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The construction and performance of a one meter long elliptically bent steel mirror

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ABSTRACT

An elliptically bent mirror of total length 1.25 m has been developed at the Advanced Light Source (ALS) for focusing soft x-rays. The mirror is used to produce a small, high flux density illuminated field of view for a Photo-Emission Electron Microscope (PEEM). The requirement to collect the maximum horizontal aperture with the need to highly demagnify the source leads to a mirror with a wide range of curvatures along the surface. This combined with the need to produce a low slope error surface at a reasonably low cost has required us to develop a mirror based on the controlled bending of a flat substrate. This is an extension of several other mirror projects at the ALS where controlled bending of glass and metal substrates has been used in micro-focusing applications [1,2,3]. Those mirrors however are a maximum of 200 mm long, and in this paper we describe the new challenges we have faced and the solutions we have adopted in developing a long and highly elliptical mirror. The mirror described here is manufactured from a low carbon steel (1006) which is capable of good dimensional stability, it is electroless nickel plated for polishing, and is bent into an elliptical shape by the application of unequal couples. We describe the mirror fabrication process, the mechanical details of the bending mechanism and the experimentally measured slope error from an ellipse. The final mirror has an rms roughness of 6Å (rms), a full aperture (1.1 m) slope error of 14 μrad (rms), and a slope error of <3 μrad when optimized over approximately 2/3 of the required optical length (0.917 m).

Keywords: synchrotron radiation, x ray mirrors, bent mirrors, adaptive optics

1. INTRODUCTION

The mirror we have developed is to be used to collect and focus a large horizontal aperture beam to provide a small illuminated field of view for a Photo-Emission Electron Microscope (PEEM). This type of microscope is the analog of a Transmission Electron Microscope (TEM), except that in this case, electrons photoemitted from an x-ray illuminated surface are imaged, rather than transmitted electrons as in the TEM. The mirror we describe here provides in one direction the same action as the condensor in a TEM, to produce an illuminated area matched to the field of view of the microscope. In the vertical direction, a single element spherical grating monochromator provides vertical focusing and dispersion [4,5]. The field of view of the microscope at its nominal magnification is around 30 μm. This type of microscopy images the whole field and hence intrinsically can have high data rates. However, in practice the low secondary electron yield of most surfaces (1 - 5 % typically) and the low throughput of the electron optics (typically 5 to 10%) mean that at high resolution, a very high photon flux density is needed to have reasonable imaging times. In addition, we intend to perform spectroscopic imaging, where a sequence of frames is taken at increasing photon energies through the region of an absorption edge, and hence we must have a flux high enough so that the total time for all the frames is reasonable. At 200 Å resolution, we have determined that we need around 10^{12} ph/sec in a 30 μm field in order to record single images with an average of 1000 detected electrons per pixel in a few seconds. This requires a bright source of x-rays such as the ALS, but it also requires that the maximum horizontal aperture is taken, and that the magnification of the mirror system provides the correct field size. The development of the resulting condensing mirror is the subject of this paper.

2. X-RAY OPTICAL REQUIREMENTS

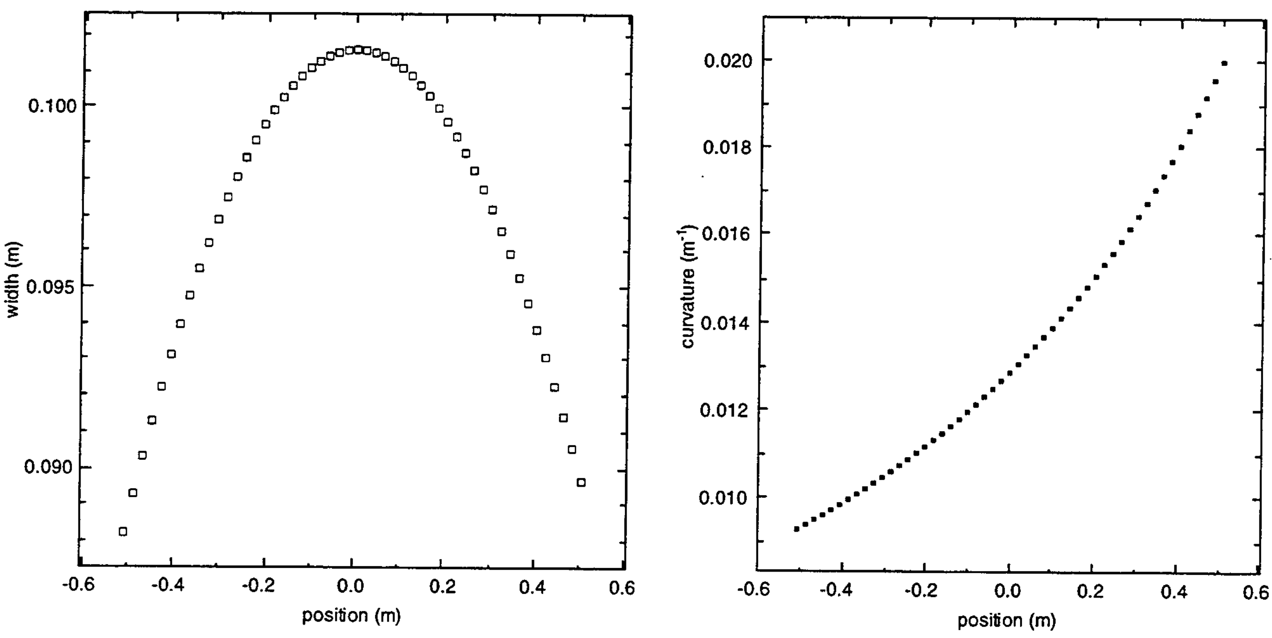
The source of x-rays in this case is synchrotron radiation from an ALS bending magnet, and at the tangent location of this beamline (BL 7.3.1.1) has a horizontal beam size of around 300 μm (fwhm). As the required field size is 30 μm, this therefore sets the required demagnification of the mirror at 10:1. For geometrical convenience and to allow a small safety factor we have used an actual demagnification of 10.8:1. The allowed aperture is set by the critical angle of reflection for the highest photon energies to be reached, and by the de-magnification to be used. In this case we wish to access energies up to 1300 eV, and so for a platinum coated reflector, a grazing angle of 2.5° is appropriate. This sets the possible range of convergence angles; clearly rays at a grazing angle less than this will be reflected, but rays at an angle much greater than this will exceed the critical angle and be absorbed. In the limit therefore, an angular convergence of twice the glancing angle could be achieved. However, in this case at one end of the mirror a ray would be parallel to the surface and at the other end would be near the critical angle. From a practical standpoint, a convergence angle of 1/2 to 2/3 of the critical angle is a good design rule. In this case we have used around 1/2 of the nominal grazing angle of 2.5° as this is the critical angle limiting the maximum photon energy to less than 1300 eV. Having identified the required demagnification and the convergence angle, the angular acceptance directly follows, and in this case is 2.0 mrads.

The image distance of the spherical grating monochromator in the vertical direction sets the distance of the vertical focus, and for a stigmatic image, from the required horizontal de-magnification we can determine the object and image distance of the horizontally focusing mirror. In this case the vertical image of the source is at 21.85 m, and so for our defined de-magnification we have an object distance of 20 m and an image distance of 1.85 m. The required optical length of the mirror is therefore 0.917m; allowing for a reasonable margin of safety for unwanted end effects, our design has an overall length of 1.25 m. The optical height of the mirror in the vertical direction is set by the acceptance of the monochromator, the monochromatic demagnification, and the distance from the mirror to the focus. In this case the acceptance is 0.7 mrads, the monochromatic demagnification is 1:1, and the image distance is 1.85 m; the required optical height is therefore only 0.9 mm.

The slope error tolerances can be derived from the angular size of the image. In the horizontal direction this is simply an image size of 30μm at an image distance of 1.85 m. This gives an angular size of 16 μrads, and allowing for angle doubling on reflection, and assuming a gaussian distribution of slope errors that would give a maximum broadening of root 2 times the demagnified source size, then an rms error of $<$ 3.5 μrads is required. In the vertical direction the monochromatic image size is the same, but a factor of 2 tighter slope error tolerance is used, as this error determines spectral resolution. After allowance is made for the advantageous effect of the small glancing angle, the required rms error is $<$ 40 μrads in the vertical direction (flat direction on the mirror).

We also need to see whether simple surfaces such as a cylinder or a cubic approximation to the height profile of an ellipse could suffice in this case. We can easily calculate the slope of an ellipse and compare it to either of these shapes [1]. If we used the full length of the mirror, and used a cylindrical shape, the slope error at the end would be around 1.7 milliradians. This has to be compared with our tangential slope error specification above of 3.5 µrads rms; using such a mirror would therefore increase the image size by a factor of approximately 200 and is clearly unacceptable. Application of unequal couples to a rectangular mirror substrate can produce a cubic approximation to an ellipse. However, even in this case the residual aberrations are large, and at ± 0.3 mrads again would produce an unacceptably large image. It is clear from the above arguments that a true elliptical surface should be produced in order to preserve the source brightness.

Having fixed the optical parameters, we can use the methodology described in detail in [1] to calculate the required width of the mirror as a function of longitudinal displacement from the center of the mirror, and the magnitude of the couples. The width of the mirror substrate has to change as a function of position in order to produce the exact elliptical shape. The radius at the center of the mirror is directly proportional to the sum of the couples, and the difference in the couples is related to the 3rd order correction (coma). As the section moment of inertia is proportional to width and inversely proportional to the cube of the thickness, for a given machining error, width profiling gives the most accurate result and was therefore chosen in this case. The width function and curvature are given in Fig. 1.



(a) **(b)**

Fig. 1. The width (a) and curvature (b) of a mirror with an object distance of 20m, an image distance of 1.85 m, a grazing angle of 2.5°, and a central width of 0.1016m

It can be seen that the width changes from around 88 mm at one end, through 101.6 mm at the center to around 89.5 mm at the other end. For a mirror 15.24 mm thick, the required couples are 46.2 N.m at the end nearest the source, and 105 N.m at the end nearest the focus, assuming a modulus of elasticity for mild steel of 19.6 x 10^{10} N.m^{-2}. The curvature changes dramatically across the surface, from a radius of 107 m at the source end, through 77 m at the center to 50 m at the focus end. Having predicted the correct width function to produce an exact ellipse in the presence of the correct end couples, we can use the same theoretical approach to assess the effect of errors and to tolerance the key parameters such as the accuracy of the width profile, the thickness and the couples [1]. In Fig. 2 we show for example the effect of a 50 μm change in the thickness of the substrate across the whole length of the mirror (wedge error).

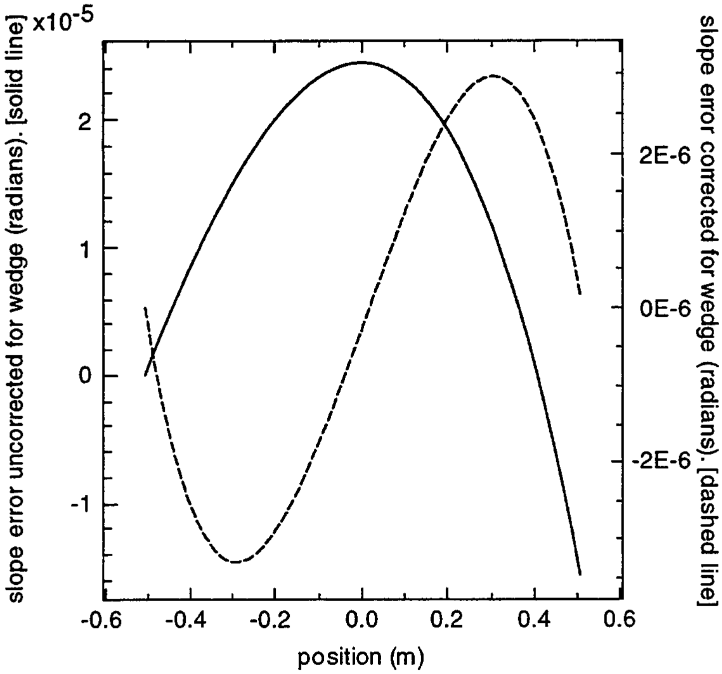


Fig. 2 Slope error produced by a 50 μm change in the mirror thickness from one end to the other.

We can see that this small change in thickness causes a large slope error (left hand curve) amounting to an extreme error of 40 μrads. However, by adjusting the C1 (larger) couple by +1.8% and the C2 couple by + 4%, the total excursion of the error can be reduced to ± 3 μrads. This just meets our slope error tolerance as described before. However, although a linear wedge can be largely corrected, large period errors cannot. Thickness errors with a period approaching the thickness of the mirror produce slope errors that become vanishingly small, but periods approaching the length of the mirror can be highly damaging and must be controlled. A fractional change in the overall thickness just changes the required couples, as does a fractional change in the width, or an overall change in the absolute elasticity. As in the above example, tolerances can be accurately calculated based on simple beam theory [1].

3. MECHANICAL DESIGN

In other mirror benders we have recently produced, the required couples were produced by leaf springs mounted perpendicularly to the mirror, with the actuating force being applied normal to the springs and hence parallel to the mirror substrate. The result is that the mirror is in tension. The use of spring actuators is however highly desirable as the spring extension is large, resulting in easy tunability, and immunity from thermal and mechanical drift [1]. However, in cases where the mirror is long, and steeply curved, the result can be that the force becomes large enough to affect the slope of the mirror. It is easy to see that a longitudinal force will tend to reduce the slope progressively as the slope increases towards the ends of the mirror. In previous cases this effect has been small, but in the present case would produce an error of 80 µrad and therefore requires the use of an alternate bending scheme.

The solution we adopted is shown in Fig. 3. The springs are attached to the ends of the mirror as before, but now run essentially parallel to the mirror along its whole length, and are interlaced in a tongue and groove fashion. In order to apply a couple, on one end of each spring there is a 40 threads per inch screw that captures one end of a wobble pin while the other end of the pin inserts into a cup on the end of the mirror. The other lever has an identical mechanism, and to produce the required couples, the springs are extended by around 12 and 25 mm for each spring. An important feature is that the cup that provides the load point can be adjusted in a direction along the short length of the mirror. This gives a mechanism with which twist can be eliminated. In addition to the adjustments for the couples, an additional adjuster was added to the center of the mirror via a C shaped yoke.

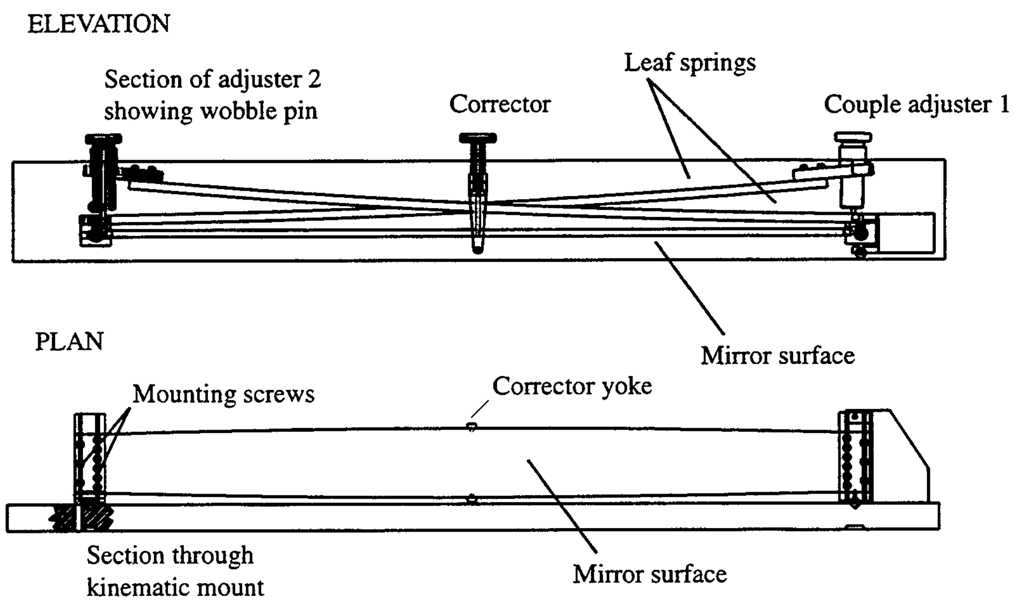


Fig. 3. Mechanical layout of the mirror substrate and its bending mechanism

This gives one additional parameter to tune, in this case to try to eliminate the effects of an initially cylindrical substrate. The mirror and bending spring unit are kinematically mounted to a base via balls resting in two V grooves machined in the mirror mounting blocks and the mirror assembly base. A third constraint is a pin that sets the vertical position of the mirror against the mirror mounting blocks.

4. MATERIALS AND MANUFACTURE

Dimensional stability over long periods of time is of great importance for mirror substrates. For this reason, a plain carbon steel with very low carbon (1006) was used. This material had previously been shown to possess exceptional stability in investigations of gage-block materials [6]. It is also readily available, inexpensive, easily machined and as it is magnetic, is easily held for surface grinding operations. In addition the material is thermally matched to the electroless nickel used to coat the surface for polishing.

Manufacturing of the mirror substrate started with selection of the flattest section from a 1.2 m by 1.2 m plate of hot-rolled, 1006 steel. The selected section was rough cut to the approximate dimensions required and then fully annealed in an air furnace at 1700 F between two thick steel plates. Rough machining was performed in such a manner as to remove approximately equal amounts of material from all sides. A finish cut within 0.75 mm of the required dimensions was made on the two surfaces to be ground. The edge profile and mounting holes were then machined into the substrate with a numerically controlled milling machine to an accuracy within 25 microns of the desired shape. The substrate was then ground on both sides, using a magnetic chuck and shims to avoid strains due to the magnetic forces. The two surfaces were parallel to within 25 microns after grinding and the desired center thickness was within 10 microns of the desired 15.2 mm as measured with a coordinate measuring machine. The substrate was then fully annealed at 910 °C before polishing. Our first attempts to anneal the substrate produced excessive warping, but by clamping between flat ground ceramic bars [7], the resulting curvature was reduced to about 0.5 km [8]. The steps in the process were;

1. The mirror substrate was placed between two ceramic plates. The ceramic plates were supplied flat to 15 μm.
2. The assembly was compressed by a force of approximately 800 N to prevent movement of the surfaces during annealing.
3. The vacuum furnace was then heated at 80° C/hr to 910° C while measuring the temperature of the steel substrate along the long exposed edges. The substrate was maintained at temperature for 3 hours
4. The furnace was then allowed to cool to 300° C at 80° C/hr at which time the furnace was filled with nitrogen.

The mirror was then nickel plated [9], lapped and fine polished using a continuous polishing machine [10]. The final polished substrate was measured on a Long Trace Profiler (LTP) to have a radius of curvature of 420 m, and with a deviation from this radius of 43 μrad (rms) [11]. This slope error was anti-symmetric with a form similar to that induced by spherical aberration. The surface roughness in the few μm to mm spatial period range had an rms value of 6Å.

5. MEASUREMENTS

The cantilever springs were bolted onto the substrate and the whole assembly mounted in its 3 ball kinematic mounting frame. The drive screws for each of the couples were then adjusted, reducing the difference between the slope as measured on a Long Trace Profiler (LTP) [11] and the theoretical slope to a minimum [12]. The resulting minimized slope error is shown in Fig. 4, curve (a).

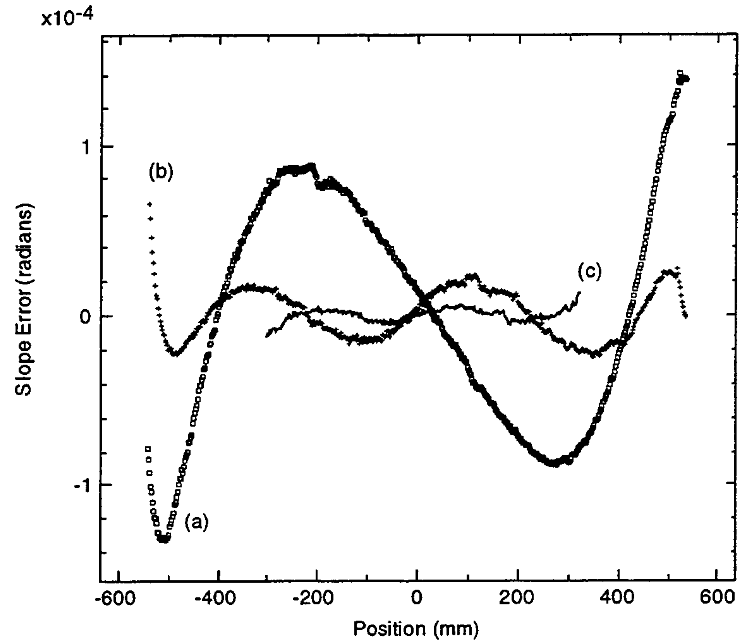


Fig. 4 Slope error from the required slope of the ellipse. (a) is with C1 and C2 adjustment only, (b) is with C1, C2 and the central corrector, and (c) is as (b) but optimized over a range of approximately 600 mm.

The peak to valley slope error minimized over the whole length is around ± 140 μrads, with an rms of 68 μrads. The dominant error is anti-symmetric, indicating that this has slope components that scale as x^3 (spherical aberration). Note that this was the type of error from a best fit circle that was found after polishing of the substrate, and is also the type of error created by bending from a circular shape rather than a flat. Fig. 5 shows the error produced by bending to the ellipse from the measured radius of the substrate, 420 m.

In comparing Fig. 4(a) with Fig. 5, we have to realize that the overall negative slope in Fig. 4(a) can be removed by altering the fitting to introduce additional curvature. This will increase the peak to valley error, but would result in a region at the center for which the slope error would be near zero. The shape of the error produced by bending from an initial radius of 420m shown in Fig. 5 is similar to that measured, but the magnitude of the error is too small.

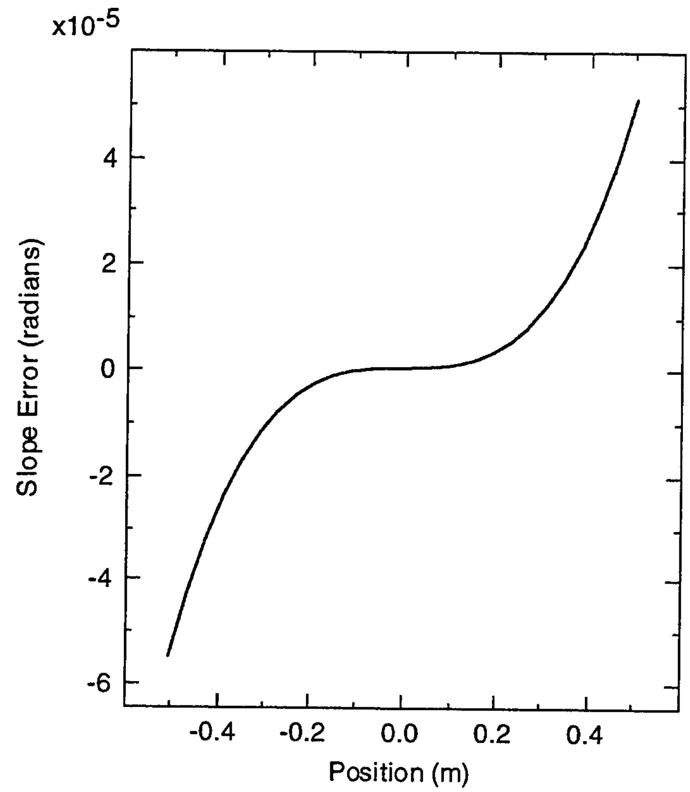


Fig. 5. Slope error created by bending from an initially curved substrate (R=420m) rather than from a flat.

This is due to the presence of errors in the initially curved substrate that also had the same x^3 slope character. In this case, the errors were additive. Fig. 5 shows the sensitivity of this manufacturing method to initial deviations from flatness. In order to reach our goal of an rms deviation from a true ellipse of < 3μrad rms, we can use similar methods to show that the initial starting radius would have to be greater than 4 km. In order to correct this error, we could adopt one of several different methods. The local section moment could be changed by changing either the width or thickness of the beam to correct for local errors. This could be done in a relatively stress free manner by wire electric discharge machining, but would in this case mean cutting through the nickel coating layer at the edge of the mirror. This might promote pealing, and as the stress state of the nickel and substrate are bound to be different, it might also induce unwanted bending. Errors can also be removed by application of point forces, and this for simplicity was the chosen solution in this case. It can be shown that application of a single point load at the center of the mirror will produce a slope deviation that can counteract the type of error measured here. The load is applied with a C shaped yoke as shown in Fig.3, that pulls or pushes on the mirror. Fig. 4(b) shows the effect of applying this force. The rms error is substantially reduced, with a value of 14 μrad rms when optimized for the whole length of the mirror (1.1 m). However, the required length of the mirror is only 917 mm, and if we optimize over smaller intervals we can find the length that satisfies our slope error criterion of 3 μrad rms. This value is reached when optimizing over 584 mm, approximately 64% of the required length. The resultant slope error is shown in Fig. 4(c).

The final adjustment required is for twist about the long length of the mirror. The initial measurement is performed with the substrate flat using a Zygo 6 inch aperture interferometer. The beam is reflected from the mirror at a small angle so that the interferometer aperture maps onto the whole length of the mirror, and the beam is reflected back along its initial path by a reference flat. The twist is removed by moving one of the couple adjuster wobble pin load points parallel to the short axis of the mirror. Twisting can also occur in application of the couples, and due to the large curvature of the mirror, the interferometer cannot be used. Instead, we use a gravity referenced digital autocollimator to measure the tilt of one end of the mirror and then of the other end. Having established the twist, we remove the twist by the above method, monitoring the attitude of one end with the autocollimator, and the other using a precision electronic level.

6. CONCLUSIONS

We have achieved close to our goal of building an elliptical mirror with an optical length of 0.917m with a slope error of less that 3 μrads rms. However, there is room for improvement in several key areas. There are two future directions to investigate, either to develop methods to produce a much flatter initial substrate, or to introduce more sophisticated methods of correction. To produce a flatter substrate appears to be difficult, and so we must learn to compensate for the resulting initial curvature. By introducing more forces,. we could clearly more precisely eliminate errors. Our yoke arrangement was added after construction of the bending mechanism, and clearly could be improved and expanded to easily include 3 force actuators. An alternate direction will be to change the width or thickness of the mirror after polishing to locally change the section moment and hence the local curvature. This could most easily be accomplished in a stress free machining operation by wire electric discharge machining of the width, and would require the edge to be free of nickel plating. Now we have worked out the methodology of manufacture, it appears that manufacture of large elliptical mirrors by this method should result in a low slope error surface at low cost.

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