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R. Chow, J. R. Taylor,
W. K. Eickelberg, and K. A. Primdahl

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Lawrence
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Testing of optical components to assure performance in a high average power environment

Robert Chow[a], John R. Taylor[a], William K. Eickelberg[a], and Keith A. Primdahl[b]

[a]Lawrence Livermore National Laboratory
[b]United States Enrichment Corporation

ABSTRACT

Evaluation and testing of the optical components used in the Atomic Vapor Laser Isotope Separation (AVLIS) plant is critical for qualification of suppliers, development of new optical multilayer designs and manufacturing processes, and assurance of performance in the production cycle. The range of specifications requires development of specialized test equipment and methods which are not routine or readily available in industry. Specifications are given on material characteristics such as index homogeneity, subsurface damage left after polishing, microscopic surface defects and contamination, coating absorption, and high average power laser damage. The approach to testing these performance characteristics and assuring the quality throughout the production cycle is described.

Keywords: photothermal deflection, absorption, total internal reflection microscopy, interferometry

INTRODUCTION

This is the third paper of three on the optical component performance in a high average power environment such as that to be deployed in an atomic vapor laser isotope separation (AVLIS) plant. The first companion paper entitled “Optical manufacturing requirements for an AVLIS Plant,” introduced the United States Enrichment Corporation (USEC), a semi-private company that plans to build the first commercial AVLIS plant from laser technology developed at the Lawrence Livermore National Laboratory (LLNL).[1] USEC will enrich U-metal to fuel-grade concentrations and sell it to nuclear electric power plants. The AVLIS process was described, prototype high power laser systems shown, and the strategy to assure a large quantity of high performance laser optical components was also presented.

The second companion paper, entitled “Specifications of the optical components in a high average power laser environment,” described the specifications and the effects that specifications have on the overall performance of the plant laser systems.[2] The motivation for the stringent requirements to maintain process efficiencies, beam wavefront quality, and component lifetime were given. Summaries categorizing the quantities, sizes, and relative coating difficulty of components that are planned for the AVLIS plant were included in this second paper.

The AVLIS enrichment process has been performed at the Laser Demonstration Facility (LDF), a prototype AVLIS system at LLNL. The LDF high power laser transport system consists of many complex optical configurations. An AVLIS plant design has begun based on this LDF configuration and experience. The plant build is expected to require the procurement, testing, and installation of over 40,000 optical components. Also, based on the LDF experience, optical testing proved essential to

Rev. June 24, 1997

timely deployment and activation of the lasers for AVLIS process optimization. Tested optics assure a level of performance which is important when trouble-shooting complex optical subsystems (Figure 1). If distorted beams or inadequate power deliveries were noted, effort was regulated to checking alignment, installation mounts, beam transport clear apertures, and so forth instead of searching for defective optical components. Even if some tested optics were not within the specifications but still used in operation, lower performance can be accounted for and, in some cases, compensated in the system elsewhere.

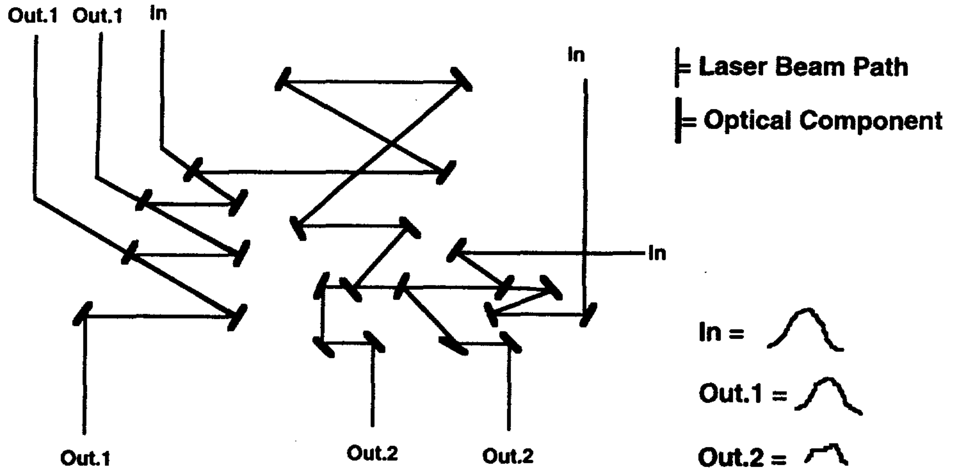


Figure 1 Where is the defective "Waldo" optical component? Testing optical components before installation assures specified performance levels.

In this paper, a review of the AVLIS test equipment and tools for assuring the performance of optical components for the AVLIS plant are presented. Optical component testing fulfills two functions. First, the test results are used to help AVLIS optical suppliers. The suppliers optimize and establish procedures for their manufacturing process, and during the production stage, use the feedback to maintain process control. Secondly, testing assures a certain optical performance level that minimizes the time to plant deployment and laser activation.

TEST EQUIPMENT

All optical components are tested at the end of every major manufacturing phase: bulk material, polishing, and coating. Suppliers are required to test parts before their shipment and confirmation tests on a reduced quantity are performed either by source inspection or at the USEC site. Defective parts are re-worked or discarded. Actual optical parts are tested wherever possible. Otherwise, 76.2 mm diameter flat witnesses undergoing the same manufacturing cycle for coatings are used if the optics are not compatible with the test instrument. For critical coatings, the witnesses are used in destructive testing. Table 1 is a list of basic test equipment for the AVLIS plant. Table 1 describes the type of equipment, commercial availability, and application. Mechanical metrology equipment include tools such as rulers, calipers and spherometers (measurement range from 9 mm to 120 mm diameters, detection resolution of 0.5 μm of saggita) that measure the overall dimensions and radius of curvature. Bright light sources (75 W halogen bulbs) are used for viewing the surface quality or texture of finished optics. Further details are obtained with Nomarski (Differential Interference Contrast and Dark Field) microscopes. The types of defects that can be sized and categorized with microscopy are polishing gray (underpolish, haze, micro-structure), scratches, pits (digs), bubbles, fixture marks, and coating blemishes (spatter, pinholes, crazing, peeling, blisters, stains, and sleeks). An optical spectrophotometer is used to measure the spectral performance. The AVLIS test laboratory has a gonio-μreflectometer with a transmission option to measure the spectral performance on curved parts. This instrument can measure optics with a radius of curvature ranging from 4 mm to infinity. The accuracy of this instrument is ± 0.02 of the read value. The current wavelength range of the gonio-µreflectometer is from 400 nm to 1300 nm. Phase interferometry equipment is configured to measure wavefront distortion to within ±0.003 waves (633 nm) p-v, refractive index homogeneity to 0.1 ppm, wedge with 1.0 x 10^{-4} arc seconds resolution. The AVLIS test facility has its own dedicated HVAC system. The temperature is controlled to within ± 0.2°C. The relative humidity is not controlled but typically ranges between 18% to 35%. Enclosures are used to minimize air turbulence and insulating barriers are installed locally to minimize thermal noise. Custom equipment in this test lab include Total Internal Reflectance Microscopy (TIRM) to characterize subsurface damage, multi-bounce laser ratio reflectometer to measure reflectances at a given wavelength up to six-place accuracy, tooling to measure optics of irregular shapes like prolated ellipsoids, absorptance (< 5 ppm) by thermal imaging, damage threshold using one of the copper vapor laser (CVL) chains, and environmental chambers to control the relative humidity or vacuum. The rest of the talk focuses on the latest custom equipment for AVLIS test lab: TIRM, absorptance and phase interferometry of samples in an environmental chamber.

Table 1 Optical test equipment for an AVLIS plant build. Mat'l = raw glass material; Subst = finished substrate; Ctg = coated optic

TEST EQUIPMENT	AVAILABILITY	MAT'L	SUBST	CTG
Bright light sources	Commercial	√	√	√
Mechanical Metrology & Spherometer	Commercial		√	
Microscope	Commercial	√	√	√
Phase Interferometers	Commercial	√	√	√
Spectrophotometers	Commercial			√
Facilities (T & RH controlled)	Semi-custom		√	√
Gonio µreflectometer/transmission	Semi-custom			√
TIRM	Custom		√	
Ratio Reflectometer	Custom			√
Special fixtures (Prolated ellipsoid)	Custom		√	
Absorptance	Custom		√	√
Survivability/Laser-resistant	Custom		√	√
Environmental chambers	Custom			√

TOTAL INTERNAL REFLECTANCE MICROSCOPY

TIRM is a non-destructive optical technique that can detect subsurface damage of transparent optical materials.[3,4,5] A fiber optic is used to feed 180 mW of laser light into the prism. Argon ion laser light is sent through the optic under test at an angle greater than the critical angle of total internal reflectance (Figure 2). The surface of the part under test is imaged with a microscope. Polarization optics are rotated to obtain scatter signals from the surface to about one half a wavelength below the surface. If the surface and subsurface have no imperfections, the laser light would reflect off the glass/air interface, and no light would be scattered into the microscope. However, in the case were there are defects in the path of the laser, the defects scatter light at angles below the critical angle and into the microscope objective. In the transport optics, commercially available polarization optics are needed to optimize the signal. A computer with a frame grabber is an useful option to store, statistically analyze, and print out the microscopic images. In Figures 3A-C, the left hand picture is a differential image contrast view of a polished surface; the middle picture is that of the etched surface of the same optic; and the right hand picture is the TIRM image of from the same optic. Case A is an optic with a good polish. There is very low density of polishing residue (at 200x magnification.). Case B is a poorly polished optic. Case C shows that TIRM can detect subsurface damage even when etching does not reveal any fractures.

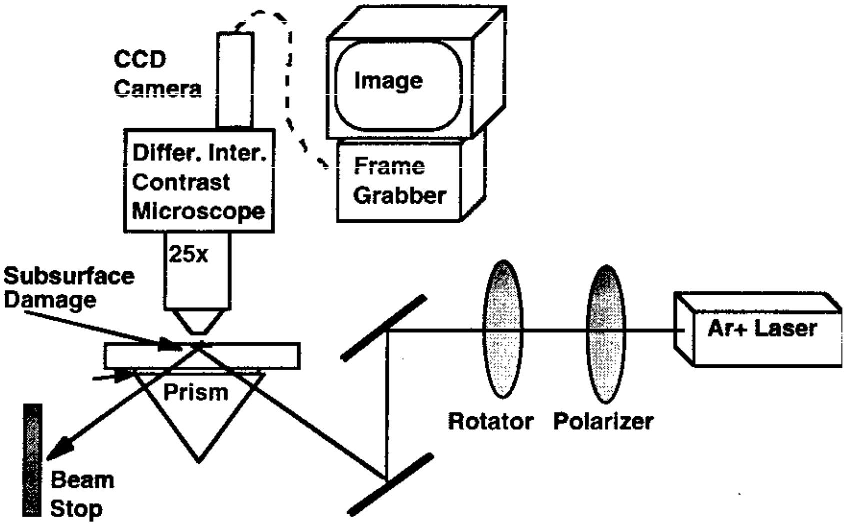


Figure 2 TIRM test set-up at LLNL. Subsurface defects scatters light into the microscope. Undamaged areas reflect light internally into the beam stop.

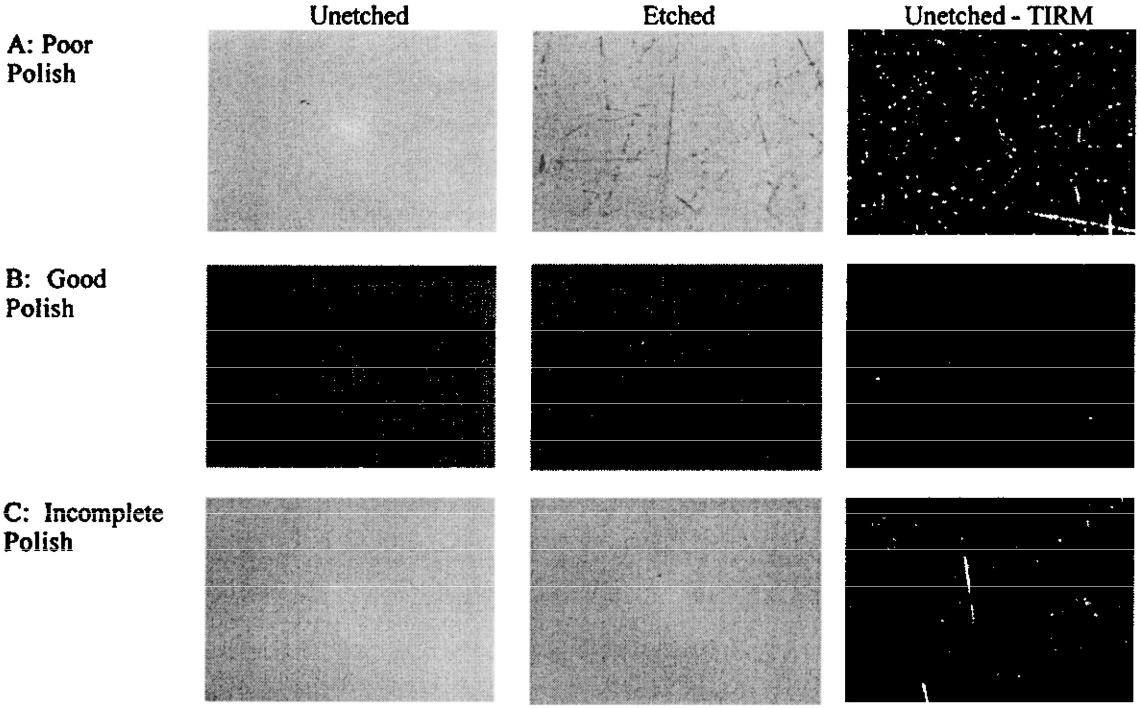


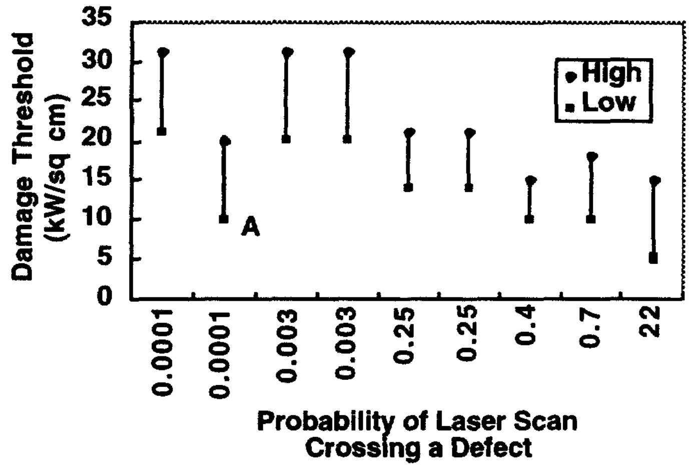
Figure 3 Case A: Comparison of polished, etched, and TIRM inspection techniques of a poorly polished surface; Case B: Comparison of polished, etched, and TIRM inspection techniques of a polished surface; Case C: Comparison of polished, etched, and TIRM

inspection techniques of a well-polished surface. TIRM is able to detect subsurface defects that etching does not reveal.

The subsurface damage that we are trying to resolve are the residual fractures from the polishing procedure.[6] Just below the polished surface, there may be cracks that are filled or covered with a mixture of polishing debris and slurry. The mixture is well packed from the polishing steps so that it is very difficult to observe even after acid-etching through the polished surface. The polished optic typically goes through many more processing steps (cleaning, coating, thermal cycles) and high laser power exposures, which may cause the fractures to open up and propagate.

The motivation for subsurface defect testing is the correlation that coated optics with a high degree of subsurface defects have lower laser-damage thresholds, even though the substrate was coated with a high reflector stack.[7] The damage thresholds of the high reflectors are plotted in Figure 4, where the diamond and square data points bracket the damage and non-damage power densities of an optic, respectively, as a function of the probability of a laser scan encountering a subsurface defect. The high reflector coating was deposited on substrates with various densities of subsurface defects, as delineated using conventional acid-etching techniques. The defect density information was used to determine the probability of a laser scan encountering a defect of a given dimension and density. The observation from this data is that thick coatings do not shield the subsurface defects from damage. One possible damage mechanism may be that the fractures are filled with polishing debris and contaminants that have low laser damage thresholds. Another mechanism may be that the fractures are growing during the coating cycle and may initiate coating defects susceptible to laser damage. The data set labeled "A" indicates that low subsurface damage is a necessary but not a sufficient condition for higher damage thresholds.

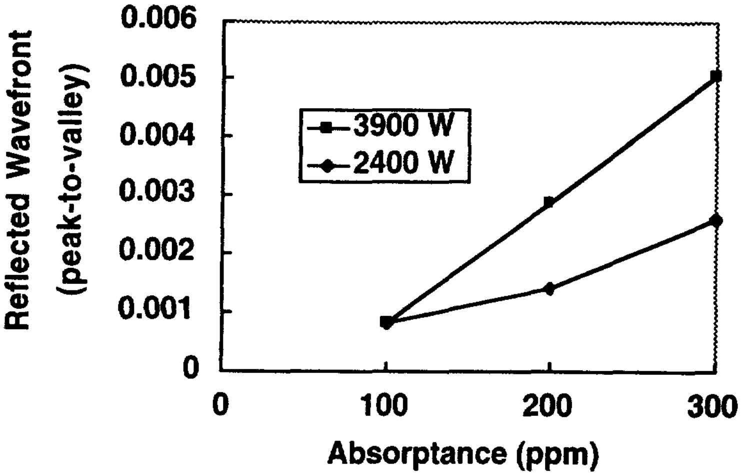
Figure 4 Survivability of high Reflector Coatings. Coating damage thresholds tend to be lower if the subsurface defect density is higher.



ABSORPTANCE

Absorptance of the AVLIS components need to be well below 100 ppm in order to minimize wavefront distortion. In Figure 5, the estimated reflected wavefronts are shown to increase as the absorptance of the coating increases. The analysis was performed at two beam input powers showing that the distortion becomes more sensitive to absorptances at higher laser powers.

Figure 5 Estimated Wavefront Distortion. Increasing absorptances leads to increasing wavefront distortion. The distortion is usually worse at higher laser powers.



The current AVLIS test set up of the absorption and damage tester has been described previously.[8] Briefly, 200 W of copper vapor laser light is transported through a Hartmann pattern, optional filters, attenuator to control power density, and imaging lens before impinging onto the sample. CCD cameras are used to monitor the sample during the laser beam irradiation. An infrared thermal camera detects the temperature difference between the irradiated and unexposed areas of the sample. The temperature difference is converted to absorptance using an empirically derived equation. Another absorptance measurement system is being developed so that the test cycle is independent of CVL availability.

The AVLIS program is investigating a variation of a photothermal technique to measure absorptances of coatings. The technique, called surface thermal lensing, uses a relatively low power (compared to the CVL) laser for pumping the coating, and a relatively large diameter probe beam (compared to conventional photothermal techniques) to sense the absorptance-induced surface deflection. The low power is desirable because the test set-up may be implemented at the suppliers' locations for them to optimize and sustain their manufacturing process for AVLIS optics. The large beam is desirable because it greatly facilitates the coincident alignment of the pump and probe beams onto the sample. In conventional techniques, the pump and probe beam are positioned juxtaposed to each other, not coincident, for the maximum signal. This low power absorptance measurement system has easily resolved absorptance levels on coatings that the CVL pumped technique just begins to resolve at ≈ 5 ppm.

The low power absorptance work has been reported on AVLIS-typical CVL mirrors.[9] The investigators observed that high reflector coatings exhibit time-dependent absorptance behaviors. Figure 6 has the plots of absorptance as a function of time for four distinct cases (the scale changes from graph to graph): Case A is decreasing absorptance with time, and this was observed in the majority of samples; Case B is a step decrease in absorptance with time; Case C is a linear increase with time, the worst situation for a laser optic; Case D is a increase of absorptance with time but stabilizes within a short time, not the ideal case but acceptable if the stabilized value is below the specification. The protocol to report more useful absorptance data should include of the test parameters and some mention of time dependent behavior.

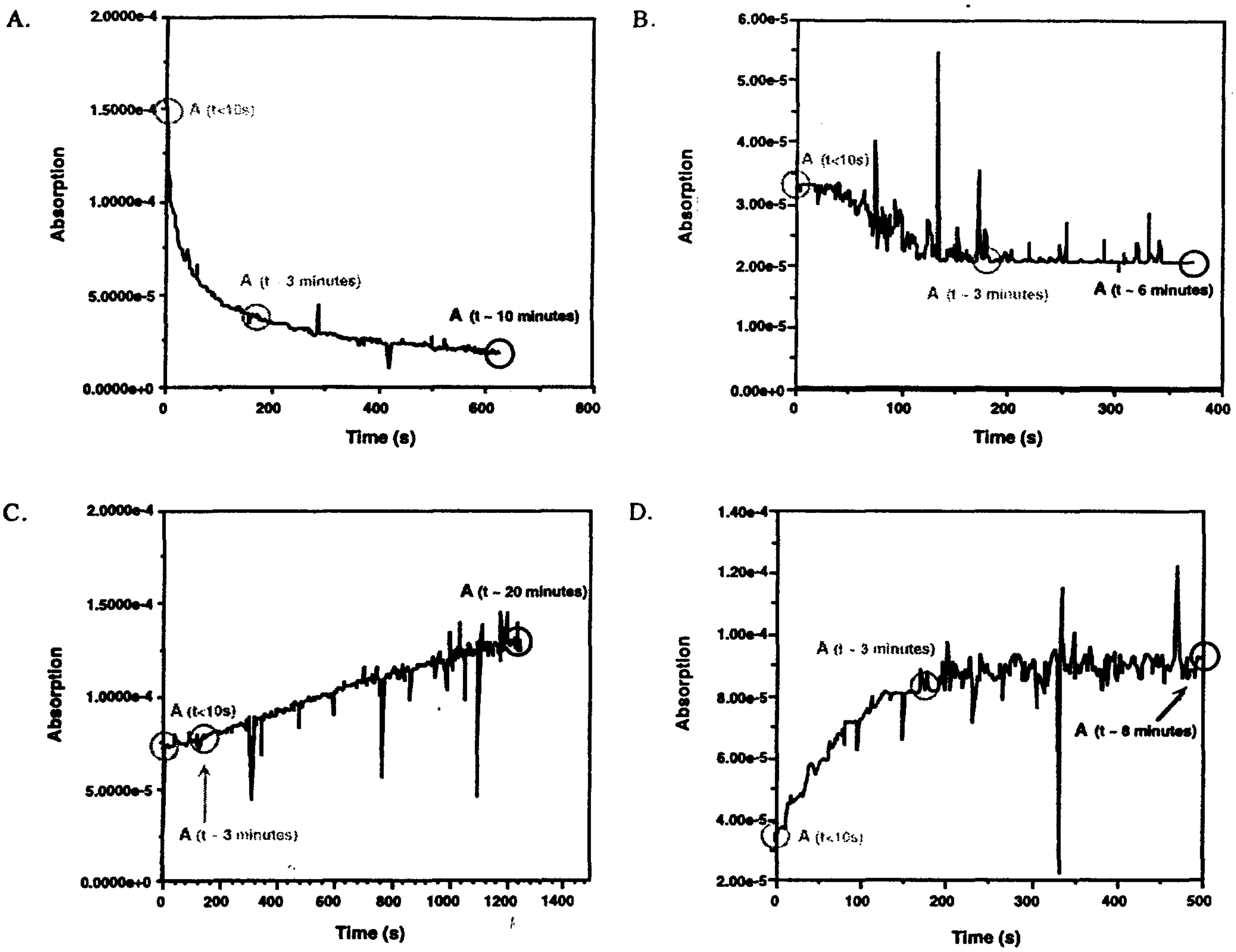


Figure 6 High reflector coatings show time-dependent absorptance behavior. Case A shows a monotonic decrease with time, which occurred in the majority of samples; Case B shows a step decrease in absorptance; Case C shows absorptance linearly increasing; and Case D show absorptance increasing to a stable value. The time trends appear to well-established by 3 minutes of exposure to the laser beam.

HUMIDITY EFFECTS ON FLATNESS

Many of the AVLIS optical components are used in environments that are different than that in which they are made. A major environmental performance driver is the ambient humidity during the operation of the optical part. The performance testing of coated optics is designed to take this and other environmental factors into account. The AVLIS test lab has chambers in which the spectral and wavefront characteristics of the parts can be measured in a controlled humidity or vacuum condition.[10] Some wavefront measurements will be reported here on large aspect ratio optics to be used in an environment of < 2% relative humidity.

One of the AVLIS components has an aspect ratio > 4x larger than that of regular AVLIS substrates, 22.5 and 5. According to the Stoney stress equation,[11] the stress depends on the square of the aspect ratio,

$$\sigma = \frac{E_S\,\delta}{3(1-\nu)t_f}\left(\frac{t}{l}\right)^2, \qquad \text{eqn. [1]}$$

where E_S is the substrate's Young's Modulus, δ is the deflection (R/WF), ν = Poisson's ratio of the substrate, t_f = is the film thickness, t/l is the thickness to length aspect ratio of the substrate. Since the sensitivity to stress depends on the square of the aspect ratio, the thin parts are 21x more sensitive to stress variations than the standard parts. This stress-sensitivity makes it imperative that the parts are tested in its operational environment to verify flatness.

A vacuum tank was modified to test thin components at specified relative humidities. The relative humidity is controlled by a mixture of potash and water contained in a petri dish at the bottom of the tank. The optical component sits in the close chamber and allowed to equilibrate at a certain relative humidity. A moisture sensor is connected to a hygrometer display that indicates relative humidities less than 0.1%. Phase interferometry of the part are taken at various humidity conditions through the tank window.

Figure 7 is a graph of flatness (R/WF) vs. relative humidity for thin parts that were coated with a mirror using two different deposition processes. The shaded area in the graph indicates the acceptable flatness region of < 1.0 wave, peak-to-valley. Although there are thin parts that are designed for either a relative humidity < 2% or at 45±5%, the data in Figure 7 are from the parts designed to be used at the dry condition. The two coating suppliers employed different methods to flatten the as-coated parts. The coating supplier that uses the reactive e-beam deposition process stress relieves the parts thermally. Part #1 data shows the flatness before annealing (open diamonds) and after annealing (filled diamonds). Part #3 data (filled triangles) shows how an e-beam deposited coating flattens as it drys out. Another part (crosses) had the mirror deposited by ion beam sputtering and its backside coated for stress compensation. This mirror met flatness requirements from dry to room to high humidity conditions.

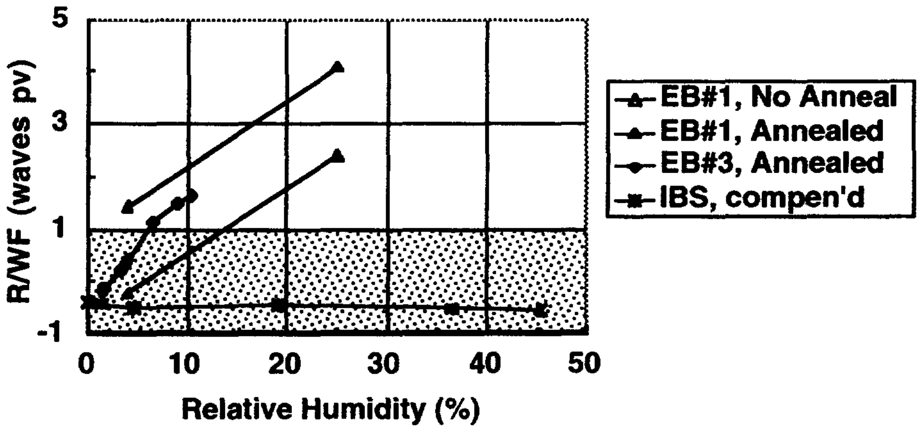


Figure 7 Large aspect ratio parts made by two different coating processes can be flattened to operate under low relative humidity conditions.

Figure 8 shows graphically the type of deformation the thin substrates undergo through the coating and flattening process. The top row are the 3-D surface images of the parts that had the e-beam deposition process and thermal annealing. The final part looks similar to the uncoated substrate in magnitude and sign of curvature. The bottom row are the images from the part that had the ion beam sputtered process and backside compensation. It meets flatness specifications but the final shape shows no relation to the uncoated substrates.

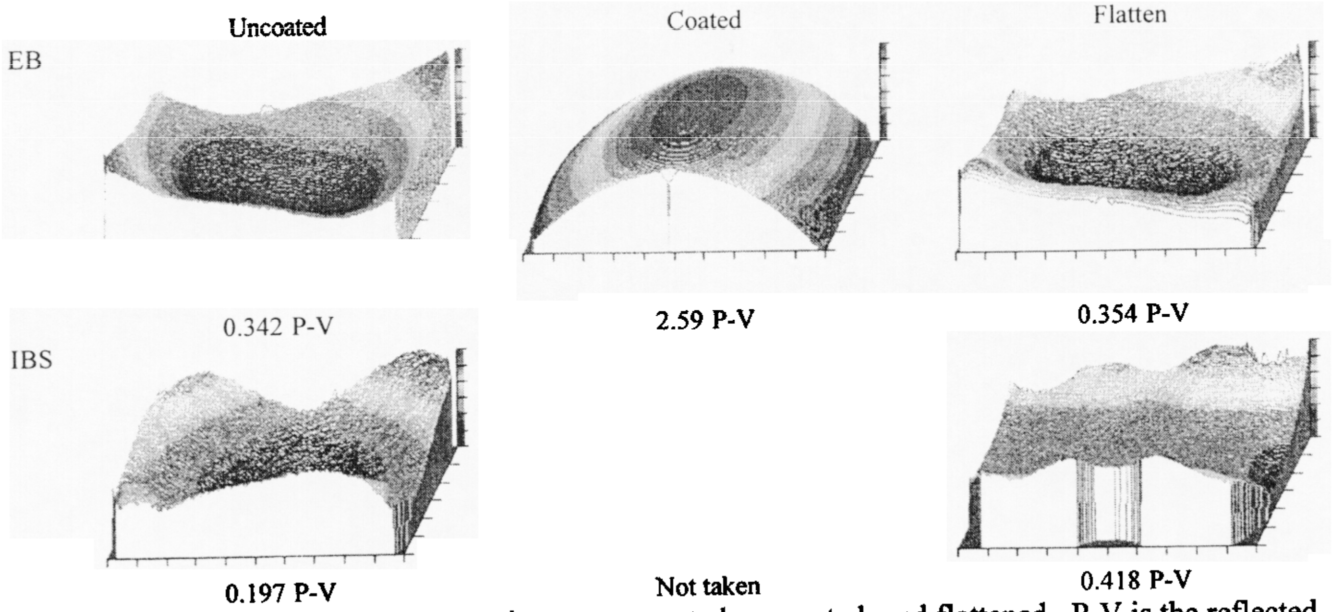


Figure 8 Shapes of the large aspect ratio parts uncoated, as-coated, and flattened. P-V is the reflected wavefront at 633 nm, peak-to-valley.

SUMMARY

Testing of optical components for the AVLIS plant will be an integral part of supplier qualification, manufacturing, and final acceptance. The strategy is to weed out defective parts as soon as possible from the manufacturing process, thereby assuring a steady stream of high performance optical components into the AVLIS plant for installation. Special test fixtures and equipment are made to test optical performance under conditions representative of the operating environment.

AUSPICES

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Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551