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Multilayered Polymer Mirror Experiment

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An experiment was conducted to determine the surface quality of two small polymeric mirrors. The mirrors were manufactured by pouring uncured liquid resin onto thick aluminum substrates and allowing the resin to cure. The substrates were flat except for an intentionally machined depression of known depth. The objective was to quantify the effects of a substrate topography flaw on the surface quality of the free face of a cured polymer material. It was proposed that the effects of such a flaw would be reduced on application of successive layers of polymer resin. To test this effect, a second layer of resin was poured onto the first layer of cured resin on both mirrors. Cured polymer surface topography for each layer was quantified using a phase-shifting Twyman–Green interferometer. The first layers of resin showed a depression exactly mimicking the underlying substrate topography flaw. The average depth of the polymer resin topography flaw for both mirrors was 0.4% of the original substrate topography flaw depth. The second layer of resin resulted in a polymer surface that had essentially no surface flaws consistent with the substrate topography flaw. Final mirror surface quality was, on average, 0.36-μm peak-to-valley (0.05-μm rms).

Nomenclature

h = flaw height/depth
n = number of layers
X = polymer shrinkage effect
λ = wavelength (for this work, 632.8 nm)

Introduction

SPINNING a contained liquid in a static gravity environment produces a parabolic surface. This concept has been known for centuries: It was first exploited early in the 20th century by Wood[1] and later in the 20th century by a number of researchers.[2–5] These researchers produced parabolic mirrors using mercury as a liquid reflective agent. In the early 1990s, Alvarez et al.[6] used a polymer resin to spin-cast a 1.75-m-diam infrared telescope mirror. The resulting mirror had a surface accuracy of 25-μm rms, adequate for the desired application. The U.S. Air Force Research Laboratory, Materials and Manufacturing Directorate (AFLR/ML), has also been pursuing this concept by using a liquid polymer as the mirror surface. Spinning the polymer produces a parabolic surface regardless of the underlying material surface geometry. In concept, the parabolic surface of the polymer resin will be retained after resin cure. A reflective coating could be applied to the now solid resin surface, yielding the desired parabolic reflector.

Initial efforts at AFRL/ML for producing a parabolic mirror used a foam core composite sandwich structure as the solid surface that contained the polymer resin. The concept called for the cured resin mirror to remain in place on the composite core, which produced the final rigid mirror surface. In future versions, a very lightweight composite structure having a very high specific stiffness and low coefficient of thermal expansion could be employed. Previous to the current effort, two 200-mm-diam foam core composite parabolic mirrors were produced. Both were made from construction-grade polystyrene foam and scrap fiberglass. Two two-part resin systems were examined: a room temperature cure silicone rubber and a room temperature cure epoxy. The total cost of the two mirrors was less than $100. When completed, both systems had substantially parabolic surface figures. However, both contained higher-order surface flaws. It was believed that three factors led to these local flaws. These factors, in increasing order of assumed severity, were resin cure shrinkage, improper resin mixing, and premature resin gellation.

Experimental Procedure and Rationale

A simple resin flow settling experiment was conducted to examine the cure shrinkage and resin mixing problems in increased detail. The experiment involved pouring an uncured resin onto a flat aluminum plate with raised walls to contain the resin. The resin was then allowed to cure. To examine how the liquid resin and the subsequently cured resin would behave with subsurface flaws, a depression was machined into the surface of the aluminum substrate before the resin was poured. This subsurface flaw was intended to simulate machining errors in the mirror substructure. A schematic of the aluminum plate is shown in Fig. 1. The plate was 12.7 mm thick, and the depression width was 9.5 mm. The plate surface was sanded approximately flat using 400-grit sandpaper. The depression was machined using a standard size endmill. The depth was determined with a depth micrometer.

Two flat aluminum mirror substrates were manufactured for this experiment with topography flaws machined into the substrates to a depth of 180 μm for the first mirror and 250 μm for the second mirror. Then a layer of General Electric RTV-615 silicone rubber resin was poured into each mirror. This polymer is a two-part resin that is known for its extremely low linear cure shrinkage (0.2%, as claimed in the product literature). The resin was mixed in a test tube with a spatula and entrained bubbles removed by centrifuging the mixed resin. Each layer was approximately 1.2 mm thick as determined by the volume of resin poured onto each mirror. After the polymer had cured, a phase-shifting Twyman–Green interferometer was used to quantify the topography of each polymer mirror surface. A second layer of silicone rubber was then poured onto each mirror; on cure, each mirror was again tested in the Twyman–Green interferometer.

The Twyman–Green interferometer used in this research borrowed a collimated beam of laser light from another apparatus. The resulting beam size was limited to an oval slightly larger than 40 by 30 mm. A $\lambda/10$ ($\lambda = 632.8$ nm) reference flat was first tested in the apparatus. The resulting topography showed that the reference system produced a wave front that was flat to 0.21λ peak-to-valley (0.038λ rms).

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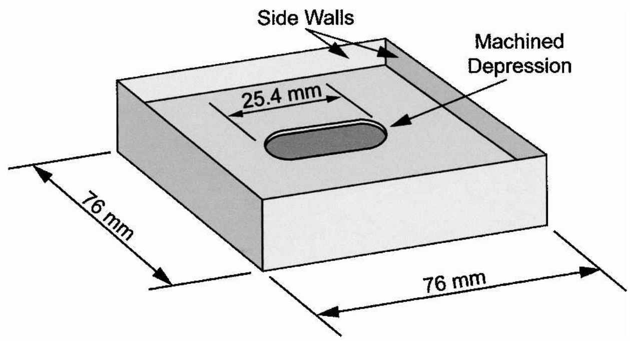

Fig. 1 Schematic of the aluminum plate used as a substrate for the resin mirror experiment.

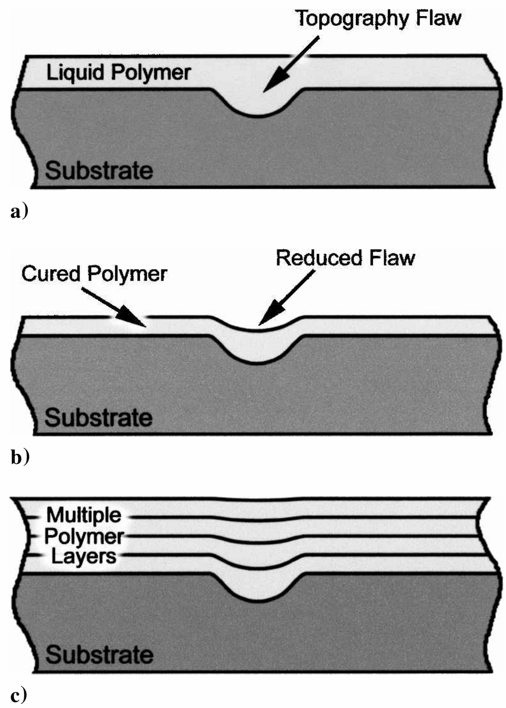

Fig. 2 Schematic of the multiple resin layer concept: a) liquid layer poured onto a substrate with a topography flaw, b) one cured polymer layer with significant surface flaw on cured resin surface, and c) multiple resin layers with greatly reduced surface flaw.

The rationale for pouring more than one layer of resin is as follows. The subsurface flaw will "print" through to the surface of the resin because of polymer shrinkage during cure. The newly created resin surface will have topography flaws that mimic the substrate topography flaws. However, it was assumed that the depth of the resin surface flaws would be reduced compared with the substrate flaws. This assumption was based on the fact that the resin used in this experiment exhibited very low linear cure shrinkage. A second layer of resin poured over the newly created polymer surface should further reduce the topography flaws. In concept, as many layers as required could be poured in succession to eliminate the original subsurface topography flaws. This concept is schematically represented in Fig. 2.

Polymer Mirror Results

Fringe pattern results produced from the digital Twyman–Green data from the first layer of the first mirror are shown in Fig. 3. The elevation data from the reference system have been subtracted from this and all subsequent Twyman–Green data. Extensive deformation is visible in a pattern mimicking the depression. Random large-scale deformation is also visible outside the region of the depression. It is suspected that poor mixing caused this result outside the depression region. The elevation of the region within the borders of the depression is, on average, 0.73 μm lower than on the flat specimen face. The expected effects of resin shrinkage are in agreement with these results. The surface of the first resin layer of the first mirror was flat to 2.90λ peak-to-valley (0.45λ rms).

Figure 4 shows the fringe pattern results from the first resin layer of the second mirror. The resin for this layer of material was very thoroughly mixed. Extensive deformation is shown in a border region exactly mimicking the underlying depression but not anywhere else on the mirror surface. The topography flaw depth for this mirror was, on average, 0.98 μm. The surface of the second mirror was flat to 1.56λ peak-to-valley (0.50λ rms). Careful mixing of the resin produced greatly improved uniformity of cure.

Figures 5 and 6 contain the fringe pattern results from the second resin layer of the first and second mirror surfaces, respectively. In both cases, special care was again taken to mix the resin thoroughly. A vast improvement in surface flatness is immediately visible. Very little evidence of the depression appears in these results. These mirror surfaces were flat to 0.45λ peak-to-valley (0.054λ rms) and 0.27λ peak-to-valley (0.045λ rms), respectively.

Discussion

Multilayer polymer mirrors significantly reduce the magnitude of substrate topography flaws. In the current research, one layer of polymer poured over an aluminum plate with a 180-μm topography flaw produced a mirror surface with an average 0.73-μm flaw

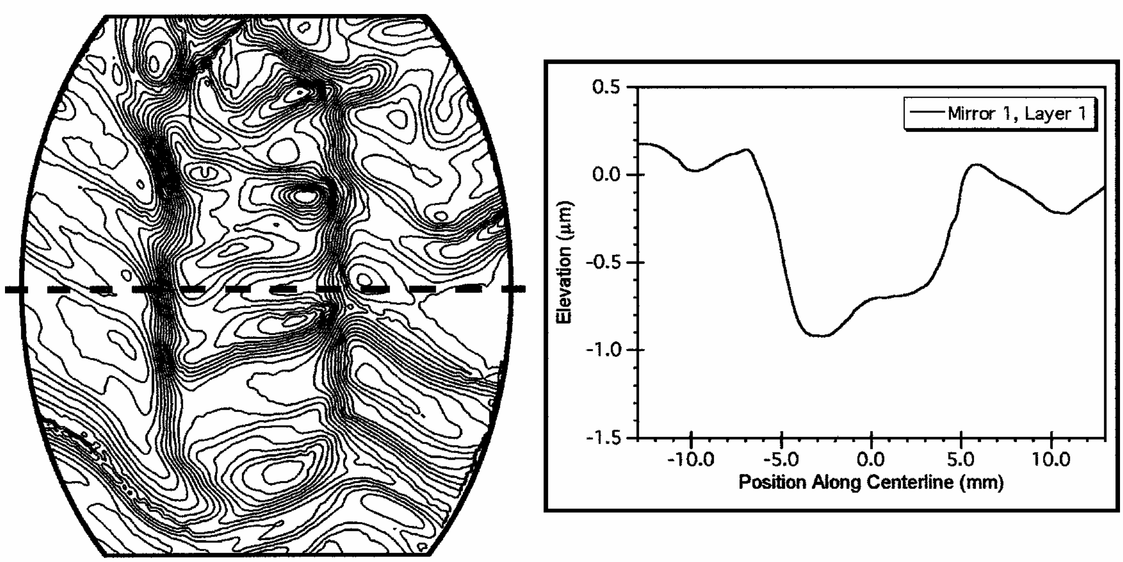

Fig. 3 Digitally produced fringe pattern results from the first resin layer of the first mirror; contour interval is λ/10.

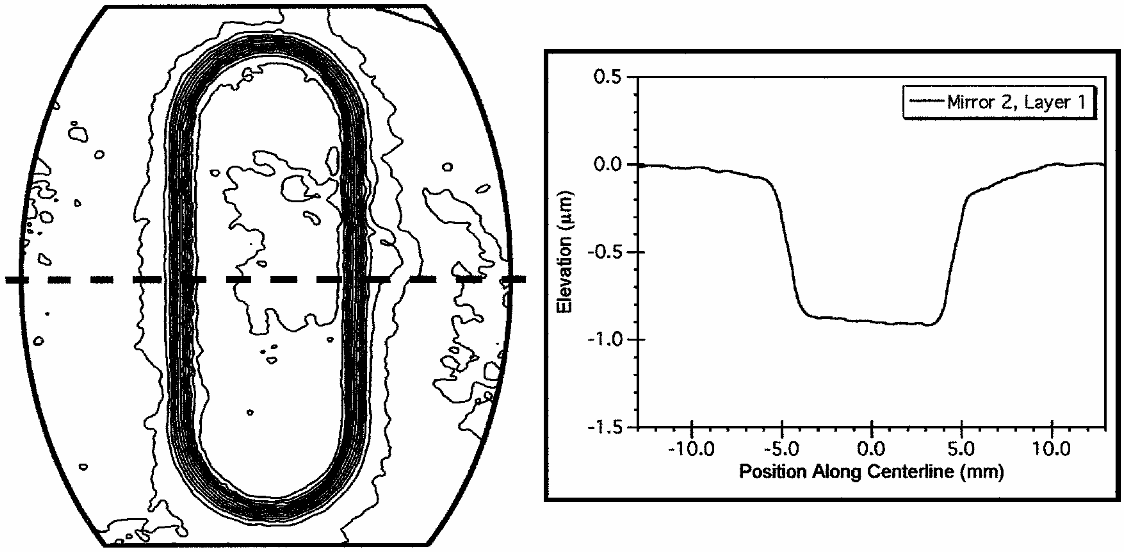

Fig. 4 Digitally produced fringe pattern results from the first resin layer of the second mirror; contour interval is $\lambda/10$.

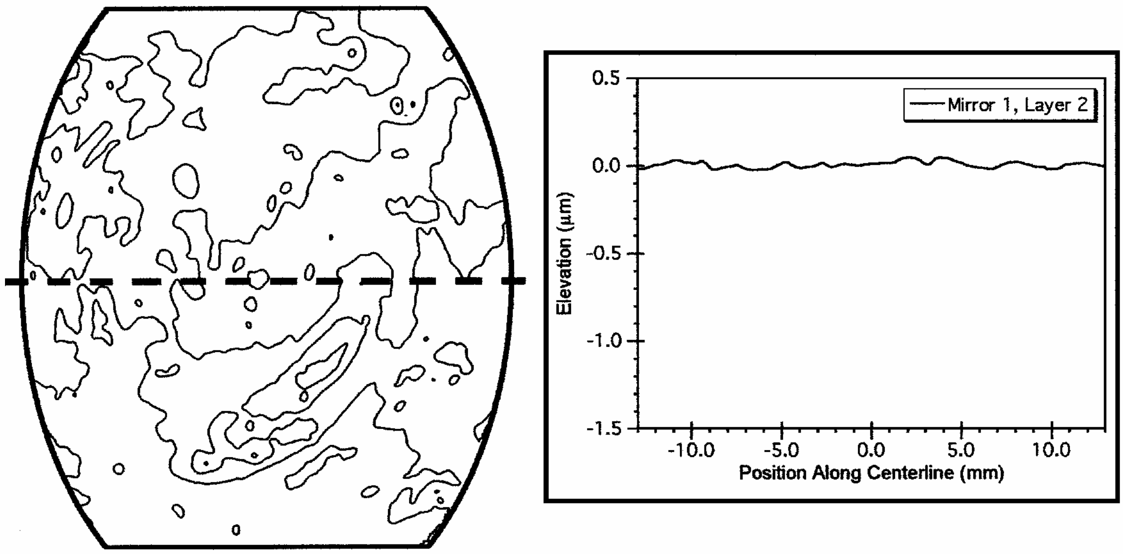

Fig. 5 Digitally produced fringe pattern results from the second resin layer of the first mirror; contour interval is $\lambda/10$.

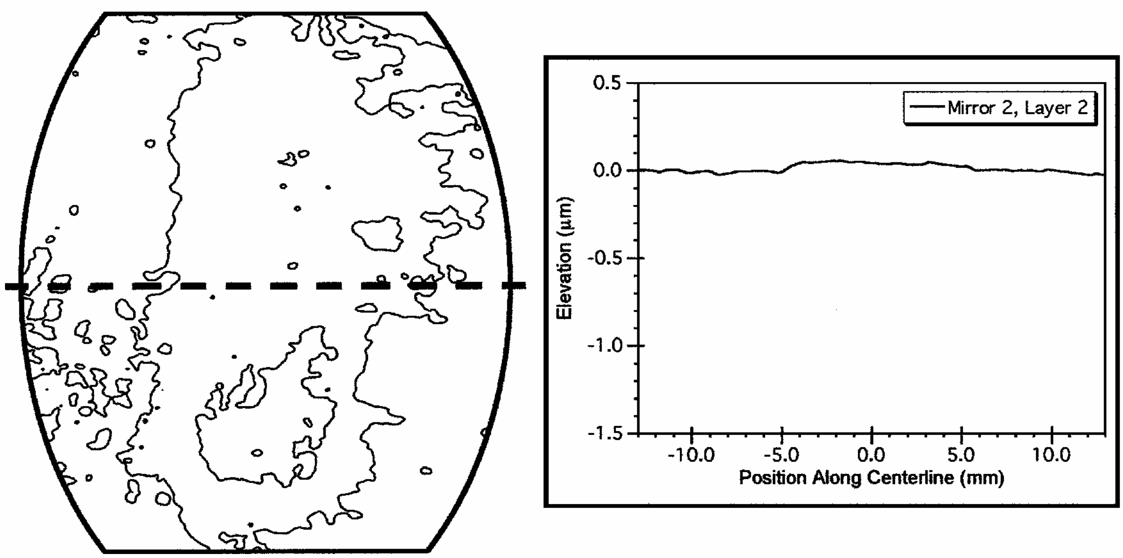

Fig. 6 Digitally produced fringe pattern results from the second resin layer of the second mirror; contour interval is $\lambda/10$.

depth. The first resin layer poured onto the substrate with the 250-μm topography flaw produced a mirror surface with a 0.98-μm topography flaw. The average reduction in flaw elevation was approximately 99.6%. A second resin layer should have reduced this further by another 99.6%. In fact, the experimentally measured second layers showed very little evidence of the substrate topography flaw. Multilayering is, in effect, a way of reducing an original flaw of elevation h to $h \times (1 - X)^n$, where X is a number associated with the particular polymer cure shrinkage. ($X = 0.996$ for General Electric RTV-615 silicone rubber as obtained from the two experimental mirrors.)

The findings in this research project are extremely encouraging. The possibility that the techniques can be scaled to produce mirrors of larger size is being examined. Other resin systems are also being examined.

Ultimately, the spin-cast method may not produce surface quality fully acceptable for optical imaging or beam control applications. If this is the case, the resulting surface figure may be close enough to require only slight polishing to produce the final finish, thus greatly reducing the overall cost of the mirror system. The multilayer polymer mirror manufacturing method, however, does not solve the myriad issues surrounding polymer dimensional stability with varying temperature, age, and moisture content. All of these effects will tend to print through subsurface topography flaws and must be resolved before this method can be effectively used to reduce the cost of large aperature mirror systems.

Conclusions

A multilayered polymer mirror manufacturing method was developed and demonstrated. Two mirrors were manufactured by flow-casting liquid polymer layers onto a rigid substrate with purposely introduced topography flaws. The cured polymer formed a specular surface that contained a printed-through version of the rigid substrate topography flaw. The depth of the polymer surface topography flaw was substantially smaller than the original subsurface flaw. The two mirrors showed an average 99.6% reduction in flaw depth after the first polymer layer had cured. The second layer of resin resulted in a polymer surface that had essentially no surface flaws consistent with the substrate topography flaw. Final mirror surface quality was, on average, 0.36-μm peak-to-valley (0.05-μm rms), thus, demonstrating the potential of the multi-layered mirror manufacturing method.

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