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The effects of epoxy shrinkage on the Advanced X-ray Astrophysics Facility Technology Mirror Assembly

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Abstract

A method is shown analytically which reduces the effects of epoxy shrinkage for an ultra-high precision X-ray telescope to within the system error budget. The three-dimensional shrinkage effects are discussed with reference to this telescope. The results of the analysis point to the use of an interrupted rather than continuous bond line as the best solution. Discussion of the finite element modelling techniques is included.

Introduction

The Advanced X-ray Astrophysics Facility (AXAF), shown in Figure 1, is designed to be a second-generation follow-on to the highly successful High Energy Astronomy Observatory - 2 (HEAO-2). The X-ray peformance goals for the AXAF High Resolution Mirror Assembly (HRMA), shown in Figure 2, are about an order of magnitude better than for the HEAO-2 HRMA, as measured by percent encircled energy and the full-width half-maximum of the point spread function. In order to demonstrate that the mirrors can be fabricated to the AXAF surface finish and figure tolerances, NASA has let two Technology Mirror Assembly (TMA) contracts. These contracts, managed by the Marshall Space Flight Center and the Smithsonian Astrophysical Observatory, were awarded to the Itek Corporation and the Perkin-Elmer Corporation. To obtain the superior on-orbit performance, not only must the mirror have an excellent surface finish and figure but the mirror structural supporting system must be highly insensitive to environmental and assembly effects. A scaled-down version of one possible flight HRMA design[1] is shown in Figure 3. This structural support system will be used to support the finished TMA optics. Each of the Wolter I optics of the TMA is held near its center of mass by a single ring. This ring is bonded inside a thin, flexible graphite-epoxy mirror support cylinder. It is the effects of the epoxy bonds at this interface (mirror/ring/cylinder), shown in Figure 4, with which this paper is concerned.

Design Requirements

The TMA was designed to meet the following eight requirements:

1. Error budget.
2. Low cost.
3. Extendable to a multielement system.
4. Adaptable to various mirror outside diameters.
5. 90% clear aperture.
6. Utilize proven HEAO-2 techniques.
7. Inclusion of environmental sensors.
8. Low component stresses.

The error budget (in terms of the maximum contribution to the RMS diameter of blurred image) for the design of the TMA is given below.

<u>Environmental</u>	
<u>Thermal</u>	
Soak	0.15 seconds of arc
Gradient	0.10
<u>Assembly</u>	
Vertical	0.10
Epoxy Shrinkage	0.14
<u>Material Instability</u>	
Mirror CTE	0.10
Graphite-Epoxy	0.15

Design

The overall matching of the thermal and physical properties of the mirror cell (Zerodur mirror, Super Invar ring, and graphite-epoxy support cylinder) determine the system's insensitivity to the thermal cases above. That is, the better we can match the coefficient of expansion and stiffness of the materials to one another, the less the thermal effects. The system's insensitivity to vertical assembly (in a 1 g field parallel to the TMA's optical axis) is due to the axial stiffness of the mirrors themselves and the proposed method of assembly. The material instabilities are not currently well enough known to be able to quantitatively describe in detail their effects on the system.

It must be pointed out that if the mirror were to be deformed radially by ~1.0 μin (at its L/2 point), the effect on the mirror resolution would not be negligible (~0.4 sec of arc). Therefore, effects of order 1.0 μin cannot be tolerated. Simple calculations had shown that the shrinkage effect could be of this order. It is for this reason that the epoxy shrinkage study was undertaken.

The effect of the shrinkage of the epoxy joints between the mirror, ring, and cylinder is dependent upon the following:

1. Type of epoxy
    a. Stiffness.
    b. % shrinkage
        1) during curing.
        2) after hardening.
2. Thickness of the epoxy joint.
3. Length (parallel to the optical axis) of the epoxy joint.
4. Method of assembly.

Only room temperature curing epoxies were considered because of the possibility of built-in thermal deformations if other than room-temperature cure was used. Two epoxies for which data is available are Eccobond 55 and Hysol 9313 (filled with quartz particles). Each of these adhesives exhibited total linear shrinkages of ~0.07%. These adhesives are quite stiff compared to other commonly-used systems (Young's Modulus E of ~ 700 ksi vs ~ 300 ksi).

The method of determining the effect of the epoxy shrinkage was to equate the shrinkage to an equivalent thermal strain. From this strain one could calculate (knowing the CTE of the material) an eqivalent ΔT to be imposed on the system.

$$-0.07\%/100 = -0.0007 = \alpha \Delta T$$

$$\alpha \sim 29 \times 10^{-6} \text{ ppm/°F}$$

$$\Delta T \sim -24°F$$

Therefore, the effect of the 0.07% linear shrinkage may be approximated by cooling the epoxy by ~24°F. This ΔT could then be applied to the mirror system structural model (with all other CTE's set to 0) and then optically ray-traced to determine the resolution degradation. This ΔT was to be applied to both inner and outer epoxy joints because of the assembly sequence as originally conceived.

Analysis of the Design

An axisymmetric finite element model of the mirror cell was generated using the ANSYS code. The full mirror cell model was comprised of ~2000 ANSYS STIF 42 elements. The epoxy joint elements had aspect ratios of ~13. This large aspect ratio was shown through test problems to yield results with errors (principal displacements and stresses) less than 10%. The test problems were chosen so as to exercise the elements in a manner similar to that in which they would be used in the mirror cell analysis.

Both inner and outer epoxy bonds (0.005 inches thick) were cooled by 24°F with respect to ambient, stress-free conditions. The resulting mirror surface deformations caused the image to be blurred ~0.4 seconds of arc. This value was ~3 times the allocated error budget of 0.14. It was obvious that one should be able to reduce the 0.4 value by ~2 if one could assemble the mirror cell so as not to compound the inner and outer shrinkage problems. It was determined that the cell could be assembled from outside in (versus from inside out, as originally baselined) to reduce the shrinkage problem by ~2. Still, a 0.2 seconds of arc blurring could not be tolerated.

It was stated earlier that the epoxy bond stiffness, thickness, and length affect the shrinkage. The adhesive stiffness (as measured by E) is fixed because the candidate epoxies have been chosen (and so is the percent of filling in the case of the Hysol). The width of the adhesive joint, originally baselined as 0.005 in, could be reduced by no more than 0.002 in. This reduction of 0.002 was limited by the roundness tolerance on the physical parts, the viscosity of the adhesive, and to some extent by the increase in stress in the epoxy bond (when exposed to a change in temperature and "g" loads).

Therefore, a study was performed to show the individual hoop, through-thickness (radial), and axial shrinkage effects. Possibly by canceling certain effects (through geometry changes) could the overall shrinkage problem be reduced.

The three-dimensional effects of shrinkage

Hoop

The hoop shrinkage ($R\alpha\Delta T$ type of effect) of the inner bond is resisted by the hoop stiffness of the mirror element, connecting ring, and support cylinder. The distortion of the mirror is directly proportional to the hoop stiffness of the adhesive. If the epoxy were less stiff in the hoop direction, the mirror would be deformed less. The hoop stiffness cannot be reduced beyond that obtainable through reduction of the bond hoop area (width x length). This value, as stated previously, will not be less than 0.003 in². However, the other component of stiffness (E_{hoop}) can be effectively reduced by removing material, as shown in Figure 5. This type of interrupted bond will produce a hoop stiffness directly proportional to the percent of adhesive not removed. This effect had to be shown to work analytially because the first intuition is to say that with an interrupted bond there is no hoop stiffness. The "true" hoop stiffness is reduced. However, for each patch of epoxy that remains, shrinkage contraction (in all dimensions) still occurs.

To prove the above, a detailed plane stress model was made. This unit thickness model was comprised of the mirror, two adhesive bonds, ring, and the cylinder. A 3.25 degree circular segment model containing ~700 ANSYS STIF 42 plane stress elements was made. The maximum aspect ratio used for this case was ~4. The ~100 elements of the inner bond were reduced (deleted) 33% at a time such that circumferential gaps were created (Figure 6). The loading condition was the same as previously mentioned (ΔT = -24 °F in the bond). The effect of element removal was measured by the radial displacement of the inner radius of the mirror. Figure 7 shows the linear effect of element removal. One can also see that at some point the radial displacement is ~0. (This will be discussed in detail later.)

The mirror cell model, as stated, is an axisymmetric solid model. The material properties of that type of model may be orthotropic (in general). However, one cannot easily model an interrupted bond using axisymmetric geometry. Therefore, to approximate the true geometry, the orthotropic Young's moduli were adjusted so as to yield approximately the same results as the true three-dimensional case. This method had to be shown to work. The three-dimensional plane stress model used to previously show the initial effect of the interrupted bond was also used to prove that the above method worked. For the case of 50% interruption, the Young's modulus used in the analysis would be reduced by half and no elements in the area of the adhesive bond would be deleted. The mirror radial displacement at the inner radius for either the true interrupted geometry or the approximated geometry were within a few percent. Therefore the reduction in hoop stiffness of the adhesive could be utilized in the axisymmetric model.

Through-thickness

The stiffness of the bond in the through-thickness direction is large (almost incompressible) compared to the hoop stiffness (AE/R type stiffness) of any of the other components. The bond will shrink in the thickness direction by an amount δ_T. Because of the bond's stiffness, the mirror (on one side) and the ring/cylinder combination (on the other side) will be drawn towards one another by an amount $\sim\delta_T$. The mirror, being stiffer than the ring/cylinder, will be deformed radially outward less than the ring/cylinder will be deformed radially inward. The magnitude of δ_T is almost constant regardless of the percent of bond interruption unless there is very little bond remaining and large spaces separate each segment.

Combined hoop and through-thickness effects

The combined hoop and through-thickness effect is, to first order, the summation of the constant δ_T value and the δ_H hoop value, which is percent epoxy fill dependent. Figure 7 shows the linearity of the interrupted bond effect on the mirror. The figure shows the ($\delta_T - \delta_H$) combined effect of subtracting a linear variable (percent of bond) from a constant (through-thickness). Therefore, for a plane stress type of problem, such as a planar mirror inside a bezel, one could conceivably obtain zero mirror distortion using the correct combination of geometries.

Axial effect

During the axial contraction of the bond, as shown in Figure 8, interface forces (shears) are set up at the mirror/bond and bond/ring interfaces. Because the force at the inner interface does not coincide with centerline of the mirror, a bending moment is introduced which causes the mirror to deform as shown in Figure 9. This type of deformation can only be reduced by reducing the bond's thickness, which reduces the total force applied to the mirror, or by reducing the bond's length, which has a similar effect. The above effect became the most troublesome to eliminate completely. In fact, it could not realistically be removed.

Overall three-dimensional effects

It was not clear initially whether reducing the hoop and through-thickness effects to zero and allowing the axial effect to dominate or to allow some small non-zero combination of hoop and through-thickness and a non-zero axial effect would result in less total mirror distortion. Figure 10 shows two cases. Case A is where the hoop and through-thickness effects resulted in the mirror radial displacement of zero at its L/2 position. The second, Case B, is where the percent of interruption is 60% (that is, 40% filled). Case B resulted in a smaller error ~0.10 (RMS diameter) than Case A and was less than the required component of the TMA error budget value of 0.14. Figure 11 shows the shrinkage resolution error as a function of the epoxy fill percentage. Hand calculations (interaction type equations) as well as computer solutions are plotted for various percentages. This curve shows that at approximately 30% fill we have a minimum value, and that we could meet the 0.14 error budget with a fill value as high as ~50%.

Discussion

One major assumption that was originally made was the 0.07% shrinkage value. Tests were performed for the HEAO-2 program to determine the shrinkage values. These tests also yielded the 0.07% value. However, what is of importance is not the ultimate shrinkage value but the time integral of the shrinkage/stiffness product. To obtain this product, we will be performing an equivalent shrinkage test utilizing thin glass plates and one of the candidate epoxies. It is quite possible that the ultimate effect of shrinkage may be ~2 times less than the 0.07% value. This is because that as the shrinkage is taking place (during the cure cycle) E has not yet attained its full value. If E linearly increased with cure, the average shrinkage/stiffness product would be a factor of 2 less than the 0.10 derived value.

During the assembly of the TMA, strain gauges will have been placed on the mirror surface for later use (environmental testing). These gauges could then be used as a crude check on the strain induced in the mirror during epoxy curing. A strain indicator with a resolution of 1 microstrain would be used. (There is a question of whether the indicator is temporally stable to <1 microstrain during the cure cycle). Additionally, optical methods could be used to give a more accurate measure of the mirror distortion during epoxy cure.

Summary

A method has been shown which analytically reduces to within tolerances the shrinkage effects of epoxy during its cure cycle. Verification of the overall analytical method was shown on a step-by-step basis as required. The actual effect of the epoxy shrinkage is now under study, utilizing materials similar to those that will be used for the TMA itself. The TMA will be instrumented so that at least a crude measure of the in situ shrinkage effects can be measured. More precise measuring devices can also be used to accurately quantify the shrinkage effects.

Acknowledgments

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References

1. Cohen, L. M., "A Conceptual Support Design of the High Resolution Mirror Assembly for the Advanced X-ray Astrophysics Facility (AXAF)," Proceedings of the SPIE, Vol. 330-07, pp. 49-59. 1982.

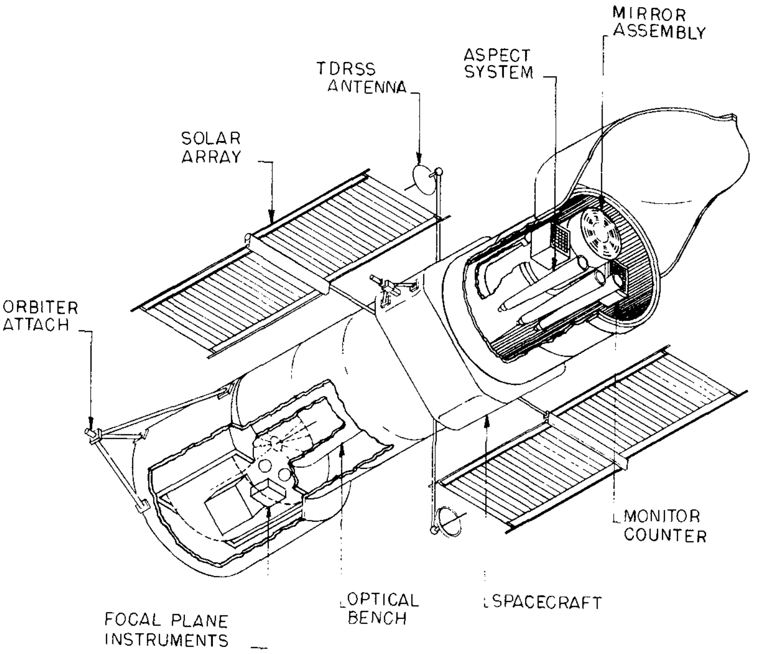


FIGURE 1
ADVANCED X-RAY ASTROPHYSICS FACILITY

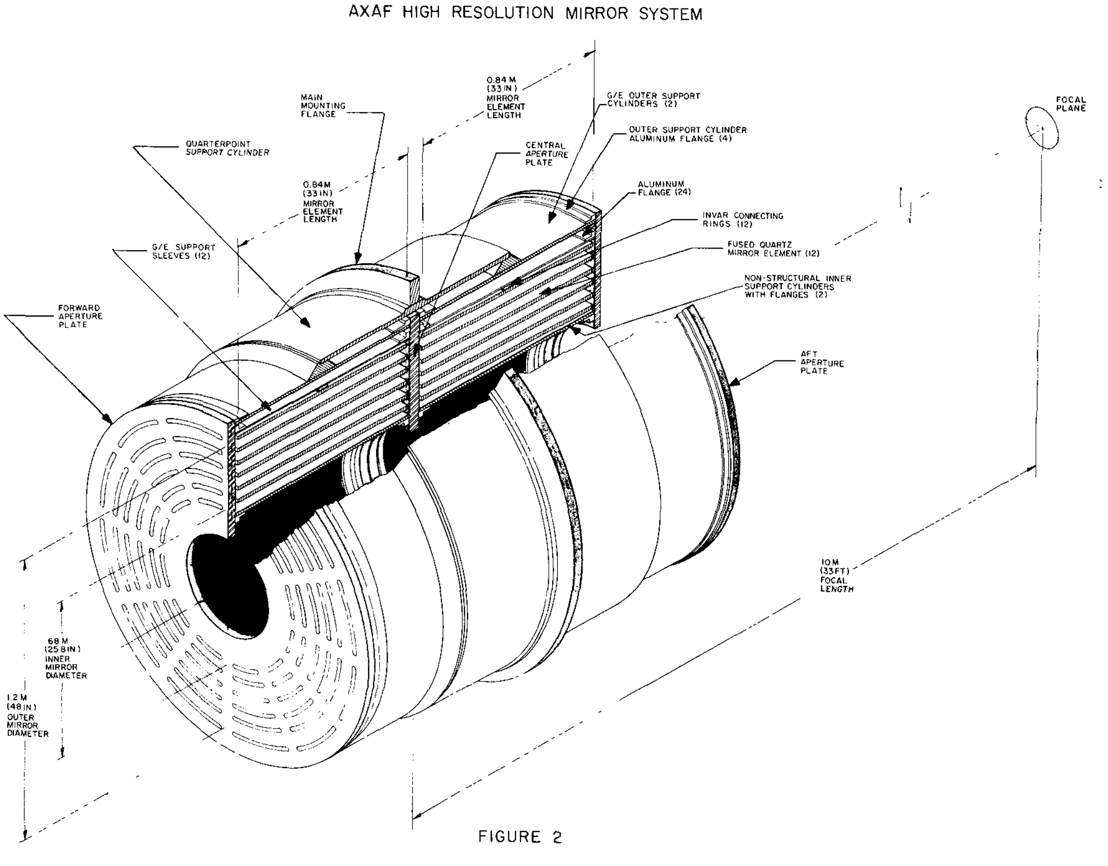


FIGURE 2

TMA "SINGLE RING" STRUCTURE

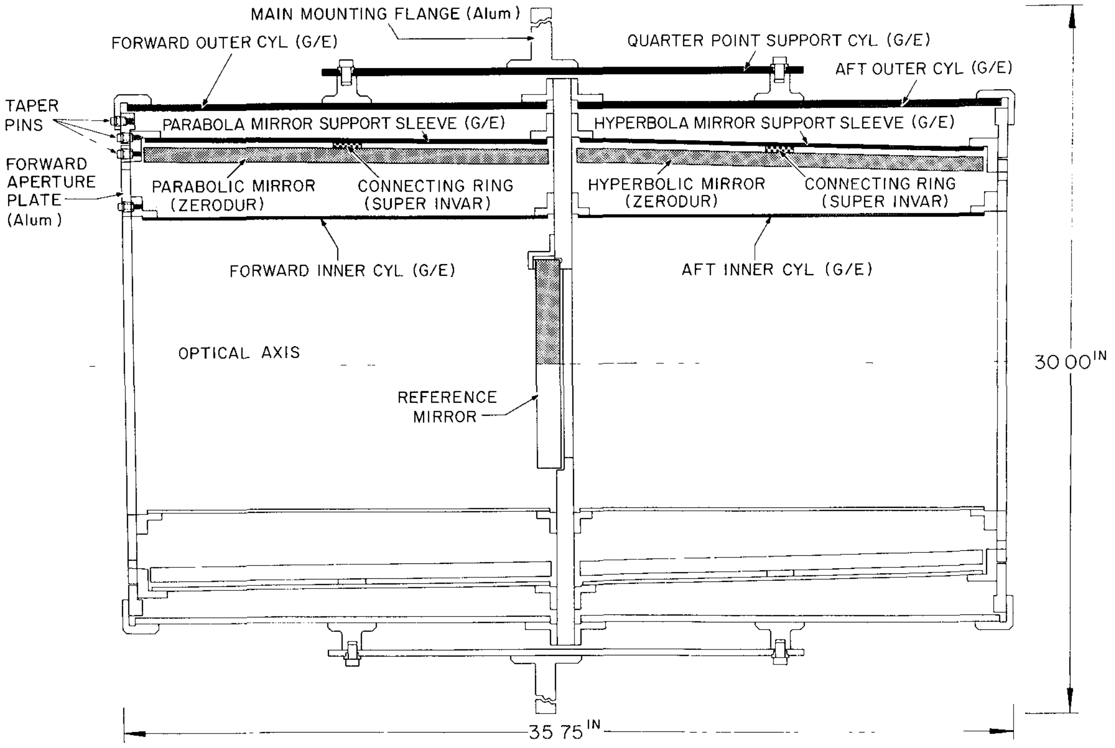


FIGURE 3

TMA MIRROR CELL

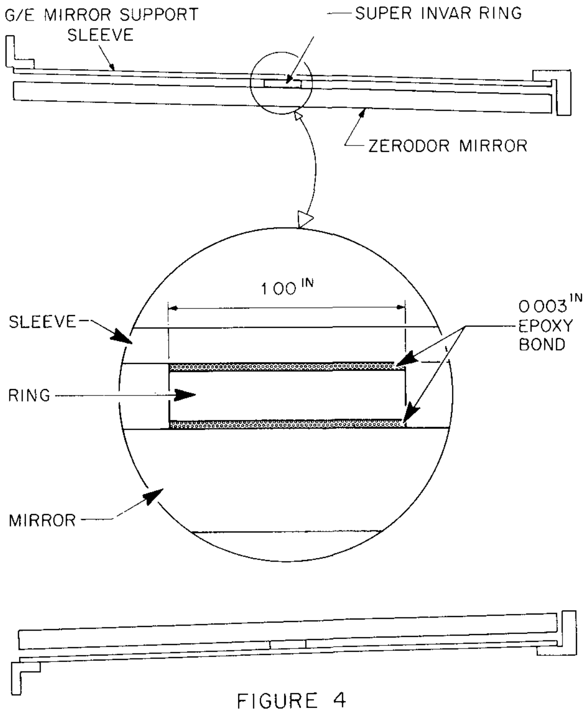


FIGURE 4

INTERRUPTED BOND DETAIL

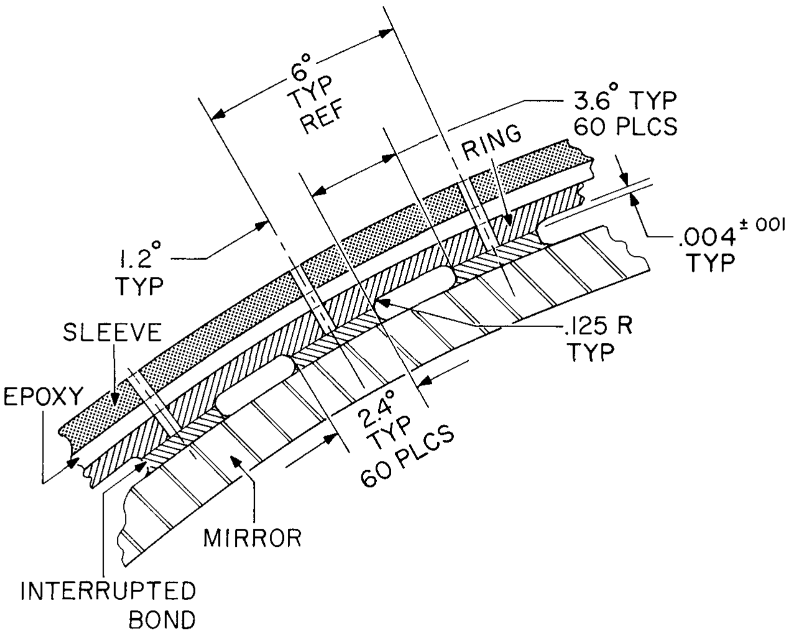
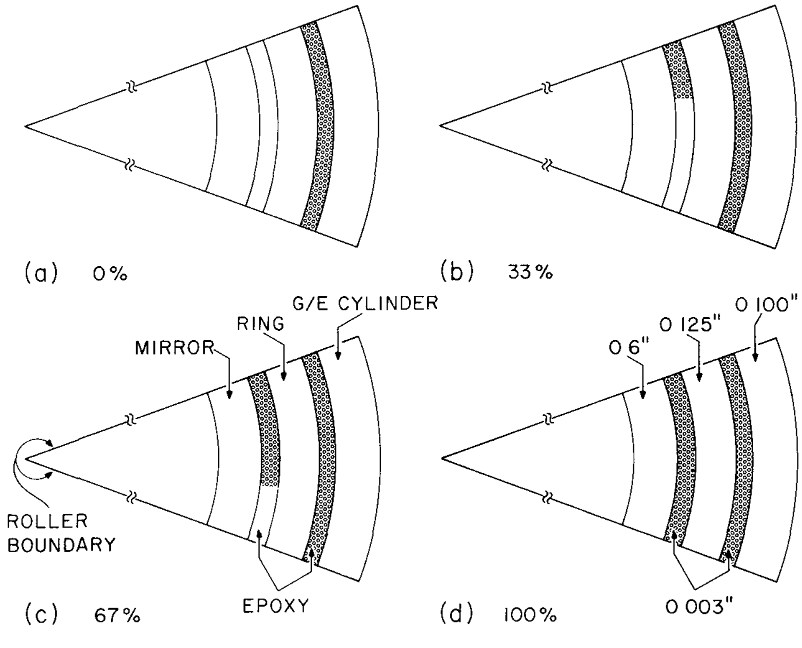


FIGURE 5

2D PLANE STRESS EPOXY EXAMPLE



(a) 0%

(b) 33%

(c) 67%

(d) 100%

FIGURE 6

2D PLANE STRESS EFFECTS

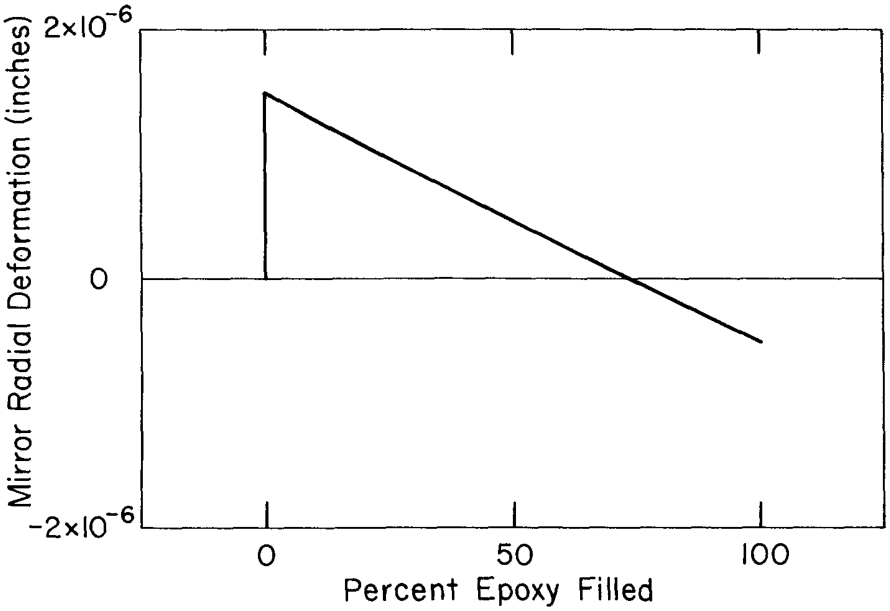


FIGURE 7

AXIAL EFFECT OF EPOXY BOND SHRINKAGE

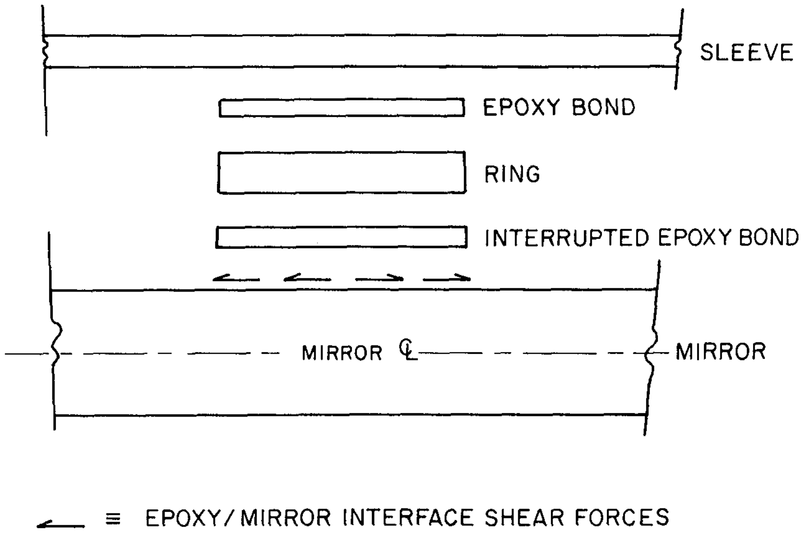


FIGURE 8

MIRROR DEFLECTION DUE TO AXIAL EPOXY SHRINKAGE

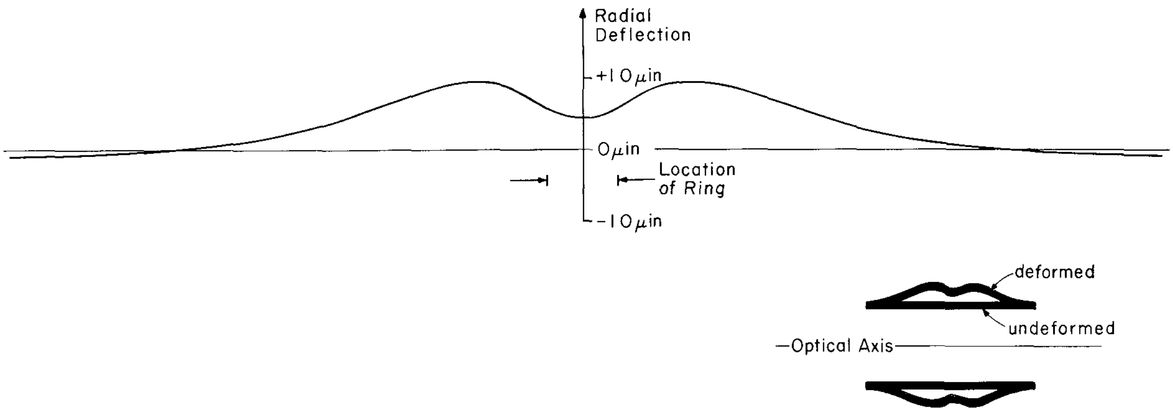


FIGURE 9

RADIAL DEFORMATION OF MIRROR DUE TO EPOXY SHRINKAGE

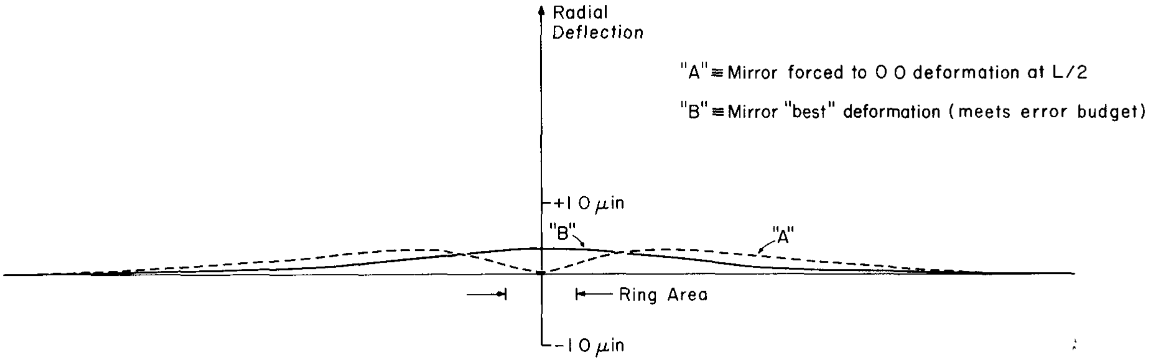


FIGURE 10

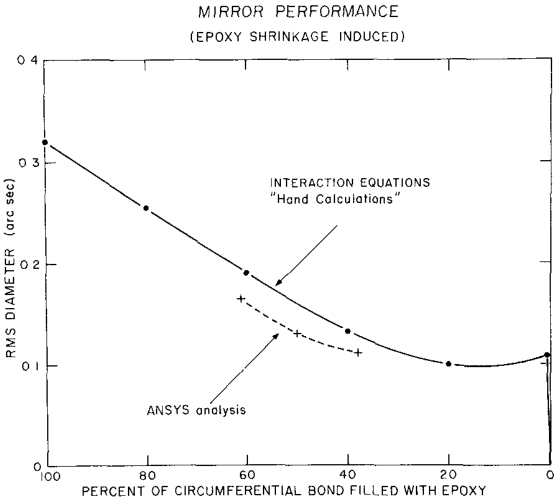


FIGURE 11