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1 Introduction

1.1 Scope

This document highlights the technical requirements and challenges in the design and fabrication of lightweight deployable mirror made from polymer matrix composites for operation at 4K temperature. Outlined in this document is the comparison between segmented or monolithic mirrors for space telescopes and current materials used for optical surfaces for astronomical observation. From there state-of-the-art technologies for reflectors and composite mirror fabrication techniques are discussed. The report then concludes with a literature review of the testing and classification of composite materials at 4k, and suggestions for how the utilisation of carbon fibre reinforced plastic composites must progress in order to reduce risk and improve the readiness level of such technologies.

1.2 Introduction

The production of lightweight optical surfaces with high accuracy in both form and texture is paramount for cost and mass reduction in future space telescope applications. In the European Space Agency (ESA) Cosmic 2015-2025 vision programme a Far Infrared Interferometer (FIRI) mission was proposed. The Far Infrared (FIR) waveband operates at between 30-300µm and is yet to be explored in detail. The FIR region contains vast amounts of information as to the origins of planets, containing half of the electromagnetic energy released during the evolution of stars and galaxies (Harwit, 2010).

The REA funded Far Infrared Space Interferometer Critical Assessment (FISICIA) project proposes the study of using interferometry to investigate this under observed waveband. An interferometer uses two or more widely separated telescopes to collect and combine the signal to achieve high resolution images greater than the diffraction limit of an individual telescope (Monnier, 2003). The greater the distance, or baseline, between the telescopes, the greater the achievable angular resolution. This technique does have disadvantages however; the telescopes in the interferometer have a small diameter so therefore collect less photons than an equivalent single aperture telescope of matching resolution. This means that the interferometer requires stronger sources, especially in the optical and infrared region. Despite this limitation space interferometry provides the high resolution imaging required for the Far Infrared without the necessary requirement for a large aperture telescope being launched into space which would be both expensive and difficult. Another issue with large aperture telescope for space is mirror deployment. The James Webb Space Telescope (JWST) is due to be launched in 2018 aboard the Arianne V space vehicle and will utilise a 6.5m diameter mirror. The size of this mirror eliminates the possibility of a monolithic mirror due to the payload area volume of the spacecraft. This causes the designers of the telescope to produce a deployable mirror that can be stowed inside the Arianne V.

Deployment technologies are not a new concept in satellite design especially for solar panels but to maintain the form accuracy required for telescope optics in the optical and far infrared wavelength still remains a significant challenge.

The ability of space interferometry to produce high resolution images is paramount to the FISICA project. It is in the wavelength of 30-300 µm that most cold object emits their light (Savini, 2014). It is therefore essential that the telescopes collecting this light do not cause photon background loading via self-emission, achieving this by the cooling the telescope mirror less than ~5K (Swinyard, 2009). Mirror diameter has previously been limited by the cooling technologies used, with Liquid Helium being the primary method in similar missions previously. This limitation in aperture size restricts the sensitivity of the optics in comparison to larger mirrors used at other wavelengths. The FISICA study has prescribed a possible conservative case, with a restricted aperture size, and a more demanding case with a much larger aperture area. The more conservative case will be investigated using technologies that currently have high Technology Readiness Levels (TRL) and would involve little risk at a reasonable investment of resource. The more ambitious case allows the project to look at technologies currently in the early stages of development that would push engineering and scientific boundaries further, inevitably with this expansion in technology comes a reduced TRL and also an increased risk. Further development of the technologies for the purpose of a cryogenically stable composite mirror would require further investment in the capability of institutions and research. This report seeks to provide sound reasoning and justification for the expansion in investment using current literature and a development of a prototype.

The areal density of the mirror is critical in order to allow as much mass budget for the reflector and other instrumentation to achieve the high resolution required at this under observed waveband. The diameter of the optical reflector is directly linked to the amount of energy it can gather and also its diffraction limit. Conventional telescope materials, zero expansion glass etc. have too high a density to support this increase in area. Studies into composite mirror technology for land and space mirrors are well documented and will be summarised in the report. One aspect of this project that stands out from the literature is the requirement for the mirror to be cryogenically cooled during operation to just 4K (-269^{o}C). Little literature exists for polymers and composites at this temperature; this report seeks to provide research into this area for the application. The research will involve material selection and then experimentation as to the material properties of composite materials at 4K environment. Once material properties have been obtained a Finite Element model will be created that explores how the mirror will behave during thermal cool down from room temperature fabrication to cryogenic operation. As the deformation is critical in this aspect results will be verified using experimentation in a cytostatic chamber and metrology.

One further area that needs to be explored is the infrared emissivity of the mirror. This will need to be controlled in order not to introduce distortion to the infra-red signal causing errors in the readings.

The baseline requirement of the mirror has been given for both a conservative and ambitious case and is shown in Table 1. These baselines have been taken as design specifications for the mirror and will need to be investigated thoroughly.

Table 1: FISICA Baseline Mirror Specifications

	Case 1	Case 2
Mirror will be deployable (Segmented Primary)	No	Yes 7
Preferred size and shape of each mirror segment	NA	Hex
Deployed overall size of clear aperture	2m	6m
Deployed overall shape	Circular	Hex
Central perforation?	No	No
Nominal form	Parabolic	TBD
Areal density target (~1.10 areal density of Hubble)	<30kg/m2	<30kg/m2
Preferred interface to sub-system	3-point	TBD
Approximate focal length	1m	<2m
Surface form error specification	275nm	275nm
Surface texture (“roughness”) specification	80nm	80nm
Mid spatial frequency specification	TBD	TBD
Maximum edge-misfigure	TBD	TBD
Maximum edge dead area (non-reflecting)	N/A	TBD
Surface coating	TBD	TBD

2 Mirror structure

2.1 Segmented or Monolithic Mirrors

The primary role of a telescope reflector, whether that is in space or on the ground, is to collect and focus electromagnetic radiation to a focal point (Cheng, 2009). The surface area of the aperture is directly related to the light gathering power and resolution of the telescope meaning that scientist and astronomers can view images more clearly and further into space than ever before.

For a single aperture telescope the maximum angular resolution (θ) achievable is

$$\theta = 1.22\frac{\lambda}{D} \tag{2.1}$$

Where observable wavelength is λ, and D is the diameter of the mirror (Cheng, 2009)

This simplified formulae is driving development of telescope mirror with increasing aperture size both in production and under discussion for both space and land applications. However monolithic mirrors are severely restricted in size by fabrication and transportation issues.

At present the largest diameter telescope mirror manufactured is an 8.4m borosilicate honeycomb primary mirror segment fabricated by the Steward Observatory lab (Walker, 2012). This forms a single segment for the Giant Magellan Telescope, due to see first light in 2020. The largest single mirror launched into space was for the Herschel space telescope at 3.5m diameter, which ceased operation in mid-2014. Herschel mirrors were made from segments of a reinforced Silicon Carbide material that is brazed before figuring and polishing. The largest glass single mirror used was for the Hubble space telescope at 2.4m manufactured from ULE, (Baiocchi, 2009).

The diameters of monolithic mirrors are generally constrained in space telescopes by the internal volume of the payload bay of the launch vehicle. The current launch vehicle of choice, Arianne V which will launch the James Webb Space Telescope, has an internal fairing diameter of 4.5m diameter Future launch vehicles are being proposed and investigated with larger fairing size such as the proposed Ares V (8.8m internal fairing). If developed, the payload of the Ares V, for launch into an L2 orbit, will also be significantly larger than the Arianne V launcher at ~56,000kg as compared to 6,600kg, (Stahl, 2009).

Ground based telescopes such as the Very Large Telescope (VLT) and Subaru Telescope use monolithic primary mirrors up to a maximum of 8.2m diameter. Manufacturing of a mirror blank this size is a challenge, but methods such as spin casting (Martin, 2004) are suited for the task. However polishing, and in particular, coating of mirrors of that size becomes a difficult due to lack of suitable facilities. Another issue is the transportation of segments of that size and mass via conventional means, particularly as most astronomical land telescopes are at inaccessible locations. This difficulty is certainly solvable, but the challenge of transportation certainly remains.

Monolithic mirrors have a number of benefits over segmented mirror design. The design and development risks associated with a monolithic mirror are significantly less than a segmented mirror. Mirrors ground and polished from slabs of slumped glass have been the choice of opticians for centuries. These types of mirrors have developed with material technologies advances from zero expansion ceramics to polymeric composites. A monolithic mirror will, in general, produce a cleaner, more uniform, Point Spread Function (PSF) (Kendrick, 2009) than a segmented mirror. It will also provide diffraction limited performance at shorter wavelengths required for FISICA. However, the largest facility available to manufacture and polish a monolithic mirror can only accommodate an 8.2m diameter mirror (Martin, 2004). If larger monolithic mirrors are required, significant investment and development in facilities and research would need to be undertaken to achieve this aim. Another issue is that monolithic mirrors require thicker substrates to alleviate gravity sag. As a rule of thumb, diameter D and thickness t, are related according to the ratio (where t is the mirror thickness):

$$\frac{D^4}{t^2} \tag{2.2}$$

Without light weighting procedures this increase in thickness will inevitably cause a large increase in mass.

Segmented mirrors enable the production of larger mirrors in comparison to monolithic mirrors. The main issue with large monolithic mirrors mainly concerns fabrication, especially the availability of coating chambers larger enough for sputter and vapour deposition operations. Discussed previously, monolithic mirrors diameters are limited by the transportation of the mirror to its operating location, whether that is on top of a mountain for land telescopes or limitations of payload fairing volume in space transportation. Segmented mirrors create large apertures by aligning the edges of smaller segments during assembly or deployment achieving a more cost effective method to creating large mirrors. This process eliminates some of the issues with manufacturing large mirror blanks, but provides other difficulties such as aligning the edge of each segment and joint print through.

Mirror segmentation is especially susceptible to wave front errors due to polishing roll off of surface edges (Kendrick, 2009). This causes an area of approximately 5mm wide at the interface of two segments resulting in scatter. Edge roll off control in glass segments has traditionally been difficult, however, this issue is reduced drastically by the use of compliant polishing tools (Walker, 2012). Edge misfigure can also affect other materials that require a conventional polished surface, such as metal mirrors. One advantage that a replicated CFRP mirror segment would have is that its edges can be accurately cut using laser or water jet cutting equipment after cure. This would reduce the unusable area at the segment boundaries to that of the gap. The error caused by excessive gaps between mirror segments must be allocated in the overall error budget of the entire aperture, reduction in errors due to edge misfigure may allow relaxation in other areas.

Expansion and contraction of the mirror segments would also need to be taken into account during design. Utilising materials with little or no expansion over the operating temperature range should be able to negate the issue but care must be taken to ensure that all connected components are also not susceptible to dimensional changes caused by temperature variation.

For a segmented mirror to form the correct shape once assembled or deployed, the edges of the mirrors must meet accurately. The system that corrects the edges can either be an active system that monitors changes in position during operation, for example the changes in gravitational vectors when tracking the sky or can be passive and fixed. The result of mismatched edges would be excessive scatter of light reducing the power of the telescope.

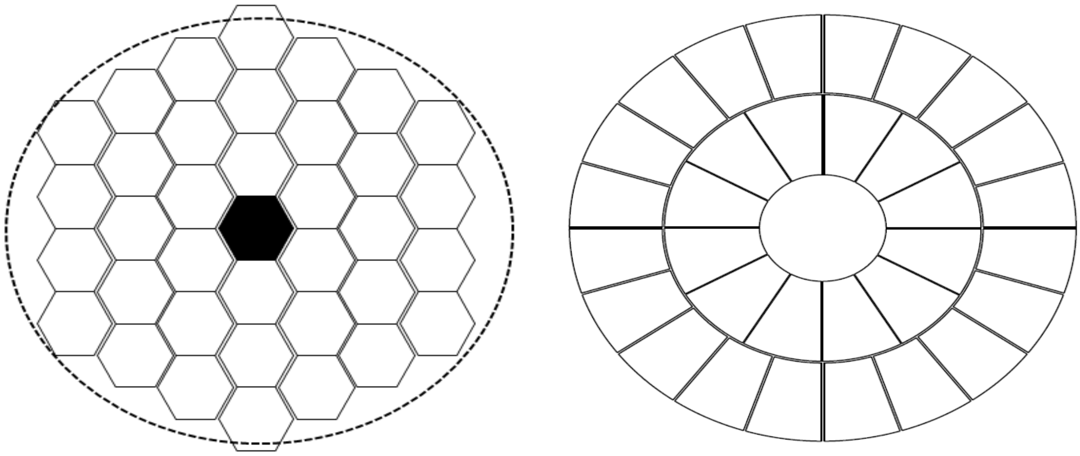

Figure 1: Segment mirror architecture

Segmentation of mirrors allows designers to create either larger aperture telescopes for land D>8.5m, for example the European Extremely Large Telescope (EELT), or relatively large space mirrors D>3.5m, such as the James Webb. Monolithic mirrors for the two examples above would not be possible due to the issues previously discussed. One choice designers and scientists have to make is segment size and shape. As most, if not all, primary mirrors used for observations are aspheric curves, the shape and size of segments is critical in achieving the correct focus of a mirror. The larger the mirror segment, the greater the departure from flat that needs to be polished into the blank, increasing production difficulty. The size of the segments determines the total length of the edges which has a direct relationship to the amount of scatter in an aperture. The segments therefore must not be too large in order to be able to control edge gaps but large enough to reduce the burden on fabrication and maintenance. A very difficult trade off decision

According to Bely the advantages of smaller segment sizes are numerous (Bely, 2003). Smaller segments deflect less due to lower self-weight and a shorter distance between supports. Small segments are less sensitive to orientation and radial positioning errors and are easier to handle, meaning smaller cranes and more available coating facilities. They are also easier to test with a wider number of facilities available for mirror segments of up to 2m. Additionally for equivalent stiffness to prevent gravitational sag smaller segments are thinner. This results in lower areal density and less time for isothermal cooling or heating (Kendrick, 2009)

Rather obviously, smaller segment sizes mean that more segments are necessary, requiring more prescriptions to be polished into the surface and more actuators and edge sensors causing greater possibility of active component failures. In deciding the segment size, one must trade off each of these issues to form a suitable decision. The key driver will most likely be which technologies have been used on past telescopes and what lessons were learned in their development. If facilities and methodologies currently exist, then the production and development of the mirror could be significantly reduced.

Segment geometry is also a critical design choice. The most common two segment shapes are hexagonal and petals as shown in Figure 1. The choice of mirror segment geometry depends heavily on the size of the mirror diameter and its final application. Most large ground based telescopes will use hexagonal segments to form the primary mirror. Hexagonal segments form multiple ring arrays meaning that the total number of prescription is higher than that of a petal segment arrangement. This means more blanks need to be fabricated, increasing cost due to more tooling and spares. However, the prescription polished into hexagonal segments is normally simpler to fabricate than that of a petal. That being said, the asymmetric geometry of a petal means that more fabrication facilities may be available. For example the largest Hydrostatic Press (HIP) for Beryllium mirrors is asymmetrical, meaning larger petal segments can be manufactured in comparison to symmetric hexagons. The symmetry of hexagonal segments is an advantage, however, because it offers more uniform stiffness, allowing simpler placement of actuators to maintain edge gaps and curvature control. In reality for large aperture mirrors the outer segments are elongated in the radial direction due to the curvature of the mirror (Baffes, 2008). The maximum elongation factor in the Keck telescope was 1.001 (resulting in 18mm of elongation in an 1.8m segment). This elongation in one direction results in an imbalance in the mirror which needs to be compensated either by the support system or by balancing out the mass using additional weights.

Petal segments, as shown in Figure 1 provide a circular outer array adding unnecessary material and mass, whereas hexagonal segments include additional area outside of the outer periphery. Hexagonal mirrors also tend to have longer edges than petals, increasing the issues discussed previously with edge continuity and scatter.

For space telescopes, the main benefit of using segmented mirrors is that the diameter of the mirror is not restricted by the size of the launch vehicles payload fairing. There will obviously be limitations due to the fairing volume and payload launch mass but the restriction of a sub 4m monolithic mirror will not occur. This advantage brings about the challenge of deploying segmented mirrors in space. For example, JWST will utilise deployment mechanisms to unfold the primary mirror, position the secondary mirror and unfurl the sunshade.

JWST uses 18 hexagonal mirror segments of 1.32m flat-to-flat diameter to form a 6.5m diameter mirror. The use of hexagonal segments deployed in space was a choice driven by the ability to actively control the position of the mirror. The deployment system that will be used only requires 6 of the 18 segments to be stowed away from their final position. This reduces the complexity in the deployment operation and mechanisms. For petal segments, the deployment is generally in the form of the petals being stowed vertically and then unfurled in what is known as a sunflower deployment.

The design and operation of deployment systems is complex. Space environment limits the use of certain materials and lubricants for bearing and hinges etc. The deployment mechanism may sometimes only be used once during the lifetime of the satellite and normally operate a number of years after manufacture. The recent failure of the harpoon to attach the Philae lander on the surface of the 67P/Churyumov–Gerasimenko comet illustrates the difficulty in this feat. The trade-off between scientific objectives and the size of the light collecting area of the aperture must be carefully studied to ensure that the cost to manufacture such a mirror doesn't become prohibitive.

3 The requirement and challenges of lightweight Optics for primary mirrors

Arguably the most important part of a telescope is the primary mirror (Bely, 2003), as previously discussed the useable area of the mirror surface enables images of higher spatial resolution and sensitivity. Unfortunately with traditional land based mirrors there are a number of consequences that occur when mirror diameter increases. Cost is the first casualty of the increased diameter; this is caused by the tube and mounts increasing in mass to accommodate the larger mirror. The effect of gravity will inevitably cause some sag in the mirror, therefore the stiffness of the mirror must be balanced with the number and proximity of the support points. The total mass of support points will also be a factor in telescope design. Stiffness in homogenous monolithic solid mirrors (and mirror segments) is a function of its thickness which further increases the mass of a mirror. The increase in total mass of a large monolithic mirror increases the size of the mirror support structure further increasing the inertia that needs to be overcome to enable sky tracking. Mirrors with larger masses also provide difficulties in maintenance, assembly and transportation. The issues with transportation are more pertinent when discussing space telescope mirrors with the cost of launching 1kg into a geostationary transfer orbit (GTO). Currently estimated to be between $15-20K (Koelle, 2007), this cost will increases significantly to the payload into L2 orbit. Therefore mirror mass is critical to the advancement of future telescope missions and the size of aperture that it requires. Significant research and investment has gone into this field and the following summarises the key areas of technology applicable for space telescope mirrors.

The decision of how to create a lightweight mirror is dependent on the final mirror design. The rigidity of the mirror is defined in four categories, rigid, semi rigid, low rigidity and very low rigidity. Rigid mirrors are those that do not flex under self-weight or disturbances and do not need excessive point supports. Supports for low and very low rigidity mirrors are vital in order to maintain the form of the mirror. Semi rigid mirrors require some support system. Flexibility of the mirror is a choice driven by the type of control required in the system. For example flexible mirrors have been designed so the mirror can be deformed to compensate for wavefront errors or form errors induced by a number of factors. These deformable mirrors require flexibility in order for actuators to change the surface form. A factor known as the mirror authority defines how much the mirror can be deformed with respect to the load applied with high authority meaning the mirror is easily deflected. High rigidity mirrors, once polished, are very difficult to deform and so have low authority. Low or very low rigidity surfaces have high authority, and can be flexed to account for waveform errors or thermal effects that change the mirror form.

In general rigid or semi rigid mirrors are used as primary mirrors and wave front errors etc. are dealt with using high authority actively control secondary or tertiary mirrors. Rigid or semi-rigid mirrors tend to require light weighting procedures or control of material parameters to control areal density.

3.1 Materials used in high precision optics

Mirrors have been produced from glasses, ceramics and metals for millennia. The earliest known mirrors dating from as far back as 8,000 years ago have been found in Turkey, made from a volcanic glass called obsidian. The obsidian surface was ground and polished to a reflective surface and was even shaped into a convex form. Although material properties of glass have greatly improved the theory behind polishing the glass has hardly changed from antiquity.

The use of ceramic mirrors was also widespread in Ancient Egypt with Mica polished to a reflective finish. The Egyptians then moved towards producing mirrors from metallic materials such as copper with examples being found that are dated between 3000-4000BC. This may have been the earliest form of reducing the mass of a mirror.
For high precision optics, glasses are still the most commonly understood, and used, material for use as a substrate. Zero expansion glasses, such as UDE, Zerodur and Pyrex are used extensively for ground and space telescopes due to their high dimensional stability ensuring near constant surface accuracy over temperature ranges, and a surface that is sufficiently hard to take a highly accurate polish.

The advantages of using such glasses are numerous; however, they all have a significant disadvantage when it comes to specific properties. The density of such materials is high, meaning that for space telescopes at least, light weighting operations must be undertaken.

In recent years, more advanced materials have been developed and tested for telescope mirrors. The following section outlines four of those materials, concentrating specifically on optical and infrared telescopes for ground and space observations.

3.1.1 Metal mirrors – Aluminium and Beryllium

Metal mirrors have been developed successfully for infrared and optical, ground and space observations. Early mirrors were fabricated from metals because of their stiffness and specular finish once polished. Glasses and ceramics eventually took over due to the hardness of their material enabling finer surface accuracies and also low thermal expansions. However due to mass restriction in space telescopes metal mirrors have come to the fore of development for large telescopes with particular reference to the JWST. Two materials discussed in this section are Aluminium and Beryllium.

Aluminium (Al) is widely used as a coating on optical mirrors in order to increase the reflectivity of the surface. It is normally deposited via evaporation and ideally should be in the order of 100nm thick (Bely, 2003). It is used for its ease of processing, high reflectivity and corrosion resistance meaning longer periods between maintenance.
Al its pure form is too soft to be used as a mirror substrate, however, so alloys of aluminium have been used as mirrors. Al alloys are cast or wrought, and in combination with different heat treatments, can be fabricated to improve properties to increase their suitability for the application.

Typically, however, aluminium has low hardness which means that traditional polishing for surface accuracy is difficult. Mirror surfaces are therefore created using diamond turning. Another option is to coat the reflective face with a harder material, such as a Nickel alloy and to fabricate a polished surface upon that. This method increases weight and complexity which negates two of the advantages of using Aluminium mirrors.

One major disadvantage of Aluminium, and its alloys, is the large expansion coefficient during temperature variation. This may cause the mirror surface to deform and increase the astigmatism in the design. Aluminium (and alloyed) mirrors do however provide high thermal conductivity and diffusivity, meaning that the thermal equilibrium through the bulk is maintained. This results in minimal changes in surface form, although this is entirely dependent on the material being homogenegous (Walker, 1995)

A further issue which is also relevant to metallic mirrors is the temporal stability of the mirror, which is the dimensional stability of a material over time known as creep. Most if not all, materials will display a change in geometry over time. This is mainly due to the relaxation in residual stresses and can cause significant deformation depending on the error budget allocated to the mirror form error.

Beryllium (Be) is another metallic material that has been widely used for telescope mirrors, especially in cryogenically cooled application in the infrared. The coefficient of thermal expansion of Be is especially low at cryogenic temperatures with thermal conductivity increasing at temperatures below 150K, ensuring relatively even cooling of the mirror, reducing thermal gradients. Be can also be polished to fine surface accuracy meaning there is no need for a coating to applied. Eliminating the risk of thermo-mechanical contraction mismatch during cool down that can cause deformation and buckling.

These properties made Be the material chosen for the mirror segments for the 6.6m primary of the James Webb Space Telescope. JWST mirror is constructed of 18 segments of three optical prescriptions (Gardner, 2008) and is passively cooled at 50K for observations at 0.6-28µm.

According to Dr Phillip Stahl, Be was chosen because of its *"….ability to provide stable optical performance in the anticipated thermal environment as well as its excellent specific stiffness"* (Stahl, 2007)

All of this is true however the specific stiffness of Be is somewhat misleading because this can be severely altered by manufacturing process and critically, removal of material for light weighting.

Be has numerous disadvantages for mirror applications. Firstly all material grades of Be must be Hot Isostatic Pressed (HIPed) to eliminate anisotropy and inhomogeneity (in reality these two factors can never be completely eliminated, but HIPed almost achieves this). Be is especially susceptible to anisotropic behaviour with thermal expansion in the basal plane of the crystal being 30% higher than perpendicular to the basal plane. The HIPed material maintains directional stability, but care must be taken when fabricating mirrors of high surface and form accuracy. The highest strength Be used for mirror substrates I-70-H is not available in large sizes via HIP and therefore limits mirror diameters using this grade.

Secondly, Be is a hazardous material to work with a potential carcinogenic result through dust inhalation. However, this can be controlled using exhaust and filtration systems.

Metal mirrors will continue to be of interest for optical designers due to their excellent specific stiffness. Be, in particular, has very attractive dimensional stability in cryogenic temperature ranges. High thermal conductivity can be advantageous in that the material can cool to the required temperature quickly which may alleviate thermal stress gradients within the substrate and the possible deformation that may induce. However high thermal diffusivity can also cause the material to have a response rate to temperature change that is hard to control. For example for IR applications such as the 4K temperature required for FISICA, radiation may cause the surface to warm in one section of the mirror and diffuse through the material at pace. The IR self-emissions of the mirror caused by this temperature change will cause distortion to be added to the electromagnetic radiation received.

Also the relatively high mass of the Be, compared to composite materials for example, means that light-weighting may be required, increasing manufacturing and design complexity, and resulting in larger costs.

3.1.2 Silicon Carbide

There has been extensive research available on the use of Silicon Carbide (SiC) mirrors for telescope mirrors. SiC is a synthetic ceramic with high specific stiffness. It also has excellent thermal properties with high diffusivity and conductivity and low CTE. Unfortunately Silicon Carbide is very brittle thus meaning that thicker mirrors are required to prevent breakage. There are three main types of Silicon Carbide explained extensively in a paper by Matson et al (Matson, 2008). Being an exceptionally hard and strong material, processing SiC can take a long time. It can be machined using conventional CNC machining techniques, but at a fraction of the speed of normal cutting process. In grinding, figuring and polishing SiC, the polishing head must move slowly due the fracture toughness of the material. Material removal rate when polishing SiC is in fact 1/50th of the time taken to remove Zerodur (Johnson, 2002)

Manufacture of Silicon Carbide blanks is difficult and may produce an inhomogeneous material due to inclusions of silicon or carbide. The main processing technologies in producing SiC blanks are Pressurised Sintering, Chemical Vapour Deposition, Hot Isostatic Pressing and the POCO conversion process, or a mixture of the procedures. For example, the POCO process produces SiC with high porosity which may cause stray light scatter on the reflective surface. Therefore to create a surface with high figure accuracy, a layer of SiC is deposited on the surface via using CVD (which has low porosity but high density) allowing the surface to be figured.

Herschel Space Telescope used a Silicon Carbide 3.5m primary mirror. The size of SiC mirrors, or mirror segments, are limited by the volume of the sintering presses available, current sizes are up to 1m x 1.6m. Therefore, for future large scale telescope mirrors, the segmentation processes need to be undertaken. That is not to say that the segmented mirror requires deployment/assembly after fabrication. Herschel utilised 12 segments which were brazed together during assembly, this is known as a quasi-monolithic mirror. After brazing the segments were ground and coated with a layer of SiC by CVD suitable for polishing. One of the benefits of SiC is that material from the rear of the mirror can be removed in order to reduce mass, without significantly reducing stiffness. It can also be fabricated with an open backed structure prior to final sinter, either by machining or by forming in a hot press. Each of these options requires expensive tooling, but reduce the residual stress that may be formed by milling operations. For example, Herschel will use a silicon powered sintered into a green blank under >1400bar pressure. The blank is then milled and further sintered at 2000^{o}C. There is some volumetric shrinkage in the final sinter and gives a volume with 2% porosity. Each segment is then brazed together and then ground to remove the joints. Once coated again with the CVD SiC to a thickness of 40µm it can be polished to a fine surface figure.

As mentioned previously, SiC is brittle and susceptible to failure by fracture and impact. A solution to this, which also increases the specific stiffness of the material is the addition of carbon fibre reinforcements, known as C/SiC. Unlike powered SiC, C/SiC does not shrink during sintering and can be CNC machined to allow near net fabrication. The manufacturing process of C/SiC requires a carbon fibre preform to be manufactured in the shape of the blank required for production and is infused with a phenolic resin for rigidity. The carbon fibre preform is then carbonised under pressure and high temperature which form a C/C felt, this in turn is heated under a vacuum to 2100^{o}C to graphitise the material. After milling to the required final shape the preform is infiltrated with Silicon to form the SiC matrix. The blank is then ready for any post fabrication required. Understandably, this is an expensive and complex process requiring some specialist equipment. It is also worth noting that C/SiC is susceptible to issues similar to that of CFRP. Firstly the material is not truly isotropic and therefore thermal and mechanical properties are directional. The CTE, for example, in plane will differ significantly to that of the CTE out of plane (through thickness). Also the presence of fibres within the material mean that polishing will most likely expose fibres on the reflective surface, causing surface errors that may be over and above what is required for the particular mission. Both of these issues are well known and research into solving them has been undertaken. For example, CVD or a slurry coating of a SiC on the surface can form a dense tough layer that can be polished and will eliminate and fibre pull through. Also the inhomogeneity can be reduced by using randomly orientated fibres. The use of chopped fibre strands randomly placed in a Silicon Carbide matrix is used in a product called HB-Cesic©.This material has been selected for the SPICA telescope mirror due to its high specific properties and quasi isotropic nature.

3.1.3 Polymeric Composites

Composite materials combine two or more individual materials whose properties combine to make a more attractive material than in the constituent parts. Typically composites include a matrix and a reinforcement material. Matrix materials are primarily metals, ceramics or polymers. Reinforcements are normally classified by their geometry, namely particulates and fibre. Fibre reinforcements can be split even further into long or short fibres. As is evident from the number of options briefly discussed above composite materials are extremely tailorable to the final requirement of a particular application, meaning that engineers can design not only the geometry of a structure but also the material properties. The mechanical properties, dimensional stability and form accuracy of a composite mirror is dependent on a number of factors. Material selection, fabrication procedure, manufacturing techniques, and environmental effects are key aspects in controlling the behaviour and application of composite mirror substrates.

Material Selection

Polymeric matrix composites are used in space applications for many components due to their high specific properties and dimensional stability after cure. Polymers are classified as either thermosets or thermoplastic, with the former being the more widely used material in structural composites due to their higher dimensional stability. Thermosets require a cure cycle during which the relatively soft uncured polymer hardens due to covalent bonding of polymer chains. This crosslinking results in the polymer retaining its shape even when heated at elevated temperatures (up to a point). At temperatures in the cryogenic range, thermosetting polymers may become brittle, their use therefore at these temperatures, needs to be carefully considered. This is discussed in a later section of the report and initial experiments to assess the thermo-mechanical properties of a thermoset based composite at cryogenic temperatures will be undertaken under this work package of the project.

Within a composite, the matrix has a multifaceted role. Firstly it binds the fibres together and acts a medium for the propagation of externally applied loads to the fibres. As the elastic strength of the fibres is normally much higher than that of the matrix, most load is sustained by the reinforcement. Secondly, the matrix protects the fibres from damage via abrasion, chemical, moisture or thermal damage. Such damage may reduce the tensile strength of the fibres, causing the material to fail at lower loads. Finally the matrix serves as a barrier to crack propagation by separating the fibres to prevent any fibre to fibre brittle fracture propagation. The matrix allows a number of fibres to fail without the strength of the composite being compromised.

Polymer matrix materials are generally ductile and weak in tensile strength but provide a vital role as a medium for load to be transferred to the fibres. This transfer of load can only take place if a strong bond is present at the interface between the fibre and the matrix. Material selection is therefore vitally important to ensure that the polymer and the fibre are compatible for this aim. Bonding between fibres and matrix can either be chemically or mechanically based.

Fibre reinforcements can be classified as short or long fibre. To be more accurate the two classifications are defined as continuous (long) or discontinued (short).
For effective strengthening and stiffening of the composite, the length of the fibre needs to be over a certain length defined by the formulae below.

$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

Eqn (3.1)

Where σ_f is the Ultimate Tensile strength of the fibre, d is the fibre diameter and τ_c. Under high tensile loading in the longitudinal fibre direction, the interface between the fibre and matrix ceases at the end of the fibre. This is due to ductility of the matrix allowing deformation at the end of the fibres in the pattern shown in figure 2.

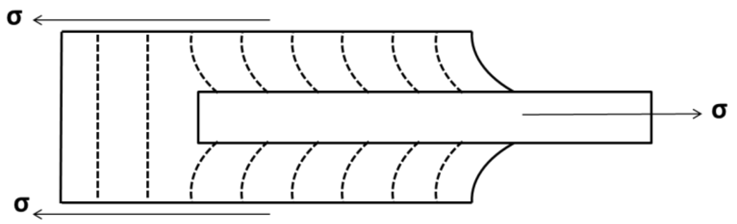

Figure 2: Resin deformation pattern when fibre is subjected to a tensile load

If the fibre length is below the critical length calculated using Eqn 3.1 the composite will not transfer load from the matrix to the fibre reducing the strength of the material significantly.

Short fibres are generally less than 15 times the critical length and are generally randomly arranged in a mat, known as Chopped Strand Mat (CSM) that is then infused with resin to create the composite. These randomly orientated fibres create a quasi-isotropic material in-plane. Out of plane, i.e. through the thickness of a flat plate, the composite tends to only exhibit the property of the matrix. The in-plane properties are considered quasi isotropic because the orientation of the fibres cannot be accurately defined and therefore load transmission is not consistent. The smaller length of fibres and the random orientation, reduces the load carrying capacity of the composite due to the load having to pass through the matrix from one fibre to the next regularly. This means that stress is passing through the weaker matrix more frequently. CSM is inexpensive and simple to manufacture and fabricate. The resin used with CSM needs to have low viscosity so that it easily flows between the fibres. This is a reasonably low technology solution to creating composites that tends to make components with air inclusions. Any inclusion with a composite can act as a stress raiser or as a void that could absorb moisture and should therefore be avoided if at all possible. To create CSM reinforced components that have been fully degassed is a difficult process and the low viscosity resin tend to include chemicals that will outgas during operation in a vacuum environment.

Continuous, or long fibres, are the most common forms of reinforcement for structural applications and tend to have a length in the region of approximately 15 times the critical length. Material properties of long fibre continuous composites are dependent on fibre distribution, orientation and concentration. This is also known as the fibre architecture. These fibres can be applied either as a dry fibre that require resin to be applied during fabrication, or as a pre-impregnated sheet known as prepreg. The most common form of prepreg contains unidirectional continuous fibres. The prepreg is cut to size and then laid on top of each other to form a laminate. The orientation of the layers, known as plies, determines many mechanical properties of the material. The stacking sequence of the laminate is normally symmetric about the mid layer through the thickness. This reduces deformation during the cure process which will be discussed at length later in this document. The number of plies and their orientation define the tensile and flexural strength of the material if the properties of the fibre and matrix are known. The concentration of fibres is dependent on the thickness of the strands of fibres, known as tow. The higher the number of fibres in a tow creates a higher the tensile strength. A tow of fibre can contain thousands of individual fibres, with the thickness of a typical single carbon fibre being 5μm. The volume fraction of fibres in comparison to the matrix is a simplified method of calculating material properties. The tailorability of composites comes from the ability to design the fibre architecture to what the engineer requires. If a component is designed to have more strength in one particular direction in comparison to another, then more fibres can be applied in the laminate in that direction.

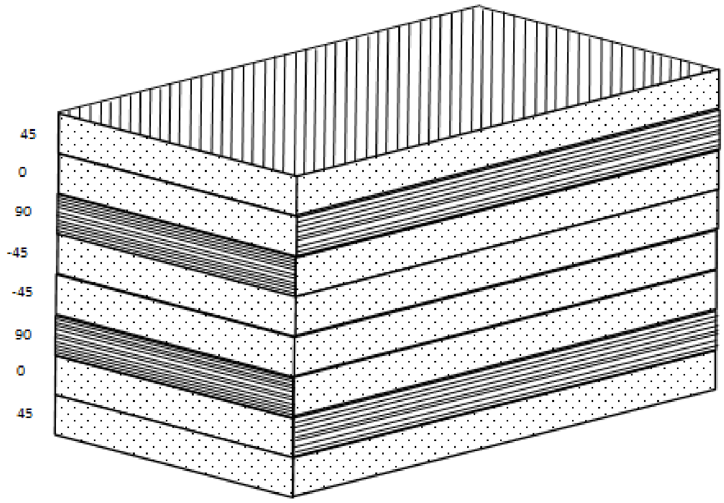

Figure 3: Ply stacking sequence of a laminate

Two dimensional weaves of fibres can also be made use of rather than using unidirectional prepregs. This reduces the amount of layers, reducing fabrication time and increasing the accuracy of the fibre layup. The 2D weave uses the terminology of warp and weft to denote the fibres along the 0^o and 90^o direction respectively. A number of different types of weaves are shown and discussed below:

Plain

Warp and weft fibre pass over one another alternately producing a dimensionally stable, symmetric structure. As the fibre pass over one another however, it causes a crimping effect which not only produces a rough surface but also weakens the fibres in comparison to other fibre patterns. The crimping effect limits the tow size. One key disadvantage is the limit in draping over complex geometries. The inflexibility of plain weave means that it is only suitable for single curvature or flat components. One clear advantage is the wettability of the material, meaning that infusing resin to create the composite is simpler.

Twill

Plain weave alternates the warp and weft filaments over each other in a regular and repeated pattern. Twill weaves one warp filaments over two or more weft filaments (or one weft filament over two or more warp filaments). In this pattern the number of intersecting wefts that the warp passes over is identified in the given name of the material. For instance the weft filament in a 3/3 twill will pass under 3 warp filaments and then over 3 warp filaments.

The reduction in bends of each filament due to the missing out of a number of weaves means that mechanical properties are higher and a smoother surface is achieved. It also means that drapeability improves, but only in the orientation of the twill pattern.

Satin Weaves

This weave is essentially a twill weave with more missed crossings and an asymmetrical pattern. This causes fewer intersections of warp and weft and a smoother surface. The reduced crossings cause fewer kinks in the filaments which increases the mechanical properties of the material. The asymmetrical pattern, however, tends to leave one surface of the weave having filaments predominantly in the weft direction and the opposite face predominantly in the warp direction. This means that care must be taken when stacking to balance this effect, if not stresses may form due to differential expansion in the warp and weft direction during cure. Also the stability of the weave is compromised by the irregular pattern and missed intersections.

3D braided fibre architecture

One issue throughout laminated composites using unidirectional and bidirectional ply layers is that the bond between layers is maintained only by the matrix material. Therefore the out of plane strength and toughness are driven by the polymer properties rather than that of the fibres. A solution to this is threading filaments through the thickness of the material. There are many 3D braiding methods used from pins that link all ply layers to interlinking filaments. These 3D weaves tend to be complex to manufacture and are also difficult to infuse with resins. Also currently these types of fibres are not widely available as a prepregs, meaning that the fabrication process is challenging and causes difficulty.

Fabrication

Composite mirrors, either in flat, spherical or parabolic form, can be made using many fabrication techniques. The most common manufacturing method is hand layup in which individual plies are cut out and laid up in a sterile environment over a mandrel which replicates the final geometry of the mirror. This procedure is normally carried out by a trained technician, and the quality of the final part is affected by the technician's ability, accuracy and experience. Another suitable technique would be an automated system through which a computer controlled arm would apply the CFRP prepreg in tape form. As the process is automated it removes a degree of variability by removing human interaction. This process however is mostly only suited to simple geometries and still requires a skilled technician to both programme and operate the machinery. Automation also allows more complex architecture to be utilised. This procedure was used in the manufacture of the Planck telescope primary mirror CFRP face sheets (Stute, 2004)

The variability in fibre architecture for fibrous composites is something that makes the material appealing for structural components. Strength, flexibility and dimensional stability can be controlled by varying the ply orientation for either unidirectional or bidirectional prepregs. The accuracy of the ply orientation has a direct implication on the overall form accuracy of the final mirror shape. A well trained technician performing a hand layup operation should be able to maintain a ±0.5 degree ply orientation accuracy. This accuracy is obviously more challenging depending on the size of the component and the geometry of the mould. The deformation of the composite that causes the greatest contribution to form error is a resultant of cure shrinkage, and also exposure to external conditions during operation. The cure and operational effects can be managed, but never totally eliminated by the fibre orientation and architecture when designing the component. However, deviations from the ply orientation, even by less than a degree, can cause significant deformation in form error that would cause defocus and astigmatism if composites were used as a mirror substrate. In research undertaken previously at Glyndwr, Thompson et al found using a computational model that for a 32 ply laminate with 22.5^{o} angular separation between plies and a symmetrical stacking sequence, an angular error of 0.1^{o} in one of the plies resulted in an average form error of 14± 7µm Peak to Valley for a 1m diameter mirror (Thompson, 2014). This form error was driven by the shrinkage of the mirror during cure and would result in a mirror unsuitable for optical wavelengths without active or passive form correction. In a similar study, Arao et al found that moisture absorption of a CFRP mirror post cure causes an increase in form error of up to 100µm if the standard deviation of angular error of 0.4^{o} throughout the stacking sequence (Arao, 2011). This research demonstrated that the deformation forces due to moisture absorption are exacerbated by the ply alignment errors. It is worth noting however, that this research was undertaken in a hostile environment that a space telescope mirror would not be subjected to. However moisture ingress and absorption will be an equally challenging issue for FISCIA application. Another point of discussion for both the Thompson and Arao research is that design using composite materials has so many variables that research for one particular configuration (fibre/matrix material, ply orientation, manufacturing technique, fibre architecture etc.,), would not necessarily be valid for other configurations. The accuracy of fibre alignment, in terms or orientation accuracy also has a related issue in the form of fibre waviness. For computational simulations the fibres are considered not to deviate from straight along the longitudinal orientation. In reality fibres within a prepreg exhibit a degree of waviness which reduces the mechanical property of the composite. The waviness is further exacerbated by the shrinkage in matrix volume during cure (Qu, 2010). This effect is discussed later on in the report. Manufacturers of prepreg materials conduct some quality assurance via visual and non-destructive inspection on their products but some fibre waviness is unavoidable. The degree of fibre waviness is random between each layer, and it is therefore difficult to ascertain the amount of deformation that may occur.

Manufacturing Technique

Most advanced composites use a thermosetting polymer as a matrix material due to their high dimensional stability and chemical resistance. When uncured thermosetting polymers are in a liquid state, as heat is applied the polymer chains connect via covalent bonds and form permanent chain networks. The application of heat is known as curing and can be applied by many different applications, at many different temperatures. Normally for a higher temperature, the cure cross-links in the polymers are denser and therefore the material is stronger and more stable. Room temperature cure resins are widely available but are not suited to applications where strength and dimensional stability are required. During curing the polymer chains crosslink with each other and the proportion of cross-linking is known as degree of cure (DoC). DoC is a function of both the temperature of the cure and also the time that the polymer is held at that temperature. Prepreg and resin suppliers normally provide a recommended cure cycle, that if followed, produces a plastic with 100% degree of cure. The figure of 100% degree of cure is not physically achievable directly after processing with some polymer chains linking after cure.

As the polymer chains link there is a volumetric shrinkage in the matrix. Dependant on the method used to cure the polymer, differential curing will occur. This means that at some points through the material, curing has activated, but at others the material is either not yet cured, or has just begun. The difference is volumetric shrinkage throughout the material can cause deformation, especially if bonds between the fibre and matrix have formed whilst the matrix shrinks. If the ply stacking sequence is symmetric then this is balanced out through the thickness so little deformation occurs. This assumes, however, that the heating of the composite is isothermal. In reality achieving an isothermal cure and cooling in the in-plane and through thickness direction is almost impossible. The causes of the isothermal cure are numerous. Firstly resins tend to have low thermal conductivity meaning the time for the heat to propagate through the material is significant. The thermal gradient is further exacerbated by the use of solid moulds on one surface of the component and a vacuum or air pressure, via the opposite side to form complex shapes. This causes heat to be applied at different rates and levels at each surface, further worsening the thermal mismatch. Secondly the application of mould pressure causes residual stress to form. The purpose of the mould is to form the composite into a particular shape, in the case of a mirror, its prescription. The component is therefore restricted from moving and so residual stresses are built up through the volumetric shrinkage and non-isothermal cure. Once the mould pressure is released, some residual stress will be relieved and the component will deform. This is a well know effect and for structural component fabrication, is dealt with by compensating the mould geometry so that the component springs into the desired shape. This approach, however, is not suitable to highly accurate applications. The level of residual stress is also a function of the geometry, the tighter the curvature in a component, for example, the larger the spring back induced by residual stress. It is also important to note that not all of the residual stress within the sample is released upon demould. Some stress stays within the component which releases over time or is released when additional stresses are applied to a component. The release of residual stresses, either after cure, over an extended period of time or with an additional loading, can cause the component to deform beyond reasonable limits. Additional strain, such as contraction at low temperature may cause the stress to be released (and component to deform) during operation.

The most convenient method of reducing residual stress is by attempting to achieve an isothermal cure. Microwave curing heats a component from the midspan outwards. In addition to this the fibres, if they are conductive, can propagate the heat through the substance. An additional heat source, for example, a convection oven system can also be applied so that heat is applied throughout the sample. If the panel is thin and has a relatively simple geometry then residual stress can be kept to a minimum, however, due to the isotropic layup and volumetric shrinkage it can never be truly removed.

One key issue in using fibre reinforced composites as optical and infrared mirrors is the existence of a sinusoidal surface error commonly known as fibre print through. Many researchers have attempted to clarify what causes fibre print through. Chemical shrinkage during cure (Jaworske, 1989), thermal shrinkage during cooling, fibre diameter, distance between adjacent fibres (Kia, 1986) and cure temperature (Hochhalter, 2004) have all been stated to contribute to fibre print through. The exact reasons are most likely a combination of all of the above and reducing fibre print though by controlling these factors is difficult. The most common solution to eliminating fibre print through is to include a resin rich layer on the reflective surface of the mirror. This resin rich layer can be polished conventionally, diamond turned, or if a replication method is used, will already have surface that satisfies the figure error limit. A resin layer of approximately 0.25mm is required to eliminate the effect of fibre print through (Masserello, 2006). Consideration must be taken as to the operating conditions of the mirror. In a paper by Kim, fibre print through mitigation using a resin rich layer can cause high special frequency errors due to differential thermal expansion of the substrate and the resin layer (Kim, 2008). This means that the radial stiffness of the mirror needs to be matched in order to alleviate this error.

<u>Environmental effects</u>

Polymeric composite materials are susceptible to many environmental factors that can degrade and deform components. Moisture in the air for example, can be absorbed by the composite via Fickian diffusion. But the damage to the material caused by moisture can be reversed. Firstly, the moisture can cause the matrix to plasticize and swell the polymer network which reduces the glass transition temperature of the material. This softens the material and reduces stiffness that may cause gravitational sag inducing mirror form error. This process can be reversed by drying the material returning the glass transition temperature to the original property.

The irreversible aspects of moisture ingress include reducing the interfacial strength between the fibre and matrix and micro cracks formed by the swelling of the polymer. The result of the irreversible damage is a vast reduction in stiffness and strength.

Additional deformation due to the matrix swelling can displace fibres and cause surface damage.

The effect of moisture can, however, be limited by correct material selection. For example, cyanate ester resins have extremely high moisture resistance whilst some epoxy resins are susceptible to moisture diffusion. Also processing conditions can be controlled so that the composite is manufactured in a temperature and humidity controlled environment and drying cycles are performed to allow the moisture to be removed.

Temperature

Polymers are susceptible to drastic and wide variations in temperature. The change in mechanical properties at different temperatures needs to be considered when selecting the material for a design. The glass transition temperature (Tg) of a polymer indicates when the material changes from a glassy phase into a more ductile, rubbery phase. At temperature above the Tg, the polymer softens and therefore become less stiff than at the desired operating temperature. This reduction in stiffness can cause additional deformation or the component to lose form. Reduction in tensile, compressive and flexural strength is also present. Humid environments combined with high temperatures are known to further decrease the Tg.

At low temperatures, polymers tend to become more brittle. If elastic deformation is required, for example in active deformable mirrors, this can be a severe hindrance. Tthe material selection is entirely dependent on the final operating conditions. Cyanate ester resins are suitable for extreme low temperature and Bismaleimide (BMI) matrices are suited to high temperature environments.

One issue is key for using polymer matrix materials at extreme temperatures, the coefficient of thermal expansion (CTE). Polymers and fibres tend to have a very good dimensional stability at different temperature. This means that there is little geometric change in the material as it is heated or cooled. However, the volumetric change, even if it is small, in the material during thermal gradients can cause micro cracks to form in the matrix. These micro-cracks cause small deformations and ultimately weaken the material. The CTE mismatch between the resin and fibre can exacerbate deformation via expansion due to the fibres having near zero expansion. As the resin is bonded via the interface to the fibre, its expansion, no matter how small, is restricted by the fibres causing high spatial frequency deformation. The contraction of a matrix during cooling may also cause thermal strain between layers of plies. If a degree of residual stress within the component is present, alongside contraction, due to cooling, interlaminar shear failure may occur, causing the material to deform. The failure will normally be in the form of delamination which may be further worsened over time as a stress raiser increasing the size of the void.

3.1.4 Ribbed and Hollow cored structures

The most common method of manufacturing lightweight structures is to either remove some bulk material in the form of pocketing the rear surface of the mirror (open back) or by sandwiching a core structure between two face sheets (closed back). The basic premise in either method is to reduce the areal density of the mirror without compromising the stiffness.

The most commonly used method with glasses, silicon carbide and metal mirrors is the creation of pockets on the rear of the mirror. The shape of the pocket is normally either triangular or hexagonal to provide the greatest stiffness. The ribs' thickness and the cell diameter of the pockets are governed by the material properties and loads applied to the mirror, induced by either gravity, vibrational during launch, transportation, and the manufacturing processes. The pockets can also be cast or brazed into the mirror, like the Herschel, Silicon Carbide mirror segments (Bath, 2005) or machined from the mirror blank like the Beryllium Mirror of the JWST (Stahl, 2007). The limit of how much one can lightweight a material is driven by manufacturing processes and handling. The removal material for the Beryllium segments of the JWST was over 90%, significantly reducing the areal density of the primary mirror (Kendrick,2009) without compromising on the surface form error of the final design.

The critical geometry is that of the thickness of the reflective faceplate surface and also the width of the cells. Conventional figuring processes exert pressure on the surface of the mirror during material removal. If the stiffness of the faceplate is too low, either caused by the faceplate being too thin, or the distance between cells too large, it will deflect and then bounce back. Under optical testing this will show as quilting, or cell wall print through, resulting in a high order spatial frequency error on the surface (Catanzaro, 2001).

The other option, is the use of core materials between the faceplates in a closed back system. The use of a closed back system offers more stiffness in comparison to open back system, which limits the use of sandwich structures as deformable mirrors. However, the thin face plates can potentially be figured prior to attachment to the core limiting the effect of quilting or print through. Core materials can be foams or honeycomb structures. The honeycomb cores can be made from a variety of different materials either by material removal or fabrication.

The use of hexagonal honeycomb cores is appealing due to the savings in mass without compromising on stiffness. However hexagonal cells have the disadvantages that they cannot drape over complex shapes due to anticlastic curvature inherent in the core when flexed. Luckily, hexagons are not the only cell geometries available with suppliers such as Hexcel producing Flex and Dual Flex Cores allowing formability without reduction in strength.

4 Composite Mirrors

4.1 Current state of the art manufacturing method

The current method preferred in the manufacture of dimensionally stable polymeric composites is known as the replication method. This requires a mandrel to be produced that has the opposite form to that of the mirror, for example a 3m RoC convex mandrel for a 3m RoC concave mirror. The process is further enhanced by polishing the mandrel surface so it is the same as the final surface figure of the replicated mirror. The addition of a resin rich layer of a desire thickness (approx. 0.25mm) eliminates fibre print through and enables the surface to take the polished surface of the mandrel. Low and mid frequency errors are reduced to below acceptable limits by this method. Due to challenges in thermal loading when applying a reflective (or indeed antireflective) coating to polymeric composites, the surface of the mirror is deposited with the coating prior to composite layup. If a suitable release agent is used beforehand, the mirror should separate from the mandrel with relative ease after conventional curing either in a vacuum bagged arrangement in a convection oven or an autoclave. The result is a fully coated fibre reinforced polymer mirror that achieves the required surface and form error requirements. Many patents claim variations on the replication method, such as using honeycomb cores by Romeo of Composite Mirror Applications (Romeo, 2006).

Manufacture of composite mirrors requires high precision fibre deposition to ensure that factors such as fibre misalignment do not induce excess deformation during or post cure. The most common fibre architecture utilised is unidirectional fibres in the form of pre-impregnated tape. The tape, which can vary from 10 to 300mm in diameter, allows the fibres to be positioned accurately over a convex mandrel. The radius of curvature of the mandrel has to be reasonably large (in the order of 1000mm) to prevent the fibre orientation deviating from its original direction. Excess deviation can result in variations in the load paths which can also contribute to astigmatism to the mirror form.

The resin used in the composite determines the cure schedule required. There is evidence to suggest that room temperature cure resins will deform less due to cure and thermal shrinkage (Massarello, 2004). This may be the case, but low temperature cure resin tend to have lower mechanical properties than high temperature cure resins.

4.2 Applications

Composite mirror technology is not a new idea with Aluminium honeycomb core mirrors that have a CFRP face sheet being used on the IRAM telescope as early as 1981. The opportunity to create a mirror substrate with a high specific stiffness is attractive to many industries and research sectors, so development and investment in this area has been significant in many countries, predominantly Japan and America.

Composite materials offer low mass and tailorable properties in combination with a high dimensional stability, perfectly suited to the majority of applications. Composite Mirror Applications, Arizona USA are currently the major providers of composite optics for telescopes, predominantly but not exclusively, land based.

CMA was formed in 1991 and has in-house design, manufacture and test facilities. CMA have worked with NASA and ESA, amongst others, to manufacture diffraction limited mirrors in wavelengths from sub millimetre to the visual and have developed optics for UV and X-ray astronomy including Ring Imaging Cherenkov (RICH) detectors. The mirrors for the RICH detectors have surface accuracies of 8µm RMS (Martin, 2007) using their patented replication process.

The majority of CMA mirrors are used for land based reflectors and are therefore not subject to the large temperature variations that space reflectors have to survive. In terms of Space reflectors CFRP has been proposed for use in the Japan Astronomy Satellite Mission for Infrared Exploration (JASMINE). This mission is currently in development and a nano-satellite, with 50mm aperture made from Aluminium alloy in scheduled for a launch in late 2015. The final JASMINE mission hopes to use an 800mm diameter primary mirror and will operate at 210K (Utsunomiya, 2013).This temperature is far higher than what is required for the FISCIA mission, but the surface accuracy and shape accuracy of achieved by Utsunomiya, 0.8µm RMS and 5nm RMS was encouraging, especially as the CTE of the mirror was near zero.

In studies by Doel at UCL, composite mirrors have been created using a CFRP substrate that is fully coated in Nickel at a thickness of 50µm (Thompson, 2008). The purpose of the mirror demonstrator was to create an active deformable mirror to be used in a large ground based telescope. The nickel coating is applied in a nickel sulphamate electrochemical bath and fully encapsulates the CFRP substrate. The coating is applied for a number a reasons, to eliminate fibre print through, to protect the substrate from environmental damage, and to create a reflective, polishable surface. Although each reason in isolation is entirely reasonable, each factor can be controlled individually with material selection or suitable fabrication techniques. The addition of a relatively thick layer of Nickel is not only difficult to achieve, but also adds mass and, particularly for a low temperature operation, dimensional stability of the mirror would be severely altered.

The Planck telescope, launched alongside the Herschel Space Observatory, used a CFRP sandwich structure to observe 0.3-10mm range at 40K. Due to the wavelength observed, the surface figure and form accuracy is factors less than required for the far infrared. However the technologies used in Planck should be considered in future missions. The CFRP face plates and the core were made from the same material, eliminating differential CTE effects in the sandwich. Additionally, the CFRP face plates were fabricated using automated tape layup procedure, improving the ply orientation accuracy and removing the variability associated with human error. The Planck telescope mirror is discussed further in a later section.

The main concern with using composite mirrors in a cryogenic space telescope is due to the variations in temperature, the effect of outgassing and also the effect of noise and vibration on the mirror surface. These factors will be discussed in a later section.

5 Cryogenic testing of composites

There is a significant amount of literature and research in the field of cryogenic testing of composites and polymeric materials. The use of polymer matrix composites (PMC) for satellites and launch vehicles is well documented, particularly for structural applications where the sensitivity to thermal expansion and contraction is less important that the significant weight savings associated.

Firstly, as terms such as Carbon Fibre Reinforced Plastics (CFRP) and PMC do not state specifically what materials are employed as a matrix or the fibre, one must be cautious to define the materials used as both constituent parts and what their predominant mechanical properties failure mechanisms at both ambient and space environments are. It is well known that the differential expansion and contraction of the matrix and fibres during cure and operation causes internal strain resulting in distortion. Many studies have researched this area, however, most studies tend not to include temperatures in the cryogenic range. As the polymer matrix is more likely to be effected by thermal gradients than the fibre, we should focus our attention there.

Results of a range of polymer tests at cryogenic temperatures were reported by CERN as far back as 1973 (Van De Voorde, 1973). Mechanical and Thermal property tests were conducted at temperatures ranging from 4K-300K, and also at room temperature as a base measure. Aside from tests at the cryogenic temperatures, sample polymers were also thermally aged and then tested mechanically for tensile and flexural stiffness. Although the results found were significant in enabling understanding of cryogenic properties limited numbers of polymers were tested. Also as the paper is nearly 40 years old, significant development in polymers for cryogenic environments has been undertaken, replacing the polymers included in this study.

Many studies into assessing the dimensional stability of composite mirrors exist concentrating on the moisture absorbance on the structure, and thermal deformation, including studies by Utsunomiya et al (Utsunomiya, 2009). The author conducts experiments on a CFRP sandwich structure with CFRP honeycomb. The matrix of both the CFRP facesheets and the honeycomb in a Cyanate Ester resin was chosen for its low moisture absorption, and low thermal expansion coefficient. The study is for space mirrors, but it does not experiment to cryogenic temperatures. This does not provide a complete picture of the material thermal stability due to the CTE of polymers, not having a linear relationship with temperature as reported in Chapter 2 of Polymers at cryogenic temperatures (Kalia, 2013). As the Utsunomiya paper does not state what the purpose or operating environment the mirror is being developed for one can forgive this to an extent and appreciate the content of the study. However for the FISICA concept it is assumed that focus must be on Cryogenic properties in its entirety.

So for example for Finite Element Modelling of a mirror to ascertain surface deformations during temperature variation it is important that the CTE over the full temperature range of the operating environment, and also the fabrication environment, must be found for a particular matrix.

In a high proportion of literature for space structures and mirror substrates using PMC's Cyanate Ester resin, seems to be used extensively, aside from the Utsunomiya study previously discussed, The James Webb Space Telescope uses a composite of Cyanate Ester resin as its matrix with carbon fibre reinforcements for its structural components. Although it is interesting to note that the chose Beryllium for its primary mirror material, due to its high specific stiffness and excellent stability at cryogenic environments (Stahl, 2007). This would create a CTE mismatch between the structure and the mirror which requires a design that decouples this effect.

A Cyanate Ester composite was tested for its cryogenic durability by Polis Et al (Polis, 2006). They provide results in micro-cracking of the matrix during thermal cycling and also the effect of degree of cure (DoC) on the interlaminar strength. No discussion as to the thermal expansion at cryogenic temperature and degree of cure is given which may be of interest.

Cyanate Ester resins were initially going to be used for the Herschel Space Telescope (formally FIRST) (Abusafieh, 2001), but eventually Silicon Carbide was chosen (Matson, 2008) due to its quasi-isotropic thermal expansion, allowing easier control of surface accuracy and form. The Planck telescope, launched in the same mission as Herschel, has a CFRP mirror that was cryogenically tested in development stage (Delouard, 2005), however no information on the matrix material has been found at present.

Extensive research into PMC materials by NASA and ESA in using composites for future space craft has been undertaken. NASA has developed a cryogenic fuel tank using an epoxy resin 5320 from Cytec Inc. and Intermediate modulus fibre IM7. This resin needs to be thermally stable in that micro cracks do not form during thermal cycling which would create a weakness in the pressure vessel.

ESA have been supporting research into novel materials for the generation of space launch vehicles past the Arianne V rocket. Carrion (Carrión, 2000) has looked into different materials at high and cryogenic temperatures, the research focused on Toughened Epoxies, Cyanate Esther resins and BMI (Bismaleimides). The research was restricted by budget to test three materials in comparison. The conclusions were that cyanate esters and toughened epoxies were best suited to cryogenic tests and BMI were suited to hot environments (200^{o}C).

Research in the micro and macro scale properties of composites has been undertaken extensively. However due to the nature of Polymer Matrix composites, the differences in matrix and fibre materials is key to determining the cryogenic properties of the PMC. Significant attention has been paid to Cyanate Ester resins, but the cost and availability of such resins may prohibit their use in this project.

6 State of the art cryogenic mirrors for space telescopes

This section will concentrate on a number of space telescopes, their design and operation.

AKARI - Originally known as Astro-F, AKARI was launch via a M5 rocket in early 2006. Containing a 685mm diameter aperture in a Ritchey–Chretien configuration, its aim was to perform an all sky survey in the infra-red band. The telescope contained two instruments on board: the Infrared Camera (IRC) and the Far-Infrared Surveyor (FIS) that operate at 2–26 µm (Onaka, 2007).

The primary mirror of the telescope was made from a Silicon Carbide sandwich construction. The substrate was made using Silicon Carbide which is easily machined and light weight due to the materials porosity. The same porosity, however, means that a high quality surface is not possible using this material alone. A coating of dense Silicon Carbide is then applied using a Chemical Vapour Deposition (CPD) technique. This creates a tough surface that is readily polished to optimise surface finish.

The mirrors were produced from Silicon Carbide due to the high stiffness and high thermal stability. The final point is particularly important as the mirror was actively cooled for 550 days to less than 6K in order to prevent self IR emission. The telescope was specified to be diffraction limited at wavelengths of 5 µm at operating temperatures.

SPICA - The Space Infrared Telescope for Cosmology and Astrophysics is a Japanese Space Exploration Agency (JAXA) led mission that will utilise a 3m aperture telescope that will be cooled to 6K to limit background emission. The candidate material chosen for the primary is a carbon fibre reinforced Silicon Carbide(C/SiC) called HB-Cesic. The material utilises short strands of carbon fibre randomly orientated to reduce inhomogeneity and anisotropy. Mirror samples of 800mm diameter have been fabricated and cryogenically tested down to 6K. The aim is for the mirror to be diffraction limited at a wavelength of 5µm.

The surface of the HB-Cesic © is sintered into shape and leaves a porous material with high specific stiffness and high thermal stability. The surface of the material however is not suitable for polishing due to fibres being present. Therefore a thin, dense (40nm) layer of silicon carbide deposed on the surface to be polished.

In tests reported by Kaneda et al, a HB Cesic © 800mm diameter mirror was polished to within 0.8-1.2nm RMS in roughness and 61nm RMS surface figure at room temperature using conventional polishing techniques (Kaneda, 2010). When measured in a cryostat at 18K the surface figure error worsened to 113nm RMS. There is no data for roughness. This increase was attributed to the inhomogeneity of the HB-Cesic©, which is almost inevitable due to the very nature of composites. Regardless of the decrease in quality, the surface error is still within the 175nm RMS surface figure error allowed for the SPICA telescope primary. It is notable however that the mirror will be cooled to 6K during operation. Any additional deformation that occurs between the measure 18K and 6K is undefined by this Kaneda's paper. The research also notes the additional deformation causes by support structures etc., something that will need to be researched thoroughly for all missions at low cryogenic temperatures.

The Herschel Space Observatory – Herschel was the largest infrared observatory launched in 2011 and ceased operating in 2014. The primary mirror was 3.5m in diameter used in a Cassegrain layout. Operating at below 70K, the wave front error of the primary mirror needs to be below 6µm meaning a surface figure error of 3µm. The Herschel telescope is manufactured by brazing 12 silicon carbide segments at high temperature. Once polished, an aluminium reflective coating is deposited on the surface and protected with a layer of Plasil. In the early design stages all composite mirror were considered (Catanzaro, 2001). The CFRP material used and fibre architecture of the mirror prototype is undefined. It did however use a segmented face sheet with an open backed structure, reducing the areal density to 10.1kg/m^2. After fabrication using the replication technique discussed previously, the mirror achieved a surface figure of 0.6µm RMS. This error rose to between 15-10µm RMS after cryogenic cooling which is higher than the tolerance stated for Herschel. However these errors could be corrected by the secondary mirror.

Planck Telescope - The Planck telescope was launched along with the Herschel Space Observatory and is used to observe the 0.3mm to 10mm range. An off axis aplanatic Gregorian configuration is used and is operated at 40K. Initially the primary mirror design was a closed back sandwich structure with a triangular honeycomb core of thickness 10-40mm and thin (1mm) CFRP faceplates. After a number of design iteration this was modified to be a hexagonal honeycomb core with cell sizes of 60mm and the face sheet thickness of 2.2mm. This design change was to reduce the effect of quilting, which is the concave surface deformation caused by the difference in mechanical properties between the CFRP and adhesive used to bond the face sheet to the core. Polished cast steel moulds where used to manufacture the face sheets over which preimpregnated fibres were placed. This technology replaced the inherent inaccuracy associated with hand lay up of prepreg tape. The volume fraction of fibres was 60% and the resin used was a low temperature cure. These two conditions reduce the residual stress induced during cure. The honeycomb was manufactured using filament wound hexagonal tubes, glued together to form the core. The curvature of the mirror was then milled to shape, and the front, and rear, face sheet adhered together with the core. A 0.5µm reflective layer of aluminium (protected using Plasil) was added to the polished surface of the mirror to provide the reflectivity requirement. The structure of the telescope is once again manufactured using CFRP limiting the thermal mismatch between the reflector and structure. The joint between the structure and the reflector also consists of three isostatic mounts further insuring the deformation of the telescope structure does not affect the reflector (Tauber, 2010).

JWST - The James Webb Space Telescope (λ of 0.6 µm to 27 µm.) is due to enter service in 2018 with a primary mirror of 6.5m, and will be the largest optical reflector ever to be launched into space. The requirements for the JWST primary are a light collecting area of 25m^2 with an areal density of 20kg/m^2. Combined with a wave front error requirement of less than 131 nm RMS at an operating temperature of <50K this provided a challenging engineering project. Especially as during the JWST inception in the mid 1990's such mirror technology was at a Technology Readiness Level of 3. This lead NASA into an aggressive development for advanced mirror technologies. Competition between vendors and technologies saw a rapid increase in TRL for large aperture cryogenic mirrors. (Stahl, 2009)

The technology that was finally chosen for the mirror segments was a primary mirror made from 18, 0-30 Beryllium segments. 0-30 Be has high dimensional stability and also has excellent homogeneity providing repeatable and predictable behaviour during cooling. This material provides excellent specific stiffness and mass was further reduced by 90% using milled triangular pockets to the rear (Kendrick, 2009). This provides a semi rigid mirror that can be corrected changes to radius of curvature via actuators on the rear. After an initial polish to 100nm RMS surface figure error mirrors were cryofigured to remove the remaining errors to the requirement of less than 24nm RMS at operational temperature. There were also tight restrictions on the surface change induced by thermal cycling and the maximum surface figure change from ambient to operational temperature.

The development of the JWST provided a demonstration of what competitive technology development, combined with defined and tight requirements can do to increase the readiness level of particular technologies. The use of a more homogeneous metallic material such as 0-30 Be enabled the mirror to be manufacture at high precision and at predictable performance. The thermal conductivity of Beryllium is much higher than a polymer composite enabling a shorter time constant during cryogenic cooling. There is, however, a long lead time in manufacturing mirror segments that could be reduced by using CFRP without the loss of CTE. It is also worth noting that the CTE of Beryllium changes dramatically between ambient (300K) and 4K, thus the requirement for Cryonulling of the surface figure error. Whereas CFRP tends to have a relatively low and constant CTE throughout.

7 Current status

At present the specification for the potential FISICA telescope mirror is still undecided. From documents produced by Maynooth University within the project, certain aspects of the mirror have been defined based on theoretical assumptions and modelling. The baseline document circulated in November 2013 mentioned two possible mirror configurations, a conservative monolithic mirror and a more challenging segmented larger mirror. It was always understood that the FISICA mirror due for investigation would be somewhere between the two. The present status is a 2m diameter mirror with a surface roughness error budget of 80nm RMS and a Form error of 275nm RMS. This allows the possibility of a monolithic mirror due to the diameter being within the shroud diameter of an Arianne V launch vehicle. Due to manufacturing constraints a segmented approach may be more viable. However if this can be avoided it would beneficial to reducing the complexity of such a structure.

The SPICA telescope is set for similar operating conditions <6K and wavelengths 35-210 µm. SPICA's primary mirror is to be produced from Silicon Carbide and requires 20nm RMS surface roughness and a form accuracy of <175nm RMS. In comparison to the FISICA target it is clear that the form and figure errors are more relaxed for FISICA than SPICA. The primary mirror for FISICA is also significantly smaller at 2m.

The possibility of a CFRP mirror is discussed further but current polishing and manufacturing methods for composite mirrors at 80K are possible at these tolerance. At ambient temperatures, mirrors of 150mm diameter have been fabricated with 200nm RMS surface accuracy, and surface roughness of 6.2nm RMS (Utsunomiya 2013). When cooled to 210K the surface accuracy improved by 115nm RMS, presumable due to the contraction of the material. It remains to be seen whether the results are scalable to 2000mm diameter and to lower temperatures.

Some cryogenic testing at lower temperatures of CFRP mirrors has been discussed in previous work. Utsonimiya again manufactured 150mm CFRP (Cyanate ester resin) sandwich flex core blanks (Utsunomiya, 2013). The mirrors had a surface accuracy of 700nm RMS and a roughness of 10nm RMS at Room temperature which, when tested at 80K, both surface accuracy and roughness improved, meaning that the mirror deformed to closer to an ideal spherical shape (surface accuracy). It is worth stating that there was a change in geometry from RT to 80K, in that the central section of the mirror became more convex and the edges formed a saddle shape. There may be many factors for this; no comment was made on what may have caused the warpage. Further investigation into the mechanisms of CFRP mirrors at this temperature was recommended. The author of this report suggests that the addition of an epoxy layer on the reflective surface of the mirror to alleviate fibre print through, may have caused differential contraction leading to the increase in concavity. In comparison to the FISCIA requirement, it can be suggested that the possibility of using a CFRP mirror at 6K is still possible. The roughness value required for FISICA seems achievable but the form error remains a challenge.

For this project a prototype demonstrator mirror is proposed to be of a diameter of 200mm and a radius of curvature of 3m. The target surface and form error will be 80nm RMS and 275nm RMS respectively at 4K. These are definitely challenging targets and will be difficult to achieve in such a time frame and budget. However Glyndwr will endeavour to propose a roadmap on how the target could be achieved in the future with development and research.

8 Issues to Investigate

The review of literature and research into existing solutions has brought into light some non-trivial issues and challenges that are to be faced if a fibre reinforced polymeric composite material is to be used in a cryogenic environment. Perhaps first it would be prudent to underline the capabilities and advantages of using this technology.

Coefficient of Thermal Expansion (CTE) – As a generality, polymeric composite materials tend to have near zero CTE. This is not the case in all directional planes due to the difference in the fibre and matrix material properties. However, if the fibre volume factor (ratio between fibre and matrix by volume) is low, the material will have decreased volumetric shrinkage (during cure) and increased dimensional stability (during operation at extreme temperatures). There will be a necessary trade-off between low volume fraction for form and figure accuracy and a more considerate volume fraction for elimination of fibre print through in the surface.

Replication method of mirror production – Replication enables multiple mirrors to be replicated in the same form and figure accuracy from a single polished mandrel. The roughness of the surface of the mandrel is replicated onto the resin rich layer of the composite mirror and this process can be repeated many times before the mandrel needs to be refigured. If the correct material is chosen, that is the volumetric and thermal shrinkage is low, the accuracy of the form can be maximised. The enablement of the replication method reduces the requirement for specific fabrication techniques such as CNC machining the blanks or sintering. Additionally with new out of autoclave cure systems, the diameter of the mirror or mirror segments, is no longer restricted to the size and availability of expensive autoclaves.

Specific properties - Monolithic composite materials have impressive specific stiffness and strength. The tailorability of fibre architecture, in combination with the different choice of fibre materials, equips designers with a huge variety of options for the creation of structures and components. The true extent of composite material design is yet to be realised and will enable engineers to produce composite materials with near zero contraction due to composites in all directions. In addition to the monolithic possibilities, one must include the use of a core material for sandwich structures. By utilising a light weight core, the second moment of area improves by increasing the distance of the face sheets from the centroid axis. This causes a gain in the flexural modulus with a small mass increase. The result is a structure with high specific stiffness. An additional advantage, especially with open backed cores, is an increase in the time constant for cooling of the panel. The monolithic face sheets are thinner and hence thermal gradients within the sheets are reduced. There are of course disadvantages to this method, in that the core can print through to the face sheet causing quilting and a resultant low order spatial frequency error. Also the addition of the core causes a reduction in compliance, especially important in active mirror.

The major advantage of polymeric composites is the areal density that can be achieved. At present this is unrivalled by other mirror candidate materials. The requirement for higher resolution space telescopes utilising larger aperture mirrors has been well documented in the space community to maintain pace with astronomical discoveries and ambitions. A common rule of thumb is that the mass of the sub-structure of a telescope scales somewhere between the square and cubic of the mirror diameter D. This scaling law will be reduced somewhat by the areal density of the mirror used for the primary mirror, and thus reducing the bulk of the support structure required. Transportation of mirrors for space and ground telescopes has traditionally been a hindrance in terms of mass and area restrictions. For space telescopes the fairing shroud and payload has been restricted by the availability of launch vehicles. Stahl discussed the use of the future launch vehicle, Ares V for launching a 6-8m class telescope. The Ares V will utilise a larger fairing and, more importantly a larger payload mass. Potentially this would enable the launch of a 6-8m class glass primary mirror, enabling low cost, low risk technologies used by ground telescopes. However, if the glass material was to be replaced with a composite mirror, whether a monolithic or sandwich structure, more instrumentation could be included within the mass budget. This would allow more observations by different institutions to be undertaken. Although the risk in using a composite mirror, or another light weight material, is high, so are the rewards in accommodating instruments for numerous different observation types.

The Arianne V payload fairing can comfortably accommodate a 3m diameter monolithic mirror. For the FISCIA project, a 2m mirror has been proposed at this early stage. The width of the failing shroud enables a monolithic (i.e. non segmented) mirror vastly reducing the risk associated in engineering a deployable mirror for interferometric measurement at cryogenic temperatures.

The advantages, and possibilities, in using CFC in space telescope primary mirrors have been outlined above. However for there is significant research and development required to achieve a PMC for a cryogenic space mirror. At present the use of PMC for telescope mirrors is at a high TRL. CMA inc regularly produces infrared wavelength reflectors of roughness and figure accuracy required for FISICA. Unfortunately the temperature that FISICA must operate at has not been realised for a composite mirror. The following chapter indicates issues that need to be resolved and possible studies that could take place to improve the confidence and reduce risk in utilising this technology.

Requirements

NASA has classified many composite materials suitable for space environments in terms of outgassing requirements. Polymer matrices, especially thermosetting resins used in pre-impregnated systems, tend to include solvents utilised to aid manufacture.

When in a vacuum environment, these solvents tend to be released from the material and can condense on space optics. The selection of a NASA-qualified material would reduce the risk in using a fibre reinforced composite in that aspect. For this project, MTM44-1 carbon fibre prepreg has been acquired. The NASA-qualified material is already extensively used for satellite structures and provided intermediate elastic strength in the fibres. This allows the material to be flexible and also reduces mass significantly in comparison to high strength alternatives. The resin used is an epoxy resin that is widely available and provides excellent temperature stability.

To enable the use of this particular material for the FISICA mirror, cryogenic properties at 4K must be characterised to build confidence in the behaviour of the material. Unfortunately there is little literature available for composite materials at temperatures below 40K. Some research exists at 40K and above but caution in extrapolating results to lower temperatures must be displayed. This caution is well founded, due literature in regards to super-Invar which was found to change its micro structure to a martensitic material, causing unexpected expansion and mirror deformation during the AKARI mission.

All materials will change properties to some degree, during cool down to cryogenic temperatures as low as 4K. Characterising this dimensional change is critical in insuring that any mirror material can be used in this environment, and if required, corrected either by utilising deformable mirror control systems or by correction in the optical system. However for secondary correction to be utilised the deformation must not only be predictable, it must also be repeatable. To enable this accuracy in prediction, computational models can be created with suitable boundary conditions and assumptions, to calculate deformation. The accuracy in the modelling is entirely dependent however on the material properties inserted into the software. As is customary, the use of a resin rich layer to eliminate fibre print through, enabling a replicated specular mirror surface is required. The selection of the resin for the surface and used as a matrix must be carefully chosen to eliminate the possibility of thermal contraction mismatch, which will induce residual stress and an increase in surface roughness.

The classification of the material at cryogenic temperatures is vital in creating models and formulating predictions. Modelling can save considerable time and effort in fabrication and testing and so the work required to test the material creates considerable savings.

8.1 CFRP Mechanical properties at 4K

The matrix material in fibre reinforced composites is the constituent that is the main provider of the flexural modulus of the material. At high temperatures, thermosetting polymers move from a glassy to rubbery state. This reduces the effectiveness of the material to withstand out-of-plane loads and changes in the natural frequency of the composite. At low temperatures it is expected that the polymer would become harder but more brittle with a clear change in the elasticity of the material. For a space mirror, toughness and stiffness may not be a key issue due to the lack of static load on the structure. However the vibration in the satellite will, to some degree, have an effect on the mirror surface. If the natural frequency of the mirror is directly related to the stiffness, the perturbations caused by mechanical cooling or some other acoustic source may modify the mirror surface causing an excess error in form/figure and possible defocus of the system.

Cryogenic measurement of the mechanical property of the constituent materials of the composite is vital. Tensile and flexural tests need to be undertaken on a large standardised scale. The orientation of the ply stacking sequence at this point is unimportant. The measurement in the fibre and matrix direction (for unidirectional materials) must be undertaken. The strain caused by tensile extension should be also be measured. Caution needs to be shown that the measurements are taken in an isothermal environment and sufficient soak time must be given so that the entire sample is at the reference temperature.

Mechanical properties at cryogenic temperature of a wide variety of materials can be found and understood in literature. The risks associated with such tests are low if correct procedures are followed and understood. Tests to calculate the mechanical properties of CFRP at 4K must be undertaken fully. Tests should also include thermal cycling in order to assess the repeatability of the properties. An issue may be thermal micro cracking in the structure of the mirror; this will alter the natural frequency of the material and may have catastrophic effects on the results.

8.2 CFRP Thermal properties at 4K

As discussed previously, temperature changes may cause dimensional changes in the material bulk. It is well understood that the reinforcement fibres do not change significantly through temperature changes, whether that is a positive or negative change. But if the composite utilises a polymeric matrix there will be some, all be it very small, expansion or contraction due to temperature changes. The fibre and matrix properties combine due to the adhesion at the fibre/matrix interface and the final property of the composite is a proportional measure of the both. There is still however some thermal change in dimension at a ply level. By designing the ply stacking and maintaining a symmetric sequence about the centroid of the material, one can prevent thermal curvature due to the couple of expansion strains being balanced. This balance however, is highly dependent on fabrication accuracy. For composite applications that require low form accuracy the small changes in form are not important. However for a highly accurate mirror surface the change in bulk, no matter how small will cause difficulty to the error budget.

In addition to this, the mirror must cool to the desired temperature in an even and measureable manner. The thermal conductivity of the material is a highly important measure to ascertain at a variety of temperatures. The conductivity and in turn, diffusivity is dependent on the reference temperature and so must be measured during cooling. Polymer composites tend to have low conductivity and thermal for a high thermal time constant. The result of this is that the bulk of the material requires a longer soak to acquire and isothermal cooling through the structure. The slow cooling can be advantageous to maintain a predictable deformation during cooling. Some materials react to the strain rate applied to a material caused by cooling, deforming to a higher level than if the cooling rate is slow. However, for space telescopes that are actively cooled, one would want the mirror to cool at a controlled but high rate. This reduces the amount of energy, or volume of liquid helium, required by the cooling system.

These two issues require that the thermal properties of the mirror must be measured at temperatures from ambient to 4K. Experiments of this type are well researched and available commercially and within academia. Early stage thermal expansion/contraction measurement of the chosen material is being undertaken by the University of Lethbridge for this project. The resulting properties from these measurements will be entered into a Finite Element Analysis package to develop a model to the change in form and figure through cooling to cryogenic levels. Although helpful for an early estimate, the scale of tests and accuracy of these measurements must be questioned for final use. The calculation of thermal conductivity will be estimated for this project, however for future research, it is imperative that the correct conductivity and diffusivity are calculated in order to ensure that the material is fully cooled through the bulk and all dimensional changes occur isothermally.

8.3 Material Selection, Manufacture and Fabrication

Fibre and matrix materials are widely available for components that are used in relatively benign environments (relative to cryogenically cooled L2 orbit). For more complex applications, such as a far infrared cryogenic interferometer, more specific material choices must be made. An earlier section discussed the availability of material data for such an operational environment and it was shown that little exists. As a starting point, this project has chosen a well-known and understood material used in satellite construction. Whether this is the most suitable material for this application is yet to be understood but due to the high cost of composite materials, it is to be considered due to budgetary restrictions. Research indicated that cyanate ester resins might be most suitable for the matrix material due to their resistance to moisture absorption and also high dimensional stability. However, the cost of such material is prohibitive for an early phase such as this. Fibre materials are most restrictive with carbon being the more obvious choice. Glass fibres would improve conductivity but add weight and be weaker. Aramid fibres are strong and have high impact resistance but are hydroscopic increasing the possibility of moisture ingress which can cause swelling of the material and premature failure.

It is recommended that significant time and interest is spent on material selection paying particular attention to the matrix material. A trade off study should be conducted and key properties compared and quantified to aid selection. Properties such as CTE change per K, glass transition temperature, ultra violet resistance, moisture resistance, flexural modulus, and availability in pure resin and prepreg from are recommended.

The mechanical and thermo-mechanical properties of polymeric composites are directly related to the accuracy, quality, and design of the manufacturing and fabrication techniques. Fibre architecture will pay a crucial part in the dimensional stability of the material. The requirement for a telescope reflector requires high dimensional stability, or failing that, predictable deformation. The very nature of composites means that true isotropic behaviour is not possible. However, quasi-isotropy in the material is an achievable goal. The strongest form of composite involves continuous long strand fibres; the fibre architecture may be unidirectional or have a woven pattern. The weave may also be 3 dimensional to improve through thickness properties. But this is fraught with possible errors that could affect the final component. To begin with, fibre misalignment and waviness during fabrication could result in further isotropic properties and expansion. The literature into this area is limited for thermal contraction but what is clear is that it will have an effect of the quality of the final component during operation. Automated layup techniques need to be employed to reduce human error in manufacture and the possibility of advanced fibre architecture (3D weaving or through thickness pinning for example) should be investigated further for applicability.

Another consideration is randomly orientated fibre matting, infused with pure resin. This is a reasonably inexpensive, and primitive, method in comparison to laminate systems but may well have applications for reflectors. For a start, the structure can create properties that are closer to being isotropic than laminates. Also there is a distinct possibility that preforms can be created that will take the shape of the final mirror, by infusing resin through the preform and with the use of a polished mandrel; a suitable mirror could be created. The disadvantages of the use of randomly orientated fibres are non-trivial however. Resin infusion over a 2m scale whilst controlling the elimination of air bubbles within the component is a challenge. Also depending on the mirror thickness, the mass of the composite would be higher for chopped strand short fibres than long continuous fibres if stiffness is to be maintained. That being said the inclusion of a core material, sandwiched between two face sheets, is a solution to that issue. The use of a honeycomb core would reduce the mass of the mirror, reduce the time constant for cooling (a thinner face sheet is required) and would also create a stiffer structure. Sandwich structures do take up more precious payload volume, and increase difficulty in production and increase the possibility of thermal mismatch during cooling (that may produce surface quilting). It is recommended that a full design study of a number of different mirror architectures is undertaken to create a better understanding of the influence of fibre directions and cores.

Once the structure and material of the composite has been chosen the manufacturing process needs to be devised. The automation of the fibre laying process has been discussed to eliminate human error in fabrication. Once produced, the component must go through a heat cycle to fully cure the material (for thermosetting polymers only). The choice of which process to use is key in the final stability and form of the mirror. The key issue in composite curing is residual stress induced within the material which, when released, changes the form of the final component, normally via spring back. Residual stress is the result of a number of processes, thermal shrinkage, chemical shrinkage, thermal gradients, pressure applied during cure and fibre architecture. The final point is controlled in fabrication using a balanced and symmetric layup for laminate composites. Chemical shrinkage is a function of how highly networked the polymer is, and can be compensated for, during selection. The remaining issues are a resultant of the cure cycle and application of heat to the system. Significant development and research has been invested into many aspects of cure profiles. What is of interest is that some of these issues are unavoidable in conventional autoclave and out of autoclave cure methods. One of the key drivers that is difficult to avoid using convection heating systems is the thermal gradient though the material during cure. This causes differential cure through the profile and expansion at different depths that induces residual stress within the part. One method that is yet to be explored for composite mirrors is the use of microwave curing. The controlled application of microwave energy could cause the materials to cure from within and if the additional application of heat via convection onto the surface could be achieved it would reduce the amount of residual stress within a part. This technology is at a relatively early stage and is at a low TRL. But the possible impact of the technology to the dimensional stability and also speed of manufacture could be high and innovative.

It is the residual stress within a composite mirror that causes the most concern to the suitability of the material for the application. The contraction of the material during cooling, in combination with compressive residual strain that may be present within the part, may cause undesirable and catastrophic deformation in the mirror. One test proposed for this project is the effect on samples that have in build residual stresses whilst they cool to 4K. The samples will be manufactured with a curved section that is known to form residual stress, and tested in the same manner as a sample with straight sides. Both samples will contract when cooled and by comparing the contraction of the two sample types it is believed that the release of residual strain will cause an increase in deformation. This will be due to interlaminar failure which is the loss of strength between ply layers. In a cryogenically cooled mirror, the failure will cause a change in stiffness, and natural frequency, but more importantly, cause the form of the mirror to change. The risk of failure due to residual stress must be investigated thoroughly and the design and manufacture devised to reduce the strain as much as possible.

8.4 Coating technology

The coating of the mirror is yet to be research fully during this project. A reflective (to infrared) coating will most likely be required upon the figure mirror surface. The application and material selection of such a coating must be investigated fully. The adhesion of the coating to the material must not affect the composites structure, therefore high temperature application is unwise, and must be maintained during cooling. The coating thickness must also be small to avoid surface errors and also thermal contraction mismatch during cooling. It is envisioned that the coating technology is a secondary feature in the development of a composite mirror for this application, but should be considered in great detail during any future design procedures. Providing the mirror diameter, or the required segments, if the mirror geometry doesn't increase, remains at approximately 2m x 2m, access and availability of suitable coating chambers will not be a significant issue.

9 Experimental procedure for Cryogenic testing of composite

Measurement of the coefficient of thermal expansion of MTM44-1 carbon fibre composite is vital to ascertain the material's suitability in creating a cryogenically cooled mirror. MTM44-1 is used extensively for satellite structures and is space qualified for outgassing by NASA. The possible contraction of the material during cooling to 4K will affect the global form and the surface error of the mirror. Measurement of the CTE is therefore vital to understand how the material will behave during the cooling process. It may then be possible to polish the mirror at room temperature so that any change in form will still adhere to the tolerances and specification outlined. There is also the option of adaptive optics being used to correct such changes in form.

There is a significant lack of information available in literature for polymeric composites at temperatures as low as 4K. It is thought that the reason for this will be due to the lack of requirement at this temperature. Space structures are rarely subjected to temperatures below 30K due to radiative heating. There is however, significant literature available for composites at 40K and above, mainly driven in recent years by the NASA reusable space vehicle development, specifically for cryogenic fuels tanks.

David Naylor and his team at The University of Lethbridge (UoL) have kindly offered to assist Glyndwr in the cryogenics testing of MTM44-1. UoL have a 6L cryostat that is capable of cooling to 4K. They have previously used this technology to test the thermal expansion coefficient of carbon fibre reinforced plastic struts which they intend on using for a large cryostat currently in development. The struts were fitted in a hexapod configuration as shown in Figure 4 and connect to an upper and lower plate. The side of the cryostat is fitted with a viewing window, through which a Renishaw differential laser interferometer can be used to measure the relative displacement of the top plate and bottom. This configuration uses a 90 degree fold mirror which directs the beam to the bottom plate. The resolution of the interferometer is ~0.4nm.

Figure 4: Hexapod structure for 6L 4K cryostat

UoL have modified the cryostat and moved the viewing window to the bottom of the cryostat rather than the side. A reference mirror is included on the bottom plate and the top plate is left free to translate with the expansion/contraction of the mirror. This removes the need for the fold mirror which was particularly susceptible to vibration causing error in the measurement.

Requested Experiments

Glyndwr hope to use the modified configuration in measuring the CTE of the MTM44-1 material described above. However, the use of struts is not achievable with the manufacturing facilities available. Therefore it has been decided that three flat panels can be used as a tripod structure to separate the upper and lower plates. The panels will be fabricated in the same manner and will be the same dimensions within a tolerance TBD. Panels will be cut to size using a water jet cutting process and will be dried in the oven prior to posting to UoL, the samples are shown in Figure 5. They will be packaged in a moisture free bag to ensure that ingress is kept to a minimum; they will also be insulated as far as possible during transit so that thermal effects during air travel are not incurred. (Note: UPS tend to keep cargo holds at between 10-29^{o}C at which the CTE of the material is relatively benign).

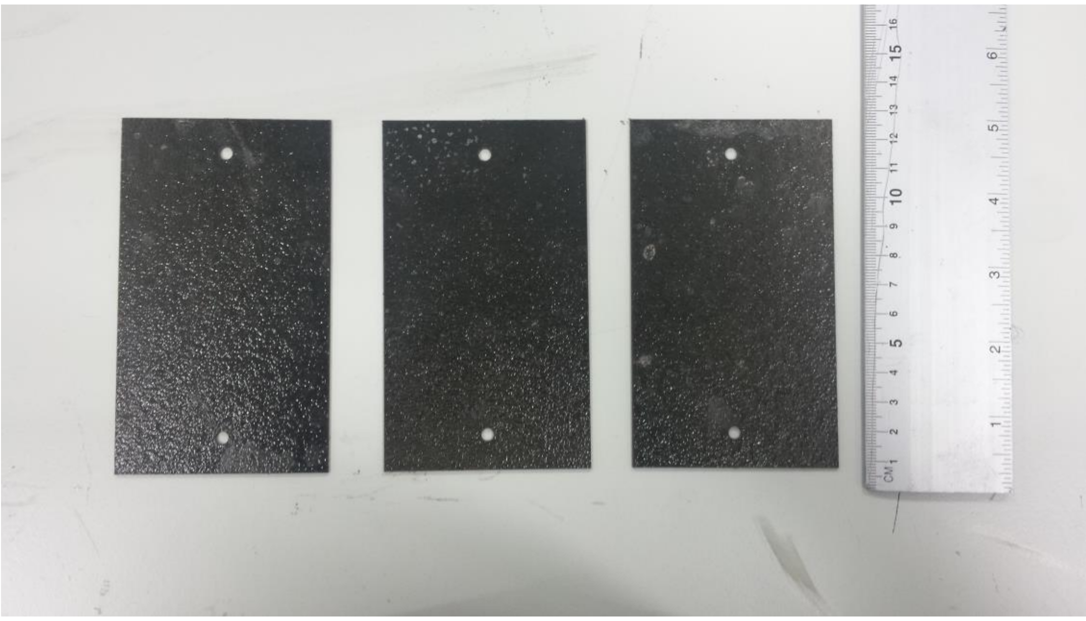

Figure 5: CFRP samples for cryogenic testing

MTM44-1 is supplied as unidirectional tape of width 300mm. The fibres run at 0^o longitudinally along the tape. The normal fabrication process of creating CFRP structures uses a quasi-isotropic symmetrical layup. This is the most likely layup to be used in mirror fabrication due to its predictable behaviour and tailorable stiffness and form. However, modelling the behaviour of the mirror during cooling using computer aided engineering requires the properties of the constituent layer of the material. Therefore, although the testing of the quasi-isotropic layup will be useful, it may be more prudent to have tests of the plies at 0^o and 90^o. The 0^o plies will provide data on expansion in the fibre direction. It is necessary however to include some plies perpendicular to the fibre direction to secure the stacking sequence.

It is also necessary to produce some panels at mostly 90^o plies. This will provide data on the CTE of the resin rather than the fibre. This information will prove especially useful in measuring the contraction of the resin through the thickness of the mirror. The contraction of the resin will potentially cause surface errors during cooling.

A second test is also being proposed that will test the mechanical properties of the material at 4K. Using the same tripod configuration, and also the same sample orientations (Quasi-Isotropic, 0^o and 90^o), a predetermined mass is added to the top plate, this will deflect the plates and from that data the Young's modulus can be derived. This task should also be repeated at 4K, and possibly at various intervals in-between, so the elasticity of the material can be measured during cooling.

A third and final test is proposed to measure the strength that bonds the layers of the laminar together, an extremely important property of the material, known as interlaminar shear strength (ILSS). During cooling, it is envisioned that the material will contract which will induce compressive strain into the material, especially between the ply layers. If the magnitude of this strain exceeds the materials interlaminar shear strength (ILSS) then the composite could delaminate causing voids in the through thickness. In loaded structures these voids will cause significant weakness in material. This is not necessarily thought to be an issue in the case of this mirror however the voids may cause small scale deformations in the substrate which would cause surface figure and form error.

One method to measure the ILSS would be to produce a plate with a curved section at its midspan running perpendicular to the expected displacement (Figure 6). When a thermosetting composite cures there is shrinkage in the matrix material due to crosslinking of polymer chains. This shrinkage begins suddenly during heating in the oven and then eases during the dwell period of the cure cycle. Also, the temperature gradient through the thickness of the composite, caused by the low thermal conductivity of the resin, causes the thermoset to cure at different stages through the thickness. These two phenomena can cause residual stresses to build, which can sometime manifest itself as deformation. If additional loading is applied, whether mechanical or thermal loading, in combination with the residual stress/strain, it can cause delamination and failure.

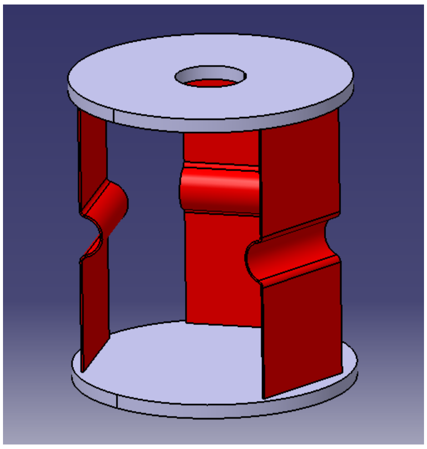

Figure 6: CAD mock-up of ILSS test

By creating a panel with curvature, some residual stresses will be built in. During cooling in the cryostat, the material will shrink and the relative displacement can be measured by the interferometer. If there is failure in the structure, caused by the residual stress and shrinkage, it should show as a clear change in gradient of the displacement. The magnitude of the strain can be derived using Finite Element Analysis (FEA) specifically using ISight package within Abacus which iteratively modifies an analysis, changing specific variables until certain conditions are met. The purpose of these tests is to obtain specific material properties to enable the production of an FEA model to simulate how the material will change in shape or form from room temperature to 4K.

It would be beneficial also to have the samples returned to Glyndwr to evaluate their properties after cooling and subsequent return to room temperature. The samples designed to test ILSS will be examined under SEM and hopefully by Non-Destructive tests to evaluate their final condition.

Table 2: List of possible cryogenic tests

Test	Layup	Geometry	Property meaured	Sample Size
1	Quasi	Flat	CTE	5
2	0	Flat	CTE	5
3	90	Flat	CTE	5
4	0	Flat	Youngs Modulus	5
5	90	Flat	Youngs Modulus	5
6	Quasi	Flat	ILSS	5

Considerations

Cooling rate

The rate at which a material is cooled will have a marked effect on the internal strain and therefore deformation. The FISICA project requires a mechanical cryogenic cooling system to reduce the temperature to 4K to limit self-emissions in the far infrared. Once the CTE of the material has been obtained, the cooling rate can be modified using FEA modelling to measure the magnitude of strain and deformation during cooling. It would be desirable therefore if the cooling rate during the experiments was not to severe and also kept constant (as much as possible).

Quality of manufacturing

Mechanical properties of composite are somewhat dominated by the reinforcement fibre orientation. Fibres carry the majority of tensile load within a composite and offer significant influence in flexural stiffness also. The thermal expansion/contraction is mainly driven by the resin as the fibre has an extremely low CTE. However during curing the resin bonds to the fibre in an area known as the interphase. Any change therefore in the bulk of the resin, either by shrinkage or expansion will be hampered by the fibres due to the matrix/reinforcement interface. It is therefore important to include test at both parallel and perpendicular to the displacement. There is also a case for the CTE at 45 degree to the lateral displacement however this is the least important of the tests.

Another issue may be the accuracy orientation of the plies. Quasi-isotropic symmetric layups normally rely on a [0/90/45/-45] repeated sequence. When placed correctly, this layup provides mechanical and thermal properties that are balanced and virtually equal in every in pland direction. However if the orientation is not applied accurately this can severely affect the quasi isotropic nature of the material. Therefore extra care must be taken during layup. Ideally an automated process would be utilised but this option is not available to the project at present.

The deformation during cooling can also be effected by manufacturing defects such as voids or inclusions. Without careful consideration during fabrication of laminates panels it is possible to create voids or trap inclusions between ply layers. The possibility of voids, or air bubbles, between layers can be reduced by vacuum debulking at regular intervals (every 4 plies for example). The chances of inclusions such as dust or debris, from consumables can be reduced by following strict cleaning and housekeeping guidelines in the laboratory layup room.

Another aspect that affects the quality of the part being manufactured and its final shape, is the curing method. Most composite components (especially manufactured from CFRP) are cured in an autoclave, providing pressure and heat simultaneously. The trend in recent years is to avoid using autoclaves due to their high initial cost and strict maintenance regime. Also as components get larger, so does the requirement for the internal volume of an autoclave which increase costs further. Out of autoclave manufacturing concentrates on hot presses and vacuum bagging techniques. Both of these methods can provide good quality fabrications, but in general, autoclave components are of the highest quality, in terms of the degree of cure and voids. At Glyndwr we only have access to vacuum bagging facilities so this is the process that will be used to fabricate the samples. It is worth noting, however, that if full and thorough procedures are followed in terms of a good vacuum bagging process and compliance with guidelines, there shouldn't be an issue with quality.

As an aside, there is also opportunity to manufacture composites using microwave curing techniques with or without the additional application of convective heating. The benefit of this method is that it does not cause thermal gradients, and subsequently residual strains, through the thickness of the material. Reducing the amount of deformation caused during cure. It may be interesting in the future to see how processing using microwaves change the CTE of a material during cooling to cryogenic temperatures.

Degree of cure

As a thermosetting matrix composite cures the polymer chains begin a crosslinking process. Although they are never fully crystalline, the crosslinking enables thermosets to form covalent bonds between the polymer chains. The crosslinking process is heavily dependent on the curing temperature and also the amount of time that the laminate is held at that maximum temperature. Manufacturers supply guidelines that provide a recommended cure schedule which should be followed in order to achieve a full cure.

If a full cure is not reached, or a cure percentage that is not consistent between sample batches, then the mechanical and thermal properties will not be predictable or verifiable. In general, the CTE of a fully cured sample will be less than that of a partially cured composite due to the reduced crosslinking of an under-cured polymer matrix. Degree of cure can be measured by taking a small sample of the material after fabrication and testing during Differential Scanning Calorimetry (DSC) or Dynamic Mechanical Analysis (DMA). Both of these tests are achievable in Glyndwr and batch samples to ensure degree of cure will be undertaken.

It may be of interest to test the effect of degree of cure on cryogenic performance in the future. Initial studies will be undertaken at Glyndwr using Thermo Mechanical Analysis (TMA) which has the ability to measure the CTE from 100^{o}C down to approx. -60^{o}C using liquid nitrogen. If the results from this test are of interest then there may be a possibility of future collaboration.

Thermal conductivity and diffusivity

As discussed previously, composites consist of two distinct materials that remain separate throughout its life and disposal. The properties of composites are a function of the properties of the constituent material, their relative amounts, and the geometry of the reinforcement material.

The assumption is that the contraction of the material will be driven by the matrix of the composite. However, the thermal conductivity and diffusivity of the polymer matrix, in this case an epoxy resin, is relatively low in comparison to the carbon fibre reinforcement. Therefore most of the heat during temperature change is dissipated through the fibres rather than the resin. The fibres tend to have a low CTE but will conduct the heat through the matrix. The diffusion of this heat through the matrix will be key to ascertaining how quickly the material will cool to ambient space temperatures and also further cooled to 4K to limit emissions.

10 Design of Mandrel

The most common and successful current method for manufacturing a CFRP mirror is to use the replication method as discussed previously. The key element of this procedure is the fabrication of an optically polished mandrel that is used to replicate the reflective mirror surface. As the project requires a concave mirror, a convex mandrel must be manufactured to a given tolerance and surface roughness. Herein exists a challenge in the measurement of the surface of the convex mandrel after figuring. Alongside this is the requirement of the mandrel to have little or no expansion during cure (up to 180^{o}C) to reduce the residual stress on the CFRP that an expanding mandrel may worsen. If the mandrel expands it may cause error in the mirror form. Therefore a material must be chosen that is simple to fabricate and polish as well as have little or no expansion. Invar was initially considered as a mandrel material and would definitely satisfy the low expansion capability required. There would, however, be significant research and development required for polishing an Invar mandrel in house at Glyndwr. It is understood that invar has been used in specular mirrors previously but it is also noted for it difficult to achieve the require accuracy in figuring.
Low and zero expansion ceramics are especially Glasses and ceramics are to be further considered for a mandrel. Two materials in particular are of interest, Zerodur and Borosilicate (Pyrex). Both of these materials are suited to the polishing facility, using Zeko CNC polishing machines, within the institution. Zerodur has a near zero expansion over the cure range for standard CFRP and Pyrex a very low expansion range and so

would be suitable for limiting the stretching and form errors induced during cure expansion. Quotations have been sought from suppliers of both Zerodur and Pyrex, with Pyrex being considerably less expensive to purchase.

One aspect of Pyrex and Zerodur that is especially attractive is that both materials can be used for microwave curing of CFRP whereas Invar would not be suitable. This opens the possibility of using non-conventional, out of autoclave cure methods in the fabrication of mirrors.

The most appealing material for the mandrel is currently Pyrex. This material is used by composite mirror manufacturers currently and therefore has a higher TRL than using Zerodur for this purpose. The cost of a Zerodur mandrel is also prohibitive with a quotation of close to £3000 for a 200mm diameter ground blank. A Pyrex mandrel, figured to 3m RoC is half that price; discussions are currently underway as to the future availability of a larger mandrel for the possible full size mirror for FISCIA.

11 Conclusion and Future progress to achieve a cryogenically cooled carbon fibre composite mirror

This report has comprehensively covered telescope mirror technologies including the materials and structure of large apertures space telescopes. Focusing on mirrors that have been manufactured for operation at temperatures down to 40K, with figure and form error budget allowances that have been comparable to that of FISCIA. Satellite's currently in development, such as SPICA are being engineered to operating at less than 40K (down to ~4K) to limit background emissions similar to that of the required specifications of FISICA. The main current materials used for cryogenic space mirrors are Beryllium or Silicon Carbide based structures. These materials are lightweight, stiff and highly dimensionally stable, so are extremely suited to the application. The research and development into these materials has been extensive and the invested time and money has been significant.

The possibility of using CFRP composites for a cryogenic space telescope mirror was discussed. CFRP can be manufactured in many forms and is highly tailorable to applications. The fibre architecture of the composite is especially adaptable with the use of long or short strand fibres dependant on the magnitude and type of loading. In terms of dimensional stability it is the matrix that is the key component of the composite. The fibres are highly dimensionally stable and can be used to control the expansion (or contraction) of the matrix, possible by altering the fibre architecture. The matrix material must be carefully chosen in order to maintain the surface and geometry during a temperature gradient, for example from manufacture to cryogenic operating temperature. If chosen carefully, the matrix can have a very small thermal expansion coefficient. However, as the matrix is reinforced by fibres which have an almost zero CTE, this can cause a coupling effect that worsens any distortion. Through fibre architecture design, this distortion can be managed and reduced significantly. The overwhelming benefit of CFRP materials is the possibility of weight reduction, either using a monolithic laminate mirror or a sandwich structure. When combined with the benefit manufacturing techniques that are significantly cheaper than those that are required for silicon carbide or beryllium, CFRP becomes an even more suitable candidate. One such manufacturing technique is replication where no polishing or lapping techniques are required after curing recuing costs and manufacturing time.

Despite the attractions of CFRP as a mirror substrate, the technology for a cryogenic mirror is at a low stage of development. Research into mechanical and thermal properties of polymers has been increased in recent years due to the challenges presented by NASA's reusable launch vehicle programme. The fuel tanks, in particular have ignited significant interest in the possible use of CFRP, and so low temperature tests have been conducted at cryogenic temperatures for candidate materials. Unfortunately the temperature is down to 40K and so more effort will need to be undertaken to take measurements at temperatures as low as 4K.

During the selection of the JWST primary mirror segments an aggressive development process was launched to provide a dimensional stable mirror suitable for use at <50K. At the launch of the development in 1996, there were no candidate materials that could be used for this purpose that would satisfy the weight and error budgets specified. It was therefore important for the project to be thorough and aggressive in order to raise the TRL of such a mirror to 6. Although such an approach is not required for a Far Infrared Space Interferometer, mainly due to the SPICA telescope mirror in development, a thorough investigation must be undertaken for the use of CFRP mirror technologies. It is important to note that the research and development required to increase confidence and TRL in CFRP cryogenic properties is beyond the scope, timeframe, and budget of the FISICA project

The following is a list of possible areas of investigation required to validate the technology further to assess its suitability for a cryogenic environment within the error budgets allowed for FISICA:

Coefficient of expansion at 4K of composites materials

Ideally the composite will need to be dimensionally stable during cool down and not require calibration either by creating a complaint mirror or using cryofiguring during fabrication. However, this is unlikely so therefore predictable, repeatable distortion is required. The key to this is classifying the coefficient of explosion of the constituent materials, modelling the predicted change in the composite geometry and then validating the model by measuring the change in a cryostat.

A number of polymer materials must be tested in order to ascertain what material is best suited for the matrix phase of a composite. As there are many types of polymers available, it is worth noting recent research into polymer matrix composites for the NASA reusable launch vehicle and considering the materials identified for that application. It is vital that the materials meet NASAs outgassing standard to avoid the possibility of gases being released from the material and condensing on optics and instrumentations. Epoxy and Cyanate Ester resins are the primary candidate material for space structures. There are many materials commercially available; however, their cost for small scale operations is prohibitive, in particular the FISICA budget of Glyndwr.

Thermal Conductivity

The optimum material properties for a mechanically cooled cryogenic mirror are low CTE and high thermal conductivity. This allows isothermal cooling to enable the mirror to reach operational temperature in a low time, but with little dimensional change. Some polymers have a very low CTE but the conductivity of polymers is normally lower than other materials. This, in itself, is not a large issue. High conductivity may cause high strain rate inside a polymer during cooling, even with low expansion/contraction during thermal cycling. The time taken to cool the mirror via mechanical cooling methods is a serious consideration because it will require more energy to create an isothermal structure.

The thermal conductivity of the material will change as the temperature decreases; therefore a full scope of conductivity measurements from ambient temperature to 4K must be undertaken.

Mechanical testing

A full range of mechanical tests at 4K, and cool down temperatures from ambient, would be required once the material and fibre architecture was chosen. Of particular interest is the flexural stiffness of the material. This would allow a computational model to be made to quantify the distortion during cooling, used in combination with the coefficient of expansion. The stiffness of the material is also a vital measure of if the mirror will withstand the vibrations during launch loads. Also the stiffness at 4K is required to measure the distortion of the mirror during operation caused by acoustic vibrations in the cooling system.

Tensile and compressive strength of the material at 4K must also be established. This allows further properties to be added into any computational models.

A key measure will also be the interlaminar shear strength of the composite. If the contraction of the material during cooling exceeds a certain amount it may cause failure if it exceeds the ILSS of the material. The ILSS failure is worsened by the residual stress within the material which is induced during cure.

Moisture ingress

The inclusion of moisture between ply layers will cause unacceptable distortion during cooling and also will modify the stiffness of the mirror. Therefore one must try at all cost to avoid moisture inclusion during fabrication. This is normally undertaken by using a drying cycle after cure and a moisture controlled environment in the laboratory using for fabrication.

Degradation via UV and radiation

Some polymers have a tendency to degrade during exposure to radiation, especially UV. If the matrix of a composite degrades, the stiffness of the material is also reduced. Therefore the resistance of the material to UV degradation must be taken into account during the material selection process. However, if the material is promising in terms of thermo mechanical properties but has poor UV resistance then it should still be considered and the use of coatings to protect the polymer. Also the effect of UV degradation during operation at 4K should also be investigated. One method to completely mitigate the risk is by coating the mirror in the reflective coating, it is then vital to ensure there is no leak through of the UV.

Polishability of the resin

The specifications for the FISICA project necessitate a highly accurate surface for the mirror. For CFRP mirrors, the most common procedure is known as replication where a composite mirror is cured over a highly polished mandrel. This process replicates the mandrel surface on the face of the mirror, and the mandrel can be used a number of times before repolishing. Further polishing can be undertaken via traditional polishing or even diamond turning. The suitability of the material for polishing or replication should be tested thoroughly.

Design and manufacturing technique

The fibre architecture is a key factor in controlling and tailoring the thermal and mechanical properties discussed above. All tests must consider this, and as a result, it is the constituent parts of the composite, the matrix material and fibre material, which must be tested initially and modelled in accordance with the chosen architecture. It is normal for CFRP mirrors to be made from unidirectional prepreg tape. There are however many other options, from short fibre chopped strand mat to 3D woven fibres. The advantages and disadvantages of composite structures are available in literature, and also relatively simple to assess using hand calculations.

Aside from the structure of the monolithic composite, the addition of core materials as a sandwich should be investigated fully. The reduction in weight using sandwich construction is significant and could be a worthy technology for large mirrors. However, this increases manufacturing complexity and may also cause some print though from the core onto the mirror surface.

The method selected to cure the polymer is also something that should be considered carefully. Autoclave, or oven curing, applies heat, normally by convection and pressure to the component. This causes differential temperature rates through the thickness of the part which induces residual stress into the part. This identifies itself as spring back once the pressure is released but some residual stress will remain and may be released during operation causing further distortion. One method of vastly reducing spring back is to use microwave curing, possibly in combination with heat applied via conduction. This would mean that the application of heat and the curing would be more evenly applied through the thickness of the material reducing the residual strain within the part.

Coatings

The application and use of coating is vital in order to prevent the mirror substrate absorbing the infra-red radiation that it is attempting to collect. The reflectivity of the material in the particular waveband should be investigated alongside the application technique. For polymeric composites, the application of heat beyond the glass transition temperature of the polymer can cause significant degradation in the materials properties and should be avoided. Therefore, the coating method needs to be chosen carefully. Another option in the replication method of manufacturing CFRP mirrors is to apply the coating onto the mandrel from which the mirror is to be replicated. Experimentation on the application of the coating, and also the survivability of the coating at 4K, needs to be undertaken.

Future Plans

The second deliverable for the FISICA project is D2.4: Prototype of cryogenic-tested polished CFC mirror. The next phase of Glyndwr’s involvement will be utilising the research undertaken to fabricate a mirror and test the distortion in both form and figure, whilst cooled to cryogenic temperatures. The mirror will be made using a replication process using a carbon fibre reinforced epoxy resin unidirectional prepreg that has been NASA qualified for outgassing, MTM44-1. The polished surface will be measured before cooling and during soak at cryogenic temperatures in order to assess the change in optical surface at very low temperature operation. To achieve the prototype, a material test, as discussed previously, will be undertaken by the University of Lethbridge to characterise the expansion of the material during cooling to 4K, the thermal conductivity will also be assessed by Lethbridge. The material properties will then be utilised in a Finite Element model in order to quantify how the material behaves as a mirror during cooling.

12 Summary of possible areas of development

The use of CFRP as a telescope mirror for an infrared interferometer carries significant risk but a large reward as discussed in this report. To summarise, the following research topics need to be considered in order to utilise the attractive specific stiffness and tailorability of CFRP for a cryogenic mirror. Most, if not all, are beyond the scope and budget of the current FISICA project but could form future research projects in order to progress the technology:

- Fibre architecture and influence of 3D weaving on the stiffness of CFRP mirrors
- The stiffness and survivability of a CFRP chopped strand mat mirror during launch loading and operation
- Sandwich construction of a CFRP mirror and its distortion at 4K
- The thermal properties (CTE, conductivity and diffusivity) of the matrix, fibre and composite at temperatures from ambient to 4K
- Mechanical properties of the chosen fibre architecture of a CFRP mirror at 4K
- Coating technologies and their survivability at 4K
- Replication method to achieve FISICA specifications for a CFRP prototype mirror
- Distortion of a prototype mirror during cooling and investigation into the scalability of results
- Methods to decrease time constant for CFRP mirrors curing mechanical cooling to 4K
- Out of autoclave, novel curing of CFRP mirrors to recue residual stress
- UV degradation at cryogenic temperatures of CFRP mirrors
- Development of cryogenic test methods for the above.
- Long term stability of CFRP mirror at low temperature loads
- Effect of thermal cyclic loading on CFRP mirror
- Effect of vibration, via acoustic and other sources on CFRP infrared mirror.
- Diamond turning of CFRP mirrors
- Statistical analysis of the repeatability of CFRP fabrication process for far infrared interferometer mirror pair
- The effect of ply misalignment on a CFRP unidirectional mirror when cooled to 4K
- The influence of residual stress on a CFRP during cooling to 4K
- Moisture ingress on a CFRP mirror cooled to 4K

(This list is by no means exhaustive and is in no particular order)

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