Therm-optic analysis of bi-metallic mirrors

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Gemini Preprint # 24

ABSTRACT

The optical surfaces of metal mirrors are often plated with electroless nickel to reduce light scattering. The thermal coefficient of expansion of electroless nickel, 13.5×10^{-6} m/m-K, is significantly different from that of a typical mirror substrate material such as aluminum. A change in temperature produces a "bi-metallic" bending stress in an electroless nickel plated mirror, which can induce optical surface distortion. Possible solutions to the "bi-metallic" bending effect include: metal matrix composites with a thermal coefficient matched to that of the plating, thick mirrors with sufficient stiffness to resist bending, symmetric cross sections producing equal and opposite bending, and plating of both sides of the mirror to balance bending deformations. These solutions are compared using a design example from a cryogenic instrument, the Gemini Near Infrared Spectrograph (GNIRS). Deflections are calculated using both finite element and closed form solutions. The closed form solution produces an order of magnitude estimate, which may not be a reliable guide to the actual therm-optic performance of a plated metal mirror. More sophisticated analytical techniques, which determine the actual type of optical surface error, such as focus, piston, and aberration terms, are required to determine the performance of a mirror undergoing "bi-metallic" bending.

Keywords: bi-metallic bending, athermalization, cryogenic optics, metal mirrors, electroless nickel plating, Gemini 8-m telescope, near-infrared spectrograph, opto-mechanical design

1. INTRODUCTION

Metal mirrors are used in cryogenic optical systems to obtain high thermal conductivity. An additional advantage is uniformity of thermal properties obtaining by using the same material in both structure and mirror substrate. Uniformity of thermal properties provides "same material athermalization," or passive maintenance of alignment and focus following cooling of the system from room to operational temperature[1].

Bare metal surfaces are not used at shorter optical wavelengths or for applications requiring high signal to noise ratios because there is optical scattering from surface roughness due to the grain structure of metals. The surface finish of metal mirrors is improved by plating the optical surfaces with an amorphous layer of nickel. Both diamond turning and conventional optical polishing techniques are used to produce low scatter surfaces on the nickel plating.

A significant disadvantage of nickel plating is the difference in thermal coefficient of expansion between the most common plating material, electroless nickel, and metal mirror substrate materials such as beryllium and aluminum. At 300 K the thermal coefficient of expansion of electroless nickel varies from 20×10^{-6} to 12×10^{-6} m/m-K due to heat treatment and chemical composition[2]. The thermal coefficients of expansion of commonly used mirror substrate metals, such as I-70A beryllium and 6061-T6, aluminum are 11.5×10^{-6} and 23.0×10^{-6} m/m-K at 300 K. The difference in thermal coefficient of expansion between substrate and plating produces bi-metallic bending of the mirror optical surface when the temperature changes.

This effect is significant in nickel-plated mirrors at cryogenic temperatures. Surface deformations of 3 to 4 waves (1 wave = 633 nm) are observed at 100 K in aluminum mirrors plated with 125 μm thick electroless nickel[3]. Similar effects occur in nickel-plated beryllium mirrors. The surface figure of a nickel-plated beryllium mirror tested at ITT Aerospace changed 380 nm due to a temperature change of only 22 K[4]. Effects of this magnitude are serious for near-infrared optical systems where normal optical surface tolerances are typically about 500 nm.

The Gemini Near Infrared Spectrograph (GNIRS) under development at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona, employs a number of mirrors. The instrument is cooled to about 65 K for background suppression. It is desirable to cool the instrument to operational temperature relatively quickly; metal mirrors are an advantage in obtaining short cooling times. Analysis of instrumental optical scattering indicated that a relatively good surface finish, about 40 angstroms RMS, is needed. Obtaining this surface finish requires the use of nickel plating on the mirrors and post polishing after diamond turning. Concerns about the thermal stability of the optical figure of the plated mirrors led to the studies discussed here.

2. ANALYTICAL SOLUTION

Barnes provides a first order analytical solution for temperature induced bi-metallic bending of plated metal mirrors[5]. This analytical solution assumes that both sides of the mirror are plated, although the plating thickness may vary from front to back. The change in the optical radius of curvature of a plated metal mirror due to temperature is:

$$\delta_{\Delta T} = \frac{r^2}{2} \cdot \left[\frac{3}{h} \cdot \frac{\psi_p}{\psi_m} \cdot \left(\alpha_p - \alpha_m \right) \cdot \Delta T \cdot \frac{h_{p1} - h_{p2}}{2 \cdot h} \cdot \left[1 - \frac{h_{p2} - h_{p1}}{2 \cdot h} \cdot \left(4 \cdot \frac{\psi_p}{\psi_m} - 1 \right) \right] \right]$$

where: $\delta_{\Delta T}$ Is the change in mirror optical surface radius

r Is the mirror radius (half diameter)

$2h$ Is the mirror thickness, measured along the optical axis

h_{p1} Is the plating thickness on the front of the mirror

h_{p2} Is the plating thickness on the back of the mirror

ΔT Is the change in temperature

α_P Is the thermal coefficient of expansion of the plating material

α_m Is the thermal coefficient of expansion of the mirror material

ψ_P Is a stiffness parameter for the plating material:

$$\psi_m = \frac{E_m}{1 - \nu_m}$$

ψ_m Is a stiffness parameter for the mirror substrate material:

$$\psi_p = \frac{E_p}{1 - \nu_p}$$

E_P Is the elastic modulus of the plating material

ν_P Is the Poisson's ratio of the plating material

E_m Is the elastic modulus of the mirror substrate material

ν_m Is the Poisson's ratio of the mirror substrate material

This solution is for an axisymmetric solid mirror without restraint. A change in optical surface radius is given without any indication of the induced aberration. Real mirrors are restrained - mounted - in some fashion. Restraint influences the thermal deformation of the mirror. A change in radius is not necessarily a serious effect, since such a change may cause a simple shift in focus. The above equation assumes a constant thickness mirror, in the form of a plane parallel plate. Real mirrors have significant surface curvature, and often vary in thickness. Finally, Barnes' solution is based on classic plate bending theory and does not account for shear effects, which are considerable for thick mirrors.

Despite its limitations, Barnes' solution is often used to assess bi-metallic bending effects. The solution indicates that there are three potential means to reduce bi-metallic bending: matching the thermal coefficient of expansion of the plating material and mirror substrate, placing an equal thickness of plating on the front and back of the mirror, and making the mirror very stiff by increasing its thickness. All of these techniques are used with varying success in cryogenic optical systems.

Matching the thermal coefficient of expansion of the plating and mirror substrate material is achieved by changing the chemistry of the electroless nickel[6] or the substrate. The thermal coefficient of expansion difference is reduced in nickel plated aluminum mirrors by the use of hypereutectic aluminum alloys containing 23% by volume of silicon[7]. An exact match in thermal coefficient of expansion is obtained through the use of a metal matrix composite (MMC) - an aluminum reinforced with particulate silicon carbide[8]. Aluminum/silicon carbide metal matrix composite mirrors plated with electroless nickel do not change in optical figure over temperatures characteristic of military applications - 222 to 344 K[9,10].

A serious drawback in matching the thermal coefficient of expansion of the substrate to the plating is the non-linear thermal coefficient of expansion of metals[11]. This non-linearity makes it quite difficult to balance the make up of a composite material in order to match thermal expansion over a large range in temperature. For example, aluminum reinforced with silicon carbide metal matrix composite is a good match to the thermal coefficient of expansion of electroless nickel near 300 K. At lower temperatures the thermal coefficients of expansion no longer match, and the optical figure of a plated metal matrix composite mirror may change[12].

Barnes' solution indicates that the bi-metallic bending is linearly dependent on the change in plating thickness from front to back on the mirror surface. This suggests that plating both sides of the mirror with an equal thickness of nickel should suppress - or at least reduce - bi-metallic bending effects. This approach is common in plated metal mirrors but is limited in effectiveness due to difficulty in controlling the exact thickness of the plating. Added to this difficulty is the optical fabrication work done to the plating on one side - diamond turning or polishing. It is quite difficult to simultaneously obtain a good optical surface figure and control the plating thickness. The analytical solution indicates that stress is always induced between plating and mirror, even when the plating thickness is equal on both sides of the mirror. This type of stress may create local deformations in the mirror optical surface.

Barnes' solution also indicates that bi-metallic bending is inversely proportional to the mirror thickness. Doubling the mirror thickness should reduce the bending by a factor of two. If weight is not an issue, increasing the mirror thickness is a common means of reducing bi-metallic bending. As mirror thickness increases, shear contributions to bending also increase. Shear may offset any improvement obtained by increasing the mirror thickness.

Related to increasing the thickness of the mirror to reduce bi-metallic bending is the use of symmetric cross sections. Bi-concave or bi-convex mirror shapes are sometimes used as a means of reducing thermal deformation. Alternately, the mirror may take the shape of a meniscus of uniform thickness. The neutral bending surface of symmetric cross sections is flat, suggesting immunity from thermal deformation. Symmetric cross sections are difficult to fabricate, and shear deformations may become significant. The analytic solution developed by Barnes does not provide any way of evaluating the effect of symmetry on bi-metallic bending.

3. DETAILED ANALYSIS OF THE GNIRS OFFNER PRIMARY MIRROR

One of the most important mirrors in the GNIRS is the primary mirror of the Offner relay. The Offner relay is a two mirror system, with a concave primary and convex secondary. The Offner is a 1-to-1 relay that transfers the image from the focal plane of the Gemini telescope to the slit of the spectrograph. A stop located near the secondary mirror (a so-called “Lyot stop”) of the Offner provides control of stray light in the optical path in front of the instrument. The overall layout of the Offner relay is shown in figure 1. Since the Offner is important in controlling stray light, a very good surface finish is required on its primary mirror. It is necessary to plate the primary mirror with electroless nickel to meet the 40 angstrom RMS surface finish requirement. The primary mirror of the Offner was selected as the first mirror for bi-metallic bending analysis.

Two methods were used to analyze the bi-metallic bending of the primary mirror of the Offner: Barnes’ closed form solution, and the finite element method. The Offner primary is 180 mm in diameter and has a concave optical radius of curvature of 560 mm. The mirror is made of 6061-T651 aluminum alloy. A flexural mounting system was assumed for all mirrors. Five different mirror shapes were studied:

1. Baseline, with a flat back
2. Uniform flat mirror
3. Thick flat back mirror (50% thicker than the baseline)
4. Meniscus mirror (constant thickness)
5. Symmetric mirror (double concave)

These shapes are shown in figure 2. In addition the plating thickness on both front and back of the mirror was varied from 0 to 175 μm.

The finite element program I-DEAS VI was used in the analysis. A typical model is shown in figure 3. Structural deformations were converted to optical surface deformations; these were broken into correctable aberrations such as piston and focus, and uncorrectable aberrations. To further simplify the analysis, a “unit load” was used, which was a change in temperature of 1 degree Kelvin.

The first case studied was the baseline flat back mirror. Due to the 560 mm optical surface radius of curvature the thickness of the baseline mirror varied from 35.8 mm at the edge to 28.5 mm at the center. The results of the finite element analysis of the baseline mirror are given in table 1:

TABLE 1: BASELINE (FLAT BACK) MIRROR

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 Al alloy, diameter = 180 mm, $\Delta T = 1° K$)

Nickel Plate Thickness		Surface Errors		Correctable Aberrations		Corrected surface errors	
Front ($\times 10^{-6}$ m)	Back ($\times 10^{-6}$ m)	P-V ($\times 10^{-9}$ m)	RMS ($\times 10^{-9}$ m)	piston ($\times 10^{-9}$ m)	focus ($\times 10^{-9}$ m)	P-V ($\times 10^{-9}$ m)	RMS ($\times 10^{-9}$ m)
175	175	168	56	1245	87	11.0	2.7
88	175	205	67	1230	105	7.8	1.5
175	0	112	38	1276	59	9.2	2.2

In the above table the surface errors are the total mechanical surface deflection predicted by the finite element model. The abbreviation P-V stands for the total span of surface errors, from the highest peak above the surface, to the bottom of the lowest valley below the surface. The RMS abbreviation denotes the root-mean-square average of all the surface errors. Correctable errors are optical aberrations that can be removed by adjustment during alignment of the mirror. These errors are normally a displacement of the surface, or "piston" error, and a change in location of the mirror focus. Corrected surface errors are the optical aberrations remaining after piston and focus errors are removed.

The results of the baseline analysis are surprising when compared against predictions based on Barnes' solution. The finite element analysis indicates that bi-metallic bending is not significantly reduced when the plating thickness is equal on front and back surfaces. Even more unexpected is the reduced surface deformation when plating is eliminated from the back of the mirror.

The surprising results of the baseline study led to studies of the second case, a uniform thickness flat mirror. The mirror was assumed to be in the form of a plane parallel plate, with a constant thickness of 28.5 mm. This case provides a better comparison than the baseline with results produced using Barnes' solution. The results of the finite element analysis are given in table 2:

TABLE 2: UNIFORM THICKNESS (FLAT BACK AND FRONT) MIRROR

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 Al alloy, diameter = 180 mm, $\Delta T = 1° K$)

Nickel Plate Thickness		Surface Errors		Correctable Aberrations		Corrected surface errors	
Front ($\times 10^{-6}$ m)	Back ($\times 10^{-6}$ m)	P-V ($\times 10^{-9}$ m)	RMS ($\times 10^{-9}$ m)	piston ($\times 10^{-9}$ m)	focus ($\times 10^{-9}$ m)	P-V ($\times 10^{-9}$ m)	RMS ($\times 10^{-9}$ m)
175	175	17	5	1340	7	7.0	1.4

88	175	24	8	1325	13	4.0	0.8
175	0	83	26	1376	40	6.7	1.4

The results of this analysis are in better agreement with the predictions of Barnes' solution for a temperature drop of 225 K. Surface deformations of a uniform thickness (plane parallel plate) mirror produced using the closed form solution are compared with those of the finite element method in table 3:

TABLE 3: CLOSED FORM VERSUS FINITE ELEMENT ANALYSIS RESULTS

Optical surface quality (P-V) for bi-metallic bending
Uniform thickness (flat back and front) mirror
(6061-T6 Al alloy, diameter = 180 mm, ΔT = 225 K)

Plating thickness difference, front-to-back (x 10^{-6} m)	Optical surface deformation, closed form solution (x 10^{-6} m)	Optical surface deformation, finite element method (x 10^{-6} m)
0	0	3.83
88	10.3	5.40
175	20.1	18.7

Table 3 indicates that the closed form solution is not a perfect means of predicting bi-metallic bending, even for a plane parallel plate. In this case the presence of a constraint - the flexural mounting - on the lower surface affects the bending of the finite element model. Although agreement between the two solutions is within about 7% for the mirror without any plating on the back, there is substantial disagreement for the intermediate case. Also of interest is the residual bending term predicted by the finite element method for the equal plating thickness case.

Barnes' solution indicates that bending is reduced by increasing the thickness of the mirror. The third case studied using finite element analysis was a mirror similar to the baseline, but with an increase in center thickness from 28.5 to 42.5 mm. The results of this analysis are given in table 4:

TABLE 4: THICK MIRROR (FLAT BACK WITH CURVED FRONT)

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 Al alloy, diameter = 180 mm, ΔT = 1° K)

Nickel Plate Thickness		Surface Errors		Correctable Aberrations		Corrected surface errors	
Front (x 10^{-6} m)	Back (x 10^{-6} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)	piston (x 10^{-9} m)	focus (x 10^{-9} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)
175	175	178	54	1570	93	11.0	2.5
88	175	199	59	1560	103	7.9	1.7
175	0	148	45	1590	78	9.2	2.0

The results of the study of the thick mirror are also a surprise when considered against the predictions of the closed form solution. The corrected surface errors for the baseline and thick mirror cases are nearly identical. This result indicates the importance of local surface deformations as well as shear in determining bi-metallic bending. Making a mirror thick does not necessarily reduce the magnitude of bi-metallic bending. A comparison of the results of the baseline and thick mirror studies is given in table 5:

TABLE 5: THICK, MENISCUS, AND DOUBLE CONCAVE VERSUS BASELINE MIRRORS

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 Al alloy, diameter = 180 mm, $\Delta T = 1°$ K)

Plating thickness difference, front-to-back (x 10^{-6} m)	Optical surface deformation, baseline mirror (corrected surface errors, P-V) (x 10^{-9} m)	Optical surface deformation, thick mirror (corrected surface errors, P-V) (x 10^{-9} m)	Optical surface deformation, meniscus mirror (corrected surface errors, P-V) (x 10^{-9} m)	Optical surface deformation, double concave mirror (corrected surface errors, P-V) (x 10^{-9} m)
0	11.0	11.0	11.5	10.4
88	7.8	7.9	7.6	7.8
175	9.2	9.2	10.2	7.6

It is suggested bi-metallic bending is reduced through the use of the meniscus mirror shape. A meniscus mirror has a surface curvature but is of constant thickness. A meniscus mirror was studied as the fourth case. This mirror had an optical surface curvature of 560 mm, and a constant thickness of 28.5 mm. Results of the finite element analysis of the meniscus mirror are given in table 6:

TABLE 6: MENISCUS MIRROR

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 Al alloy, diameter = 180 mm, ΔT = 1° K)

Nickel Plate Thickness		Surface Errors		Correctable aberrations		Corrected surface errors	
Front (x 10^{-6} m)	Back (x 10^{-6} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)	piston (x 10^{-9} m)	focus (x 10^{-9} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)
175	175	166	50	1246	88	11.5	2.1
88	175	210	63	1229	109	7.6	1.3
175	0	96	30	1281	51	10.2	2.1
175	88	132	40	1263	70	11.0	2.1
88	88	175	52	1246	91	7.1	1.3

The results of the fourth study indicate there is no significant reduction in bi-metallic bending obtained by the use of the meniscus shape. Corrected optical surface errors for the meniscus shape are nearly identical to those of the baseline shape. This is shown in table 5.

The fifth and final mirror studied was a symmetric shape. This mirror was bi-concave, with a 560 mm radius on both front and back surfaces. The center thickness of the mirror was 21.2 mm, and the edge thickness was 35.8 mm. Results of the finite element study of the double concave mirror are given in table 7:

TABLE 7: DOUBLE CONCAVE MIRROR

Optical Surface Quality due to Bi-metallic Thermal Effect
(6061-T6 AL, diameter = 180 mm, ΔT=1°K)

Nickel Plate Thickness		Surface Errors		Correctable aberrations		Corrected surface errors	
Front (x 10^{-6} m)	Back (x 10^{-6} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)	piston (x 10^{-9} m)	focus (x 10^{-9} m)	P-V (x 10^{-9} m)	RMS (x 10^{-9} m)
175	175	160	49	1247	84	10.4	1.9
88	175	208	62	1229	109	7.8	1.4
175	0	85	26	1284	46	7.6	1.4
175	88	124	38	1265	66	9.1	1.7
88	88	172	51	1247	89	6.4	1.2
88	0	133	40	1266	70	5.9	0.9

The results of this study indicated a reduction in bending for the double concave mirror when compared with the baseline. The finite element model indicates that eliminating plating from the back of the double concave mirror always reduces bi-metallic bending when compared with the baseline.

This suggests that the idea of equal thickness plating front-to-back is not always a good way of minimizing bi-metallic bending. This is shown in table 5.

The results of the fifth case led to the selection of the final design for the Offner primary mirror of the GNIRS. The final design is a double concave mirror, without plating on its back. This is a very different design than suggested by the initial closed form analysis using Barnes' solution. The final design is shown in figure 4.

4. CONCLUSIONS

The application of finite element analysis to the bi-metallic bending induced by a temperature change in plated optical mirrors produced results that are different from those predicted using a closed form solution. Important results of the finite element studies of the primary mirror for the GNIRS are;

1. The closed form solution is valuable as a means of estimating the magnitude of the bi-metallic bending, but should not be relied upon for detailed analysis.
2. Surface deformations predicted by the finite element method should be separated into correctable aberrations such as piston and focus, and residual aberrations that cannot be corrected. A simple prediction of total mirror surface error may not be an accurate measure of the optical effect of the bi-metallic bending.
3. Placing an equal thickness of plating on both front and back of a mirror may not reduce the bi-metallic bending effect, and may increase surface deformations. This somewhat surprising result is due to the restraint provided by the mount against the back of the mirror.
4. Increasing mirror thickness does not provide a reduction in bi-metallic bending.
5. The meniscus mirror shape does not reduce bi-metallic bending when compared with a conventional flat back shape.
6. Symmetric shapes reduce bi-metallic bending, particularly if the back of the mirror is not plated. The reduction in bending when the back of the mirror is not plated is probably due the restraint provided by the mirror mount.

These results should be considered preliminary. Further study of the influence of different types of mirror supports on bi-metallic bending is indicated. Such studies should examine edge mounts as well as varying the location of the back support. It is planned to measure the optical surface deformation at 65 K of the primary mirror of the Offner in the GNIRS during the testing of the instrument, in 1999.

5. ACKNOWLEDGEMENT

The research in this paper was funded by the International Gemini 8-m Telescopes Project. The Gemini 8-m Telescopes Project is managed by the Association of Universities for Research in Astronomy, for the National Science Foundation, under an international partnership agreement

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Figure 1: Offner Relay

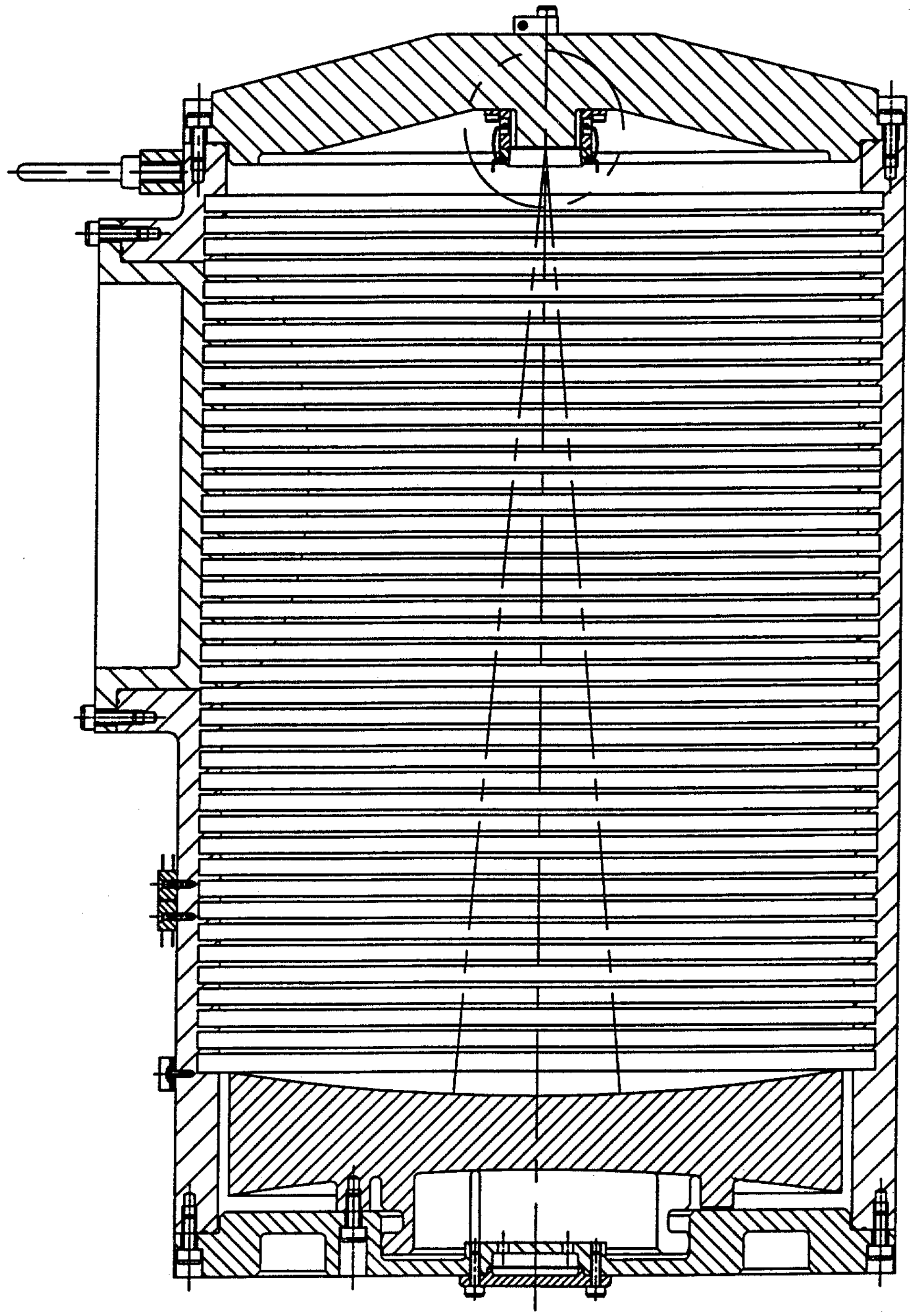
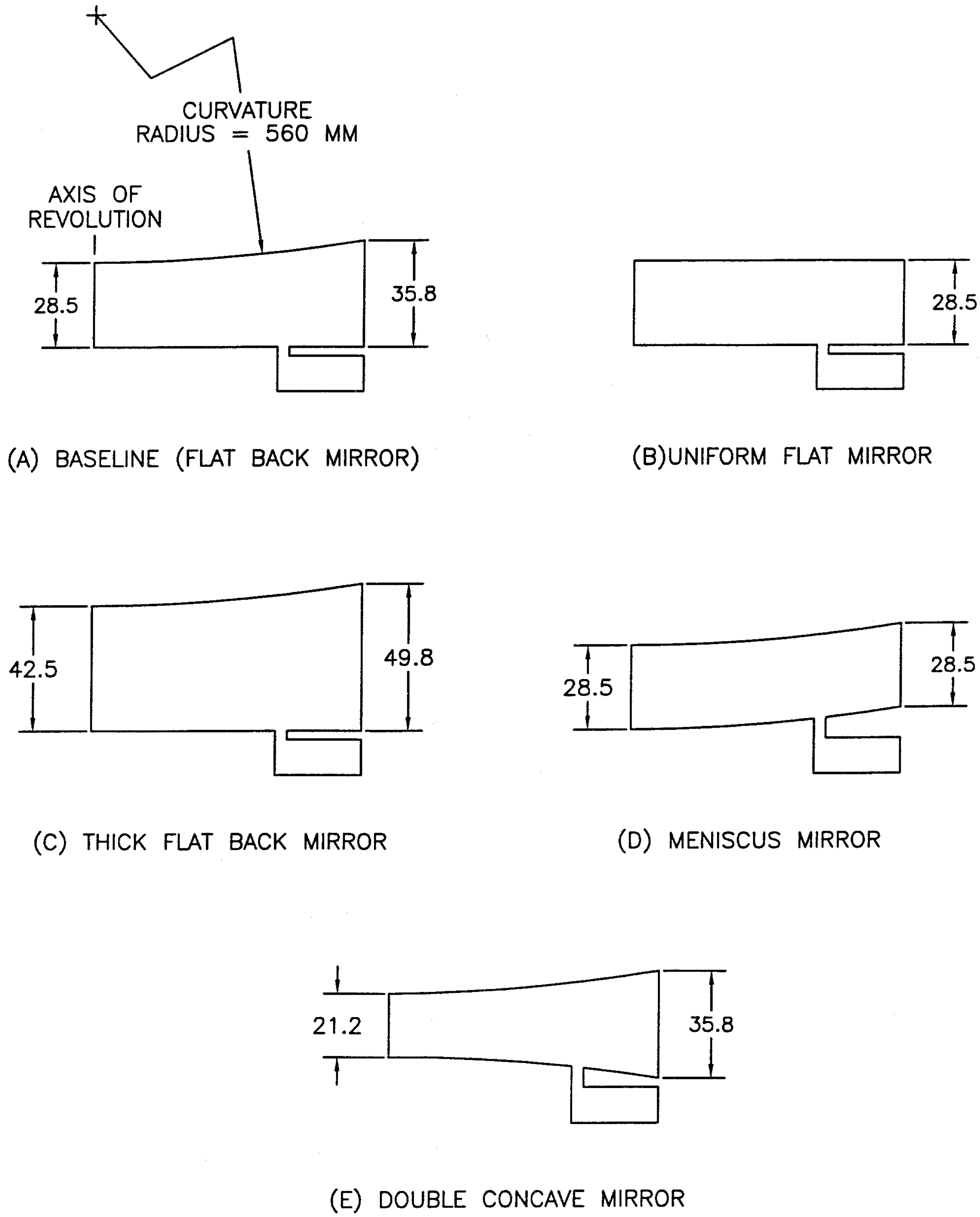


Figure 2: Various Mirror Shapes



Curvature Radius: 560 mm - Mirrors A,C,D,E
Diameter: 180 mm
Material: 6061-T6 Aluminum Alloy

Figure 3: Finite Element Analysis Model

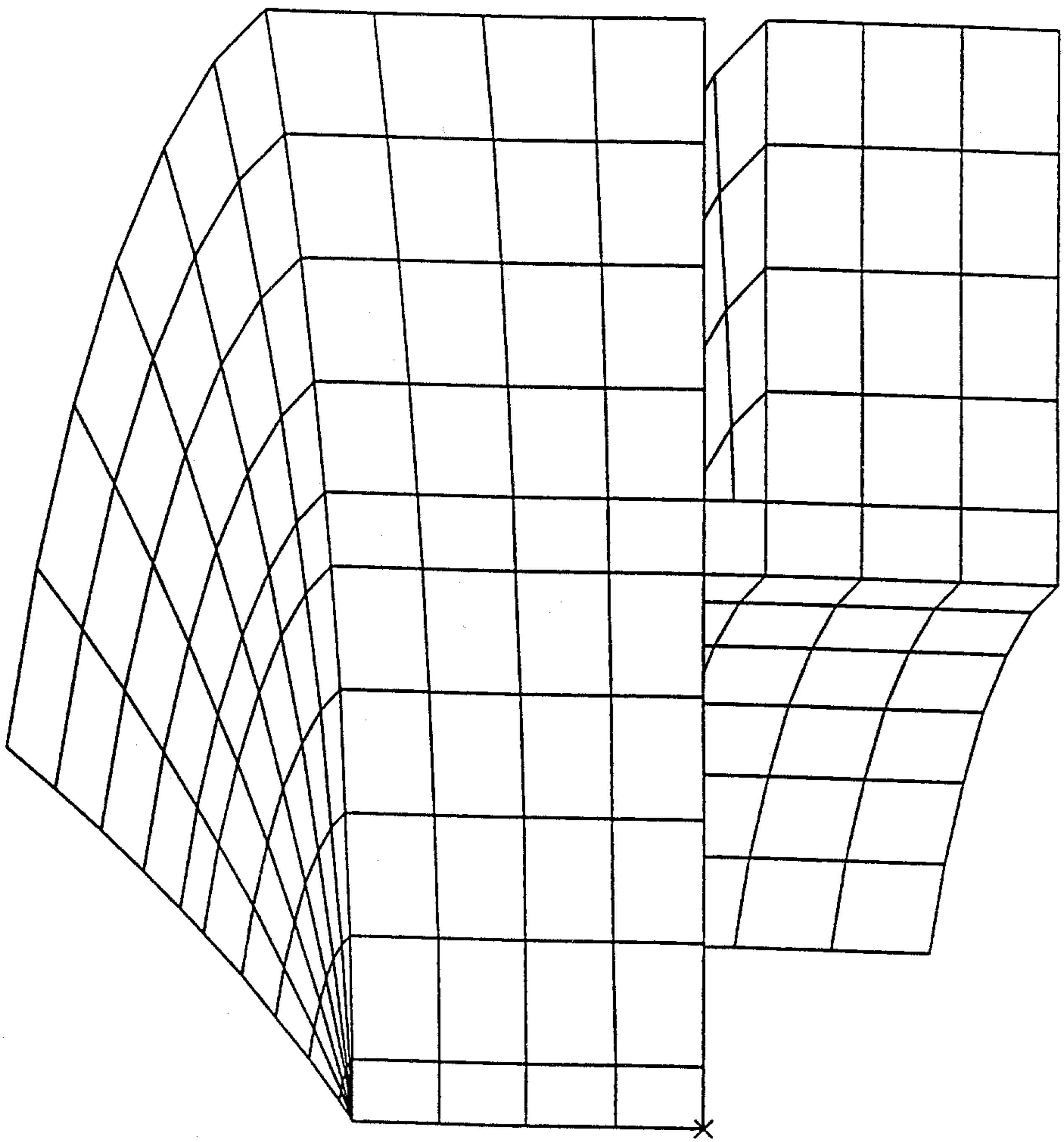


Figure 4: Final Offner Primary Mirror