pursued. Within the Test Bed, Manufacturing Cells contain the individual finishing operations. Materials of interest are metals i.e., Beryllium, SXA composites, Silicon, and Electroless Nickel coated substrates. Ceramic materials of interest are principally versions of Silicon Carbide.

Because these operations are focusing on Nanolevel finishing technology, the manufacturing cells that house these operations are capable of excellent control of the environment. The Cells are shown in Figures 1 and 2. Temperature variations within the inter-compartment can be controlled to within a tenth of a degree fahrenheit. This is only one of the factors important for reproducible operations in the nanolevel regime. The ability to consistently produce products to a few tens or hundreds of nanometers requires consistency of the operations. Equipment required to achieve this type of control is commercially available at about $\$75/ft^2$.

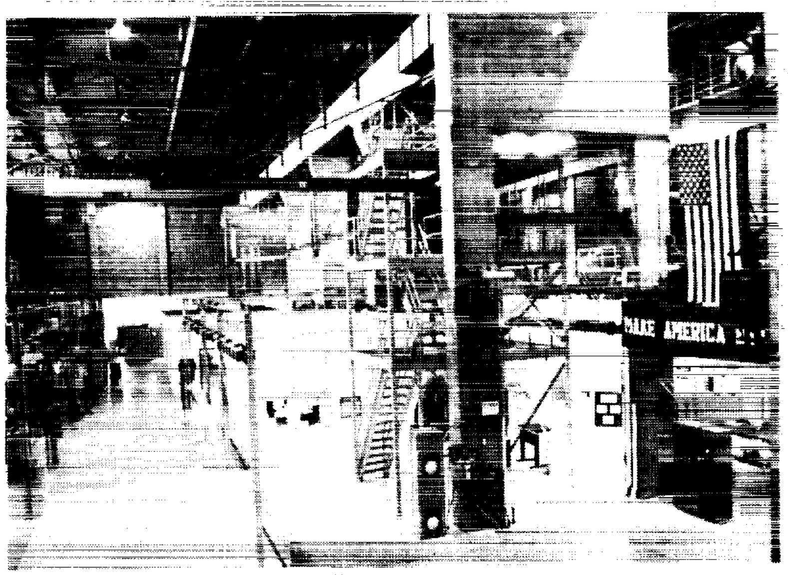

Figure 1: Holonic Manufacturing Cells in Producibility and Validation Test Bed (PVTB)

Figure 2: Interior View of Manufacturing Cells

It is envisioned that these cells would be deployed in businesses such as system houses, special machine shops or perhaps adopted by optical polishing/coating firms as alternative technologies that significantly expand capabilities, lower manufacturing labor, increase yield, and greatly reduce the time necessary to finish the optical surface. A deterministic process that would make optics cheaper, faster, and perhaps better. The overall strategy of developing a manufacturing operation for the finishing process with metal substrates and/or ceramic substrate is shown in Figure 3.

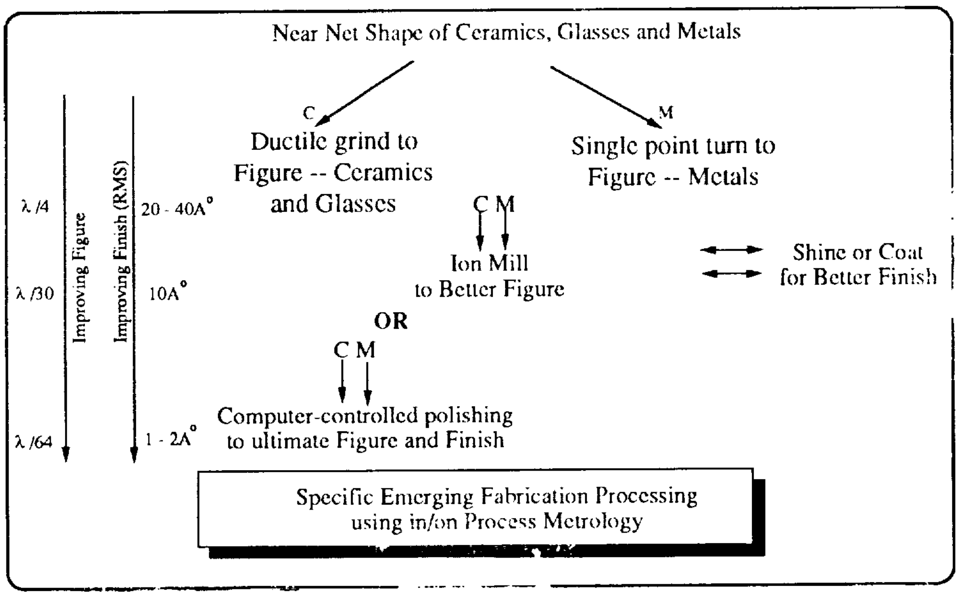

Figure 3: Mirror Fabrication Strategies

Our single point turning efforts utilize a Rank Neumo 600 single point turning machine. This commercially available unit housed in the Productivity and Validation Test Bed (PVTB) is the prototype model developed in this country. Two more units have been sold to U.S. firms and are being delivered by Rank Pneumo during 1991 and 1992. The Japanese are also now buying a unit. A photo of this machine is shown in Figure 4. Mirrors being viewed are shown in Figure 5. We currently have produced Single Point Diamond turned optical surfaces that have figure accuracy of 1/4 to 1/6 wave for small sizes having a Tallystep surface finish about 20 Å RMS. The BRDF light scatter at 10.6 microns was as low as 100 ppm. These as machined surfaces have very low scatter for IR applications. Photos of some as-machined mirrors are shown in Figure 6. To date for small optics, i.e., 155mm diameter F/4 convex hyperbolic mirror, the surface finish is about 25Å RMS for Electroless nickel surface and the figure accuracy has been about one-sixth wave. For larger mirrors, such as a 400 mm diameter, nickel coated SXA foam body, the figure accuracy peak to valley was about one quarter wave (RMS). On the larger parts, centering, fixturing and tooling errors dominate. These data are shown in Table 1. Fixturing schemes are shown in Figure 7. Work by Bob Parks of the University of Arizona has demonstrated that the surface smoothness of these diamond turned parts can be improved by a factor 5 by using a brief flexible lap polish.

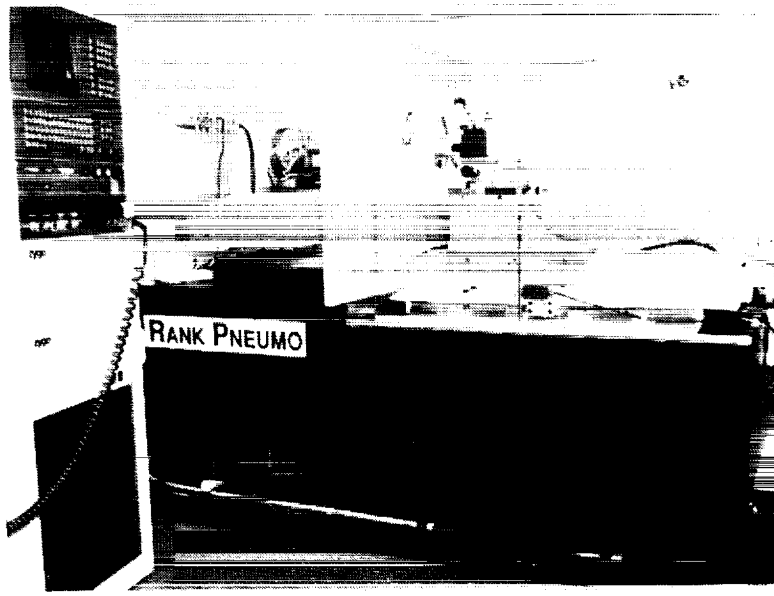

Figure 4: Prototype Rank Pneumo 600 Turning Machine

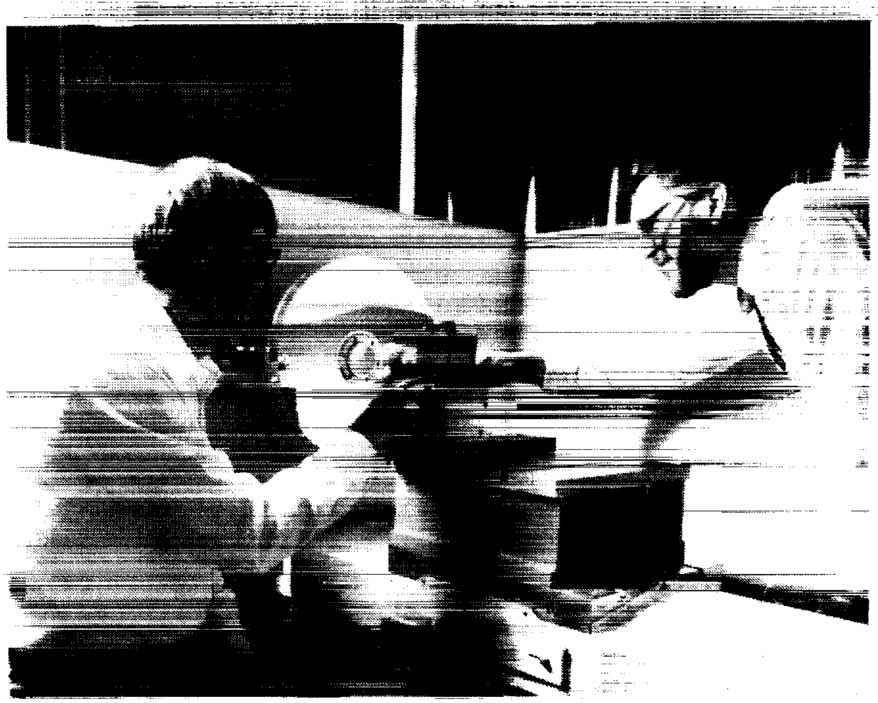

Figure 5: Complex Surfaces of Turned Mirrors are Examined by Staff

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

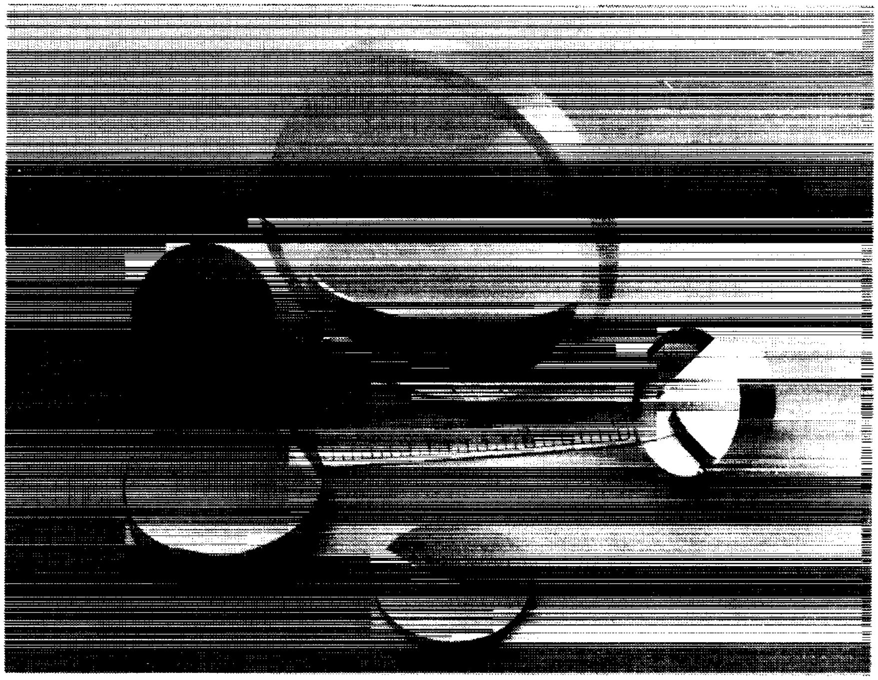

Figure 6: Typical Single Point Diamond Turned Mirrors

Size of Optic mm	Shape of Surface	Peak to Valley Figure Accuracy (visible waves)	Finish			Material
			BRDF			
			10.6	0.633	Å RMS	
40	Flat	0.25	E-4	E-2	---	Aluminum
75	Sphere	0.16	E-5	E-6	20	Copper & Aluminum
155	Hyperbola	1.3	(a)	(a)	25	Electroless Nickel
200	Parabola	0.5	(a)	(a)	---	Aluminum
400	Parabola	1.5 to 0.5	(a)	(a)	---	Aluminum

(a) Currently being deterined

Application in the IR Range

Table 1: Single Point Turning of Metallic Mirrors

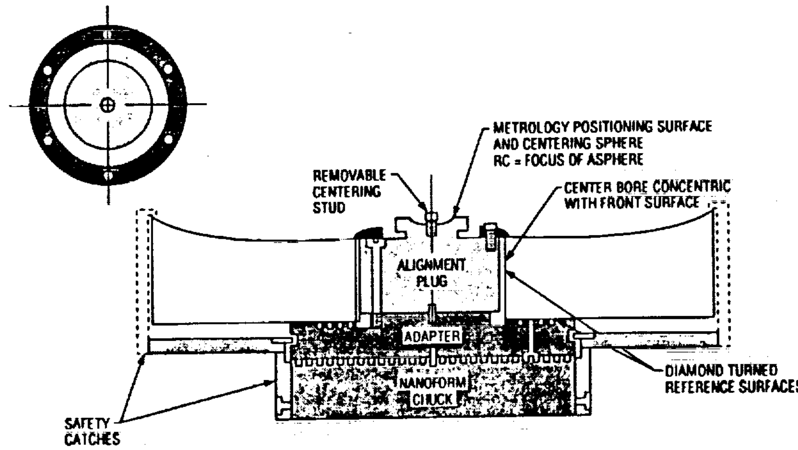

Figure 7: Fixturing Scheme for 400mm Diameter Parabola

A key to saving time in the manufacturing shop, is to be able to inspect the mirror while it remains in the fixture. One approach that is being pursued is a modified scanning Hartmann technique. The device, shown in Figure 8, has been built by Talandic Research Corporation. While the hardware is in the exploratory phase of its deployment, it has attractive potential. Those advantages are that it is non-interferometric with reduced sensitivity to vibration and thermal gradients and can test aspherics as well as spheres without auxiliary optics. Also very fast optics can be tested and readings can easily be integrated into SPT numeric control. A disadvantage is that the basic measurement is slope and those measurements must be properly integrated to determine contour. To date, the technique has not been used in-process but has been demonstrated for on-process. Its capability at this phase of its development is the ability to measure figure accuracy to about one quarter of a wave. Other techniques for on-process figure metrology that are being further developed include point polarization interferometry (developed for RADC) and diffraction null corrector. Overall we desire to focus on aspheric testing.

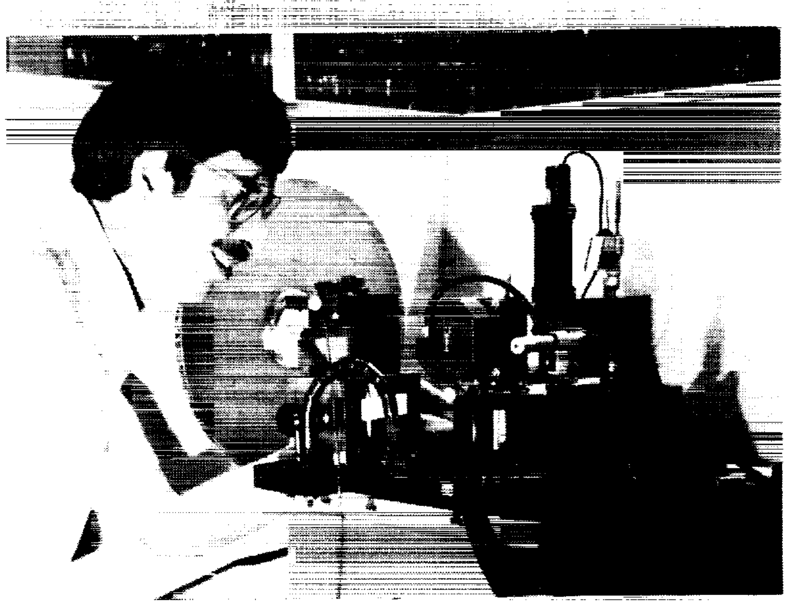

Figure 8: Modified Scanning Hartman Device Built by Talandic Research Corporation

Although an increasing number of materials can be single point turned, ceramics are more easily ground. If conditions can be established to allow grinding in the ductile regime for a particular ceramic or glass, the surface finish is improved dramatically and the mechanical integrity of the brittle material is enhanced because of fewer surface cracks. In the PVTB, a motorized block head spindle (Professional Instruments) has been installed on a Moore Turning machine, Figure 9. Currently, that ductile grinding cell is being used for exploratory tests on silicon carbide. To date, small SiC coupons, 75mm diameter, have been ground to surface finish of 35Å RMS. A photo of that surface is shown in Figure 10. Work by T. Bifano of Boston University on cubic silicon carbide (CVD) indicate that this type of SiC can be ground without creating new surface or subsurface cracks.

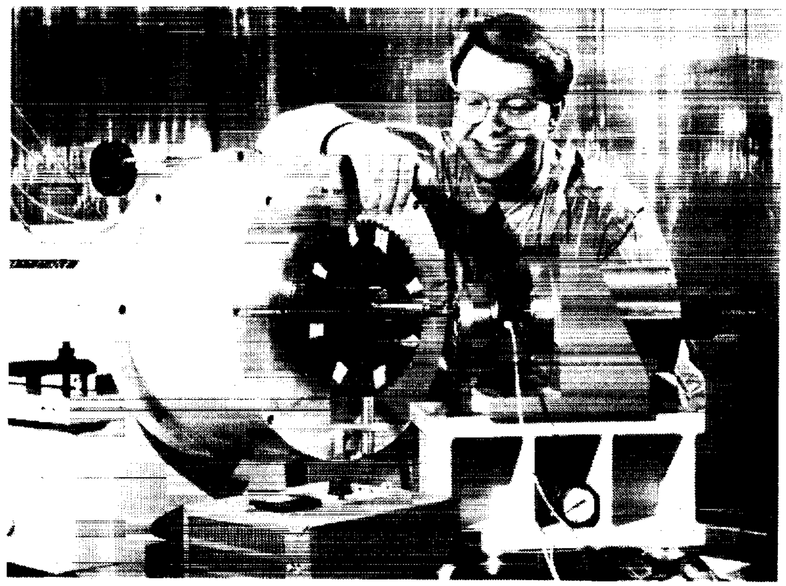

Figure 9: Grinding Spindle Setup in PVTB Cell

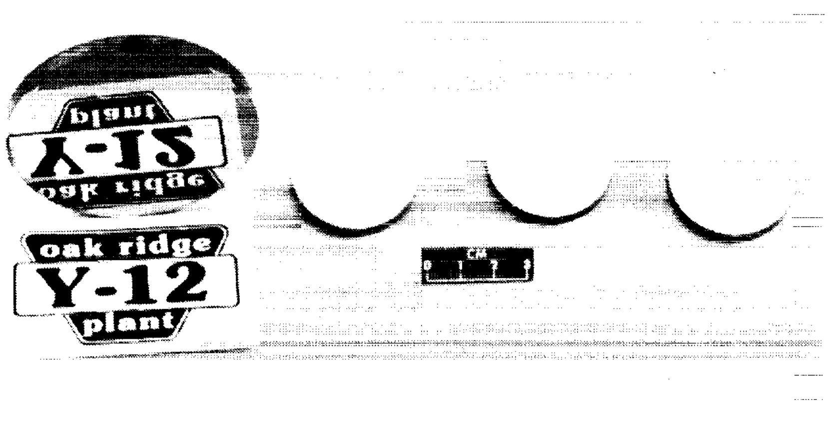

Figure 10: As-ground CVD Silicon Carbide Specimens

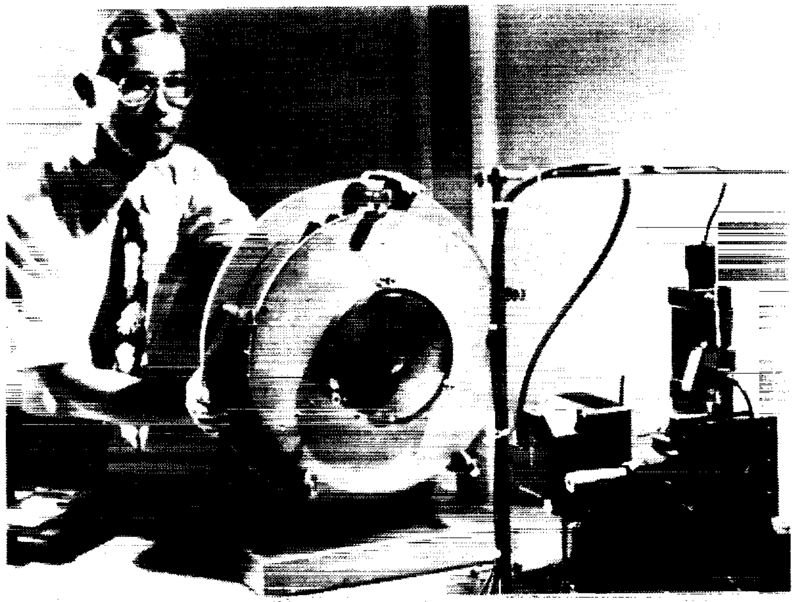

Figure 11: Testing of Opt.cal Figure Usii.g Scanning Hartman Device

Inspection techniques for in/on-process metrology (Figure 11) for grinding of ceramic mirror substrates and for some optical window materials will be the same as used for the Single Point Turning operation. However, acoustic emission techniques are being evaluated to control the grinding parameters within or near the ductile regime. Efforts at Boston University will produce a device to measure acoustic emission caused by cracking of brittle materials during the grinding operation with the potential for real-time feedback as process control. This technique could allow the process to be controlled in the optimum range for grinding.

Beyond the precision capability of ductile grinding and single point diamond turning, is the nanolevel capability of ion milling. The PVTB has two units, one capable of milling a 55mm disc while the second unit is capable of finishing 600mm diameter. The smaller unit is shown in Figure 12. Up to 200 microns of single crystal silicon can be removed by ion milling and the surface finish remains better than about 25 Å RMS. The same is true for non-crystalline materials. However, polycrystalline metals such as aluminum, copper, silicon begin to roughen as the ion milling progresses unless the grain size is very small. To date, removing a layer of about 300 nanometers increased the surface roughness of polysilicon from about 30Å to slightly above 40Å. Tests are continuing. Rates of surface removal for ion milling operations indicate that it would be possible to improve the figure of a mirror from one half wave to one twentieth of a wave in about 3/4 hour for a small optic (100mm) and in about 4 hours for a larger optic (400mm). This assumes that one X-Y raster of the ion gun will be perfect and the in-process inspection technique is fully integrated into the process operation. Currently, our operation is far from that capability, but we strive with our industrial partners to evaluate this technique as a deterministic process because the potential is very high that the manufacturing technology will be ready to be deployed prior to the 21st Century. We are also considering the manufacture of binary optics using these techniques.

Our metrology plans for Ion Milling are different than those we are developing for Ductile Grinding and Single Point Turning. We are examining the potential use of Electronic Holography coupled with interferometry to perform metrology on ion milled parts within the vacuum chamber.

The manufacturing operations and process integration continues for these ultra-precision techniques. While the concept of using as-diamond turned optics for IR application has been proven, there is much work yet to be completed in order to implement these costs and time saving operations in the U.S. industrial base. We applaud the industrial tripartite who are contributing their time, money and other resources to this collective effort. We anticipate that the spin-off to other applications could be numerous and a new manufacturing segment will be born in the United States.

Figure 12: Small Ion-Milling Machine in PVTB

BUSINESS PERSPECTIVES FOR THE FUTURE

If this segment is born, will it survive? As we look about this country, we see marvelous capability to make unique and complex parts in our optics manufacturing base. Our industrial base can make almost anything, given enough time and funding. Many of these expensive facilities were built and utilized for a particular job, but now have a very low utilization factor. On the other end of the ultra-precision scale, we have smaller shops using less expensive equipment, whose operation is labor intensive and also non-deterministic. All of these businesses are generally high technology job shops, but the use factor is not very high.

Given this historical pattern, isn't it likely that the technology being developed by the Optics MODIL and others will either (a) never be incorporated into the optical market place or (b) used to build unique optical components for SDIO and then find no commercial market to sustain it as a viable business.

The notion is proposed that before this country can have an ultra precision manufacturing capability for optics that is commercially viable, one of at least three criteria must be met: (1) The market for ultra precision optics must be significantly larger and more stable, or, (2) Customers must be willing to pay a higher price for optical components so that the industry can generate the resources to support new equipment, etc, or (3) A change in how the manufacturing business is defined for those who make ultra precision optics.

We support the third criteria as the most plausible and one that could be globally competitive. If we can have a mind set that our business is not to manufacture ultra precision optics, but to manufacture ultra precision shapes - what a difference it could make in the potential market size of our business. If the equipment invested in this enterprise is more deterministic, perhaps even "lights-out" holonic operations, and flexible in its capability with regard to materials and shapes, then the manufacturing operations can produce a broad range of products to ultra precise shapes and surfaces.

If a given business redefined its mission to say, we manufacture and sell ultra-precise and complex shapes with a range of surface qualities, i.e., finish and stability, then the Marketing and Customer Service people who support that business become the experts who appreciate the different customer requirements. Those customers are the users of optical components i.e., mirrors, windows, lenses, bearing surfaces, molds, etc.

For the 21st Century, we will have the opportunity to establish an ultra precision manufacturing capability in this country, but a different mind set on the business will have to be developed to make it a viable commercial entity.

ACKNOWLEDGEMENTS

I wish to acknowledge the funding support and guidance provided by G. Stottlemyer of the Strategic Defense Initiative Organization and the excellent work of A. Miller, J. Cunningham, C. Egert, K. Kahl, C. Maxey, P. Steger, and C. Griffies in the development of material removal processes. Among the many contributors to the strategic directions pursued by the Optics MODIL, are the legions of attendees to our Industrial Briefings and Workshops. I thank them all.