Towards a large, lightweight mirror for AO - Development of a 1 m Ni coated CFRP mirror

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ABSTRACT

We present our recent developments towards the construction of a large, thin, single-piece mirror for adaptive optics (AO). Our current research program aims to have completed fabrication and testing of a 1 m diameter, nickel coated carbon-fibre reinforced cyanate ester resin mirror by the last quarter of 2009. This composite mirror material is being developed to provide a lightweight and robust alternative to thin glass shell mirrors, with the challenge of future large deformable mirrors such as the 2.5 m M4 on the E-ELT in mind. A detailed analysis of the material properties of test mirror samples is being performed at the University of Birmingham (UK), the first results of which are discussed and presented here. We discuss the project progress achieved so far, including fabrication of the 1 m flat moulds for the replication process, manufacturing and testing methods for 20 cm diameter sample mirrors and system simulations.

Keywords: Large deformable mirrors, adaptive optics, carbon-fibre composite

1. INTRODUCTION

The design studies for next generation ground-based optical telescopes are underway. A number of these (e.g. the Giant Magellan Telescope (GMT)[1] and the European Extremely Large Telescope (E-ELT)[2]) are considering the incorporation of large adaptive mirrors as an integrated part of the telescope. Of particular relevance to this research is the adaptive M4 in the E-ELT design which is a 2.5 m diameter flat; current thin glass shell technology will be difficult to scale to this size for a monolithic mirror and segmented designs pose other problems and increase the operational complexity. The GMT design has alleviated this problem by having the same number of adaptive secondaries as there are primary segments and mapping each primary segment to a particular adaptive mirror of a size that is within manufacturing range for thin glass mirrors. For designs requiring larger adaptive mirrors or where fracture of thin glass plates is of concern, carbon-fibre composite (CFC) mirrors are a possible solution. Carbon-fibre mirrors can be useful where weight is an issue, both in space and ground based telescopes. CFC can be made to large diameters (limited only by the size of the autoclave), are lightweight, robust and can be handled and cleaned without risk of breakage. Carbon-fibre is available with a wide range of properties and can be combined with a variety of different resin systems to provide a material tailored to requirements.

Carbon-fibre has been used for a number of years to construct the panels in radar dishes, communications satellites and other longer wavelength (down to sub-millimeter) telescope apertures. So far CFC mirrors have not been used for visible wavelength imaging due to surface quality issues and low form accuracy. The Optical Science Laboratory at UCL has been investigating different types of carbon-fibre composite mirror for use in optical applications for over 5 years. Initial prototypes were stiffer, actively controlled mirrors composed of an electroformed nickel face-plate bonded to a carbon-fibre-aluminium honeycomb sandwich.[3,4] More recent developments have been towards adaptive mirrors made from thin carbon composite cores and electroplated in nickel to provide the reflective surface.[5,6]

The aims of this project are to manufacture, coat and polish a 1 m diameter nickel coated carbon-fibre composite mirror, including a detailed analysis of material properties to highlight any potential problems. We

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also aim to test the reproducibility and consistency of the mirror material properties over different manufacturing runs. The suitability of the mirror for use as an adaptive optic will be investigated in simulations and by testing with a variety of actuation technologies, including a lifetime actuation test.

2. DESIGN AND MANUFACTURING

The creation of a Ni-CFC mirror involves 3 key stages: (1) making an appropriate mould for the CFC replication process, (2) CFC lay-up and curing, (3) nickel electroplating and polishing. Finite element analysis (FEA) has been utilised at each stage to optimise the design and also to investigate problems in the manufacturing procedures. These simulations will be discussed in the relevant sections.

2.1 Moulds

The carbon-fibre mirror core is made via a replication process. A mould or mandrel of the inverse required mirror form is first manufactured and the carbon-fibre plies are placed on to this mould. Since the carbon-fibre core will undergo further processing in preparation for the electroplating stage, our moulds do not have to be polished to the final optical quality required. The moulds are ground to a 1-2 μm form accuracy and have a uniform, fine ground surface finish. The required number of disks are cut-out of the CFC material to the same diameter as the mould and placed onto the base mould tool in the desired sequence (termed a 'lay-up') as discussed in the next section.

For this project the mirror form is a flat, as is also the case for the adaptive M4 in the ESO E-ELT design. We have made concave mirrors in previous projects. For the smaller test mirrors we are using a 20 cm diameter, 70 mm thick, solid aluminium mould. The test mirrors are trimmed down to a 19 cm diameter to remove any edge effects.

2.1.1 1 m mandrel fabrication

Designs for the mandrel on which the 1 m CFC mirror will be formed are complete and fabrication is underway. The mandrels are being made out of rolled aluminium, type 5083 in 'O' condition (a heat treated form to reduce internal stresses) to ensure the mould will not deform during the various processing stages of optical grinding.[7,8] The base mould is 1.05 m in diameter and 125 mm thick; the oversize in diameter allows trimming of any spurious edge effects to produce the desired 1 m diameter mirror. Since the mould will be seated on an uneven surface in the autoclave it was designed with a 3-point support underneath, the position of these points was optimised in FEA to minimise any sag due to gravity. The mould will be ground to the required form whilst resting on these 3-points and so essentially the sag due to gravity will be removed. However, the optimisation ensured that the variation in amount of material removed due to the gravity distortion was minimised and also provided the best

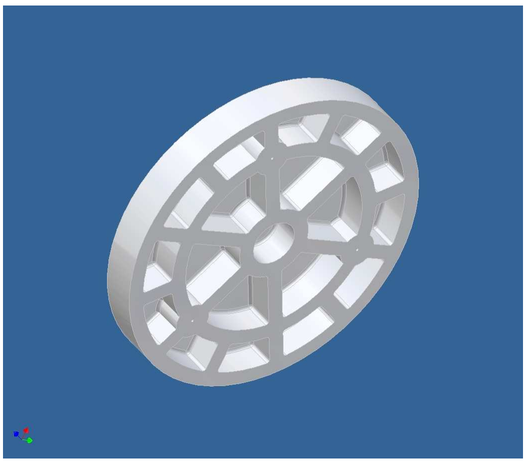

Figure 1. Computer-generated image of the 1050 mm diameter aluminium mould, view from below.

support on 3-points should the surface deviate from the horizontal. Figure 1 shows the design from underneath to illustrate the cut-out pattern (to reduce the weight) and the 3 support points. The final mass of the mould is 171 kg, within the 200 kg constraint imposed for handling considerations and the maximum load bearing of some measuring equipment.

2.2 Composite design

The carbon fibre core of these mirrors is constructed out of unidirectional (UD) carbon fibre material pre-impregnated with a resin. The proportion of fibre to resin is given as a volume fraction (Vf) and is usually around 60% fibre. The fibre/resin system we are currently testing is IM7 made by the Hexcel Corporation and LTM123 cyanate ester resin by the Advanced Composites Group. The UD material in this case is 70 μm thick and has a 60% fibre Vf. Material is available in thicknesses greater and less than this, however as the material thickness decreases inconsistencies increase due to the spreading out of the 5 μm fibres on the rollers resulting in increased likehood of gaps and twists in the fibre bundles but thinner material also allows more plies (layers) in the stacking sequence which has other advantages as will be discussed here. Cyanate ester resins have superior properties compared to epoxy resins for our purpose; they have much improved micro-cracking resistance and low absorption of water. As a comparison, the mirror material used in the proof of concept project[6] prior to this is also being tested; this used a higher modulus fibre, M55J, with the same resin system.

2.2.1 Lay-up sequences

Different ply lay-up patterns are being tested to find the best compromise between increased isotropy, number of plies (thickness) and number of sequence repeats. Since the bending stiffness of the mirror increases with increasing thickness a rough limit on the maximum thickness can be calculated depending on the Young's modulus of the chosen fibre type. A lower limit on thickness also occurs due to the requirement for a fully symmetric, balanced lay-up sequence needing a minimum number of UD plies.

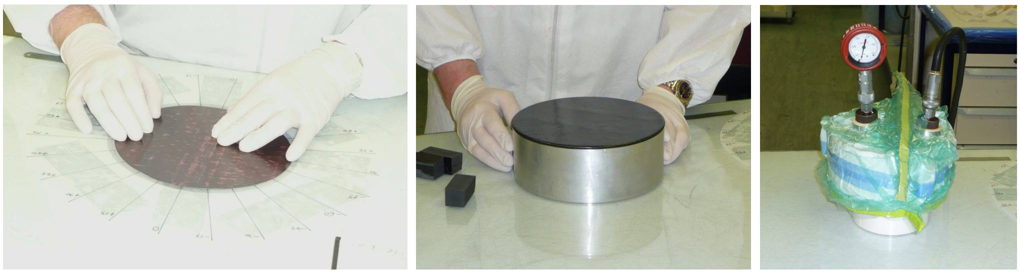

Figure 2. Some stages in the procedure for making the CFC core.

We have intiated our tests based on 2 alternative lay-up patterns consisting each of 48 plies of 70 μm thick as follows:

- $2 \times [0/90/15/-75/30/-60/45/-45/60/-30/75/-15]_S$
- $3 \times [0/90/22.5/-67.5/45/-45/67.5/-22.5]_S$

resulting in a mirror ~3.3 mm in thickness. The numbers in square brackets detail the angular lay-up sequence in degrees with the multiplier indicating how many times this sequence is repeated; the subscript 'S' shows that this is a symmetric lay-up and so the sequence is reflected about the mid-plane. Computer simulations have shown that a greater number of sequence repeats in the pattern should give an increased resistance to any angular positioning errors, also the smaller the angular increment and the greater the number of plies there are should provide increased isotropy in material properties and good linear elastic behaviour. New lay-up sequences can be devised should the need arise.

Some key stages in the manual lay-up procedure are illustrated in Fig. 2. A CAD template is drawn up with radial marks at the angular increments required and circumferential marks to allow accurate centering of each circular ply. To allow accurate angular positioning a membrane is applied to the upper surface of the CFC material on which a line is drawn to indicate the fibre direction; this is done on the cutting machine before the disks have been cut-out from the roll. To facilitate this stage for the 1 m mirror lay-up a pegged rotary table will be engineered to replace the simple CAD template. The mirror is assembled in smaller stack sequences than the whole since there are a reasonable number of them. Each of these stacks are consolidated (vacuum pressed to remove air) before being assembled into the whole mirror which is again consolidated. The ply stack is placed on the moulding tool and vacuum bagged for the autoclaving.

2.2.2 Curing cycle

Once the lay-up is complete it must undergo a controlled heating and cooling in an autoclave to fully cure the resin and ensure minimal stresses are introduced into the composite due to the resin shrinkage as it sets. If some parts of the mirror fully set before others, stresses will be locked into the material causing the piece to deform on release from the moulding tool, so the mould tool must be well insulated on all sides and a slow thermal ramp (e.g. 1°C per minute) up to the full curing temperature of 177°C must be performed to ensure all parts are in thermal equilibrium.

2.2.3 Estimation of properties

An estimate of the material properties of the resulting composite can be calculated using a number of techniques. The simplest is to apply the 'Rule of Mixtures', which is a weighted mean of the different material components of the composite based on the volume fraction of each. It can be expressd as follows

$$P_c = fP_f + (1-f)P_m \tag{1}$$

where P_c, P_f and P_m are a given property of the composite, fibre and matrix (resin) respectively; f is the volume fraction and is a number between 0 and 1. Equation 1 is used to calculate the density and gives a good approximation for the axial Young's modulus of each ply when the Poisson's ratio of both materials are similar. A value for the transverse Young's modulus is more detailed and can be obtained using the Halpin-Tsai method.[9] Theoretical estimates of the thermal expansion of composites requires a more complex treatment, a summary is given in Hull and Clyne (1996).

Since each ply has orthotropic properties, the overall properties of the composite must be calculated by summing over all the plies in their angular orientations. Some FEA computer programs, such as the laminates calculator in I-DEAS allow you to design plies from basic fibre and resin properties, enter your lay-up sequence and produces the materials data for the new composite. The theoretical properties of 2 types of composite calculated in this way are given in Table 2 alongside the measured values for comparison. A theoretical value for the CTE of the IM7/LTM123 composite was not calculated as no thermal data was available from the manufacturers for the IM7 fibre; it is estimated to be greater than that for the M55J/LTM123 composite since it is a general trend that as the modulus of carbon-fibre decreases the coefficient of thermal expansion becomes increasingly positive. For the data so far obtained there is good agreement between the estimated and measured properties.

2.3 Nickel Electroplating

To address issues relating to the resistance of CFRP to environmental factors, both UV degradation and moisture absorption and expansion, the CFC core is totally encapsulated in a thick ($\sim 50\,\mu$m) layer of nickel. This thicker metal coating also eliminates the problem of fibre print-through[5] which is usually seen in thin reflective coatings over CFC. The coating is applied in a nickel sulphamate electrochemical bath, operated at room temperature, low current density and negligible chloride ion content to give a stress-free nickel deposit, full process details are given in a previous paper.[6] Since the coating is required on all sides and edges of the mirror and to reduce the likehood of distortions being introduced by bonding and removal of electrode contacts, a plating rig was devised to provide a moving electrode contact as shown in Fig. 3. The current is supplied to the mirror via a titanium roller in contact with the edge of the mirror which is spinning in the rig by means of a motorised rubber roller.

Scalability of the spinning electrode rig to a size suitable for the 1 m mirror is an outstanding issue. Adaptions to the current design are ongoing, to optimise the working efficiency and reduce the chances of the mechanism failing during the several hours it has to operate in the plating tank.

Figure 3. (Left) The spinning electrode mechanism. The titanium electrode contact is on the bottom left of the rig, with the motorised roller on the bottom right to spin the mirror. (Right) The nickel sulphamate electroplating tank into which the entire mirror rig is immersed and connected to the brass cathode.

3. OPTICAL POLISHING AND TESTING

3.1 Grinding and polishing

The nickel coating obtained using the electrochemical deposition is of a uniform matt silver-grey on removal from the bath and needs to be ground and polished to produce the desired reflective, optical surface quality. Further thin coatings can then be applied to the polished nickel to provide the level of reflectivity required e.g. an aluminium or gold vacuum deposit. Since these mirrors are designed to be thin and reasonably flexible great care must be taken during the polishing process to ensure an unwanted form of stress-polishing does not occur. This would result in an incorrect mirror form being produced when the polishing forces are removed.

3.2 1 m flat optical test set-up

Optically testing large flats is challenging. Tests are normally carried out using a reference parabolic mirror which is nominally more than double the diameter of the flat to be tested and the Optical Science Laboratory at UCL does not possess one. Using the largest lens we have in-store (a reference sphere of radius of curvature = 2744 mm and diameter = 1066 mm) two optical test set-ups were devised that could be used to measure the 1 m mirror and

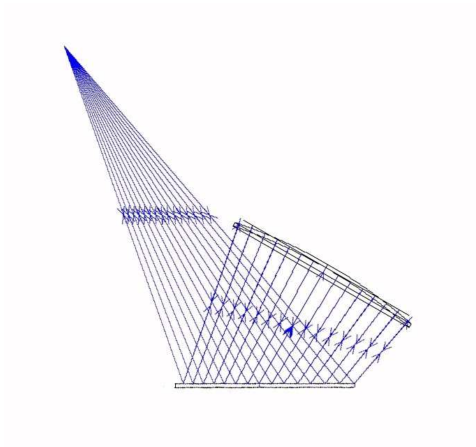

Figure 4. Optical ray trace of 1 m flat mirror tested against a reference sphere (R_{curve} = 2744 mm, diameter = 1066 mm).

Table 1. Methods under consideration for supporting the thin optic during polishing.

Method	Pros	Cons
Wiffle tree system with support points at the actuator spacing	Accurate	Large number of points required, bulky, expensive
Hydrostatic mount of linked pistons	Accurate, excellent support	Large number of pistons required, expensive
Using hard button pitch and an optical flat to adhere mirror to a robust support plate	Simple, quick to set-up	Stresses can be pressed in, need large optical flat
Floating mirror on layers of bubble wrap	Simple, quick to set-up, low cost	Needs complicated edge constraint
Mounting on a compliant bag of viscous fluid	Good support, low cost	Needs complicated edge constraint, applies more pressure at edges
Mounting mirror on its actuator system	Supported on final system	Handling, potential for damage to actuators
Mounting in a pressurised container with mirror fixed at edge	Good support, can adjust pressure to modify form	Complicated edge constraint

mould. The first of these is a reverse Hindle sphere test using an Offner corrector to compensate for the spherical aberrations generated. The second is a simple test utilising the reference sphere as a mirror and folding the beam using the 1 m flat we are manufacturing. The flat is mounted on the polishing machine and the reference sphere set at a 30° angle in the test tower. An additional fold flat is also required to steer the beam from the interferometer. We decided to use the second method since this gives a perfect null test with zero aberrations; a ray-trace of the set-up is shown in Fig. 4.

The support structure that will be used during the grinding and polishing has yet to be decided. Methods that have been used successfully in the past for manufacturing other thin optics are being evaluated for use on the 1 m diameter, 3 mm thick Ni-CFC mirror. A summary of some of the methods being considered are listed in Table 1; small scale experiments are being envisaged to test the most suitable of these that can be used in OSL.

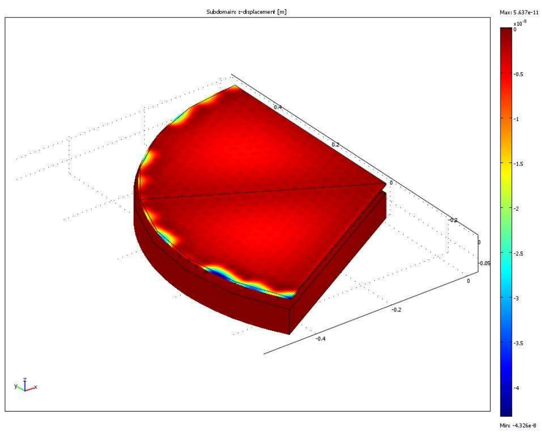

Figure 5. Finite element analysis of a section of the 1 m Ni-CFC mirror mounted on a lightweight circular backing plate with piezo-ceramic column supports at a spacing of 30mm, hexagonal pattern. Model shows the system sag due to gravity (vector in -z direction), as might be supported for polishing.

3.3 Backing supports and actuation

Design work and simulations are being carried out to investigate suitable backing structure supports for the 1 m Ni-CFC mirror and overall system simulations of it's actuation, thermal effects, sag due to gravity etc. The proposed backing plate will be comprised of an aluminium honeycomb sandwich structure with face-sheets of reasonably thick, high modulus carbon-fibre composite. If required for the actuator mounting, through-holes can be pre-drilled into the the structure and lined with CFC (which furthermore can be threaded) at the forming stage to provide a more robust structure. A backing plate for the 1 m mirror of this composition might weigh as little as 12.5 kg, based on preliminary designs. A choice for the type of actuator to be used in the system is still under review, a short-list has been drawn up and individual actuators will be tested on the smaller mirror samples before a final decision is made.

An example of a possible system, supported on column actuators is shown in Fig. 5. The result shown here is the sag due to gravity when the backing plate is supported around the outer edge and along radial struts on the base at a 60° spacing.

4. MATERIALS ANALYSIS

A microstructural and mechanical property characterisation of the Ni-CFC mirrors is being undertaken at the University of Birmingham. The results of this are being used to confirm theoretical calculations of the composite at the design stage, determine material homogeneity and address any lifetime issues.

4.1 Properties

A nominally 190 mm diameter, 3 mm thick carbon fibre reinforced polymer (CFRP) disk was supplied by UCL. This was instrumented with 8 Kyowa biaxial strain gauges (2 mm long etched copper gauges mounted orthogonally) at mid-radius and spaced at 45° intervals to measure radial (R) and circumferential (C) strains as shown in Fig. 6. The 0 - 180° direction is defined parallel to the fibres on the surface UD ply.

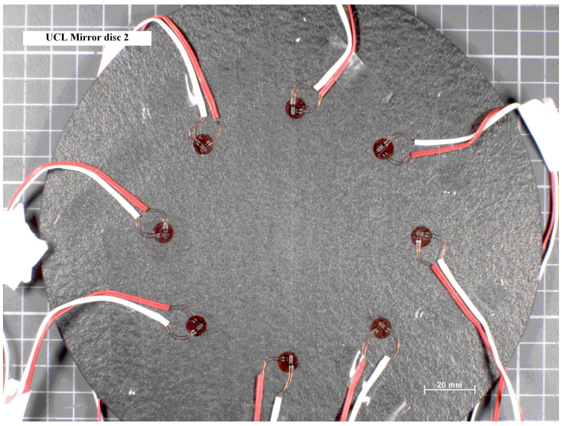

Figure 6. The 8 strain gauges attached to rear surface of a 19cm diameter CFC disk.

The disk was simply supported (horizontally) around its outer circumference and loaded centrally with weights from 1 to 10 kg, photographs of the experimental arrangement are shown in Fig. 7. The deflection of the disk centre was measured using a vertically mounted Solartron S55 long travel transducer. Figure 8 is a plot of 6 loading and unloading cycles, as measured by the Solartron transducer. During these loading and unloading cycles the deflection of the disk centre showed an initial settling of the loading points followed by lower stiffness region up to around 5 kg loading and then a stiffer region up to 10 kg loading. During loading and unloading there was no noticeable time dependence and the composite disk showed linear elastic behaviour.

An overall measure of the Young's modulus, E, of the disk can be calculated from the data in Fig. 8. The standard formula for Young's modulus of a point, centre loaded circular disk, simply supported around its lower

Figure 7. Experimental set-up used to measure the Young's modulus of the samples.

edge can be found using[11]

$$E = \frac{3(1-\nu^2)WR^2(3+\nu)}{4\pi\delta t^3(1+\nu)} \tag{2}$$

where R is the disk radius, t the thickness, ν Poisson's ratio and δ the measured displacement for the applied load W. Equation 2 is only applicable where the displacement is a result of an entire bending of the disk in a circular arc. This is not the case for the disks tested so far as the radial strain gauge readings were much lower compared to the circumferential readings. A modified version of the formula[12] is used, for the case where the disk deformations are principally located in the central region around the applied load, the difference being an approximate factor of 2 greater than that quoted. An estimated value of $\nu = 0.3$ is currently being used until a measurement can be taken.

Strain gauge readings were taken during loading and unloading via a 4 channel PCD-300A amplifier. Two channels were used for the radial and circumferential gauges at the 0° position in each test with the other two being used sequentially for the 45 - 315° positions (radial and circumferential). Repeated measurements are required to get a reasonable average, but from the initial round of testing on the first sample a variation of approximately 10% was recorded in the microstrain readings between the different positions. This variation does not correspond to fibre lay-up orientations; our current hypothesis is that the variations are due to fibre-

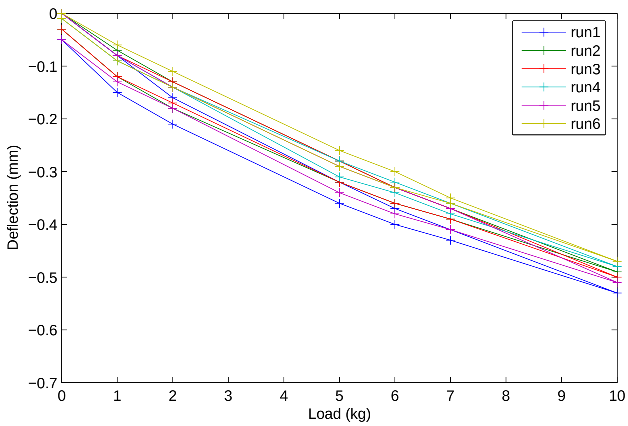

Figure 8. Graph showing the deflection of the mirror centre over 6 loading and unloading cycles.

Table 2. Material properties of two types of carbon-fibre cyanate ester composite that we have used and measured; 'tbd' denotes that the value is yet to be determined. Both are of a 15 degree increment lay-up, fully balanced and symmetric.

Properties	IM7/LTM123		M55J/LTM123	
	Theoretical	Measured	Theoretical	Measured
Youngs Modulus, E (GPa)	65.5	61.5 (av)	109.5	110.0 (av)
Density, ρ (kgm^{-3})	1545.2	1498.0	1637.5	1547.2
Coefficient of thermal expansion, α ($\times10^{-6}K^{-1}$)	$>$ -0.5	tbd	-0.53	tbd
Fibre volume fraction (%)	60		62	
Number of plies, ply thickness	48, 70μm		24, 120μm	

rich/resin-rich patches, found adjacent to each other and could be alleviated by more careful handling of the plies during the forming process.

Variations and general measurements of the Young's modulus can be taken using a variety of techniques. A novel method[13] that will be used as a follow up investigation uses forced and free vibration spectral analysis using a Brüel and Kjær PULSE system to determine variations in the excited modes compared with computer models of the isotropic system case.

To obtain an estimate for the thermal expansion coefficient, the radial and circumferential strain gauge readings at the 0 and 135° positions were monitored as the disc was heated in an oven from room temperature (16°C) to 73°C and compared with the strain in an unmounted gauge and a gauge mounted on an aluminium block over the same temperature range. An unexpected variation in strain from an increase to a decrease was observed for the gauge mounted on the CFC disk, possibly indicating a removal of residual stresses from processing or a geometric distortion arising; further investigations are required. A summary of the properties of 2 different CFC samples are listed in Table 2. This includes the expected values as calculated from theory and the experimental data that has been obtained so far.

The measurements discussed here were on the uncoated CFC core, prepared as it would be just prior to the electroplating stage. In the near future these same samples will be electroplated with nickel and polished and the material analyses performed again to monitor how the properties change.

4.2 Structure characterisation

The nature and strength of the bond of the nickel coating to the CFC core has yet to be determined experimentally. However, the amine groups on the cyanate ester resin should form relatively strong bonds to any oxide groups on the metal, although since the resin is fully cured when the metal is deposited this bonding is not as strong as when the resin is in a reactive state and so will need some investigation. Nickel forms no known stable carbides and so the Ni-C bond will be Van der Waals forces only. The fact that nickel carbides are unstable are a benefit in this case, as this means that one path for corrosion at the Ni-CFC boundary is eliminated. In addition, metal carbides only form at very high temperatures and since the nickel is deposited at room temperature and the operating conditions for the mirror are at significantly lower temperatures than those required for carbide formation the likehood of any forming is negligible.

5. CURRENT STATUS AND FUTURE WORK

The 1 m mould tool is currently being manufactured and is expected to be completed over the next few months. Tests are on going using the smaller 20 cm diameter mould tool, experimenting with alternative lay-ups, lay-up strategies for the case where each ply is made up of more than one section (as will have to be the case for the 1m mirror), and resin cure cycles to ensure minimal stresses and hence distortions in the CFC core produced.

Additional materials analyses are planned; these include image analysis using Birmingham University's KS400 sytem to study the through-thickness material characteristics (including the nickel layer), a Jeol 7000 scanning electron microscope to assess grain size of the nickel deposit and crystallographic texture and a dilatometer which can be used to measure the coefficient of thermal expansion both in and out of the sample plane. The material will be studied both before and after electroplating and after a lifetime actuation test to investigate any changes that may occur.

It is also anticipated that the Ni-CFC mirror samples (19 cm diameter) will be tested on some externally developed AO systems to compare alongside other mirror materials. The 1 m Ni-CFC mirror and subsequent testing of it is scheduled for completion by end-2009.

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