Design and development of thin quartz glass WFXT polynomial mirror shells by direct polishing

L. Proserpio[*a,b], S. Campana[a], O. Citterio[a], M. Civitani[a,b], H. Combrinck[f], P. Conconi[a], V. Cotroneo[a], R. Freeman[f], P. Langstrof[d], E. Mattaini[e], R. Morton[f], B. Oberle[d], G. Pareschi[a], G. Parodi[c], C. Pels[d], C. Schenk[d], R. Stock[d], G. Tagliaferri[a]

[a]INAF-OAB Astronomical Observatory of Brera, Via E. Bianchi 46, 23807 Merate -LC- Italy
[b]Insubria University, Via Valleggio 11, 22100 Como -CO- Italy
[c]BCV Progetti, Via S. Orsola 1, 20123 Milano -MI- Italy
[d]Heraeus Quarzglas GmbH & Co KG, Reinhard-Heraeus-Ring 29, 63801 Kleinostheim, Germany
[e]INAF-IASF Milano, Via E. Bassini 15, 20133 Milano -MI- Italy
[f]ZEEKO Ltd., Vulcan Way, Coalville, Leicestershire LE67 3FW, United Kingdom

ABSTRACT

The Wide Field X-ray Telescope (WFXT) is a medium class mission for X-ray surveys of the sky with an unprecedented area and sensitivity. In order to meet the effective area requirement, the design of the optical system is based on very thin mirror shells, with thicknesses in the 1-2 mm range. In order to get the desired angular resolution (10 arcsec requirement, 5 arcsec goal) across the entire 1x1 degree FOV (Field Of View), the design of the optical system is based on nested modified grazing incidence Wolter-I mirrors realized with polynomial profiles, focal plane curvature and plate scale corrections. This design guarantees an increased angular resolution at large off-axis angle with respect to the normally used Wolter I configuration, making WFXT ideal for survey purposes. The WFXT X-ray Telescope Assembly is composed by three identical mirror modules of 78 nested shells each, with diameter up to 1.1 m. The epoxy replication process with SiC shells has already been proved to be a valuable technology to meet the angular resolution requirement of 10 arcsec. To further mature the telescope manufacturing technology and to achieve the goal of 5 arcsec, a deterministic direct polishing method is under investigation. The direct polishing method has already been used for past missions (as Einstein, Rosat, Chandra): the technological challenge now is to apply it for almost ten times thinner shells. Under investigation is quartz glass (fused silica), a well-known material with good thermo-mechanical and polishability characteristics that could meet our goal in terms of mass and stiffness, with significant cost and time saving with respect to SiC. Our approach is based on two main steps: first quartz glass tubes available on the market are grinded to conical profiles, and second the obtained shells are polished to the required polynomial profiles by CNC (Computer Numerical Control) polishing machine. In this paper, the first results of the direct grinding and polishing of prototypes shells made by quartz glass with low thickness, representative of the WFXT optical design, are presented.

Keywords: WFXT, X-ray Telescope, polynomial profile shells, large size grazing-incidence mirrors, thin quartz shell, deterministic direct polishing, epoxy replication

1. INTRODUCTION

The Wide Field X-ray Telescope (WFXT) is a proposed medium-class mission dedicated to survey the sky in the soft X-ray band (0.2-6 keV) [1,2]. It is designed to be 2-orders-of-magnitude more sensitive than any previous or planned X-ray mission for large area surveys. WFXT is the only X-ray survey mission that will match the next generation of wide-area optical, IR and radio survey, in terms of area and sensitivity. It will support simultaneously planned projects and missions, ground-based, as future giant telescope (e.g. ALMA), or in-orbit observatories (e.g. JWST and IXO). In five years of operations, WFXT will carry out three extragalactic surveys, allowing direct physical characterization of a very

[*]laura.proserpio@brera.inaf.it; phone +39 039 5971028; fax +39 039 5971001; www.brera.inaf.it

large amount of sources (in particular AGN and clusters of galaxies) via X-ray spectroscopy with no need of follow-up observations. All the acquired data will constitute a scientific legacy to address key questions about cosmic origins and physics of the cosmos. To those ends, WFXT foresees an X-ray Telescope Assembly whose main requirement is to be orders of magnitude more effective than previous and planned X-ray missions in carrying out surveys. This is obtained through a telescope design that makes use of polynomial profiles for the mirror shells together with focal plane curvature and plate scale corrections. This design guarantees an increased angular resolution at large off-axis angles with respect to the usually adopted Wolter I configuration; in this way, it is possible to get the desired almost-constant angular resolution on the entire Field of View (FOV). WFXT main scientific requirements and goals are reported in Table 1.

Table 1: WFXT Mission Performance Requirements and Goals.

Parameter	Requirement	Goal
Effective Area at 1 keV (cm^2)	6,000	10,000
Effective Area at 4 keV (cm^2)	2,000	3,000
Field of View – diameter at 50 % vignetting (degrees)	1	1.25
HEW across the entire FOV at 1 keV (arcsec)	< 10(HEW)	<5(HEW)
Energy Band (keV)	0.2 – 4	0.1 – 6
Energy Res. (ΔE/E)	> 10	> 20
Time Resolution (s)	< 3	< 1

To meet the effective area and mass requirements, the shells need to be very thin, with wall thickness of few mm or less. SiC and quartz glass are two materials whose thermo-mechanical (T/M) properties (in particular low density and high rigidity) are very attractive and suitable to reach the necessary stiffness of the peculiar WFXT mirror shell configuration. The WFXT mirror shells are not only thin, but characterized by a very small Length-to-Diameter ratio (L/D 3 times smaller than for XMM-Newton mirrors) making more difficult their bulding. The SiC and quartz T/M parameters are reported in Table 2, compared to those of Ni that has been used for the production of high effective area X-ray mirror modules such as XMM-Newton.

Table 2: Comparison of main thermo-mechanical parameters of materials suitable for the production of thin mirror shells.

MS material	ρ [t/m^3]	E [GPa]	ν	CTE [1/K]	K [W/mK]	Bending merit figure
Electroformed Nickel	8.8	180	0.3	12.7×10^{-6}	60	1.0
Quartz (HSQ300)	2.2	72.5	0.17	0.55×10^{-6}	1.38	24.2
CVC SiC	3.18	456	0.21	2.33×10^{-6}	140	51.1

The bending merit figure here considered is a value that expresses the ratio between the bending stiffness of a slab 0.5 m x 1 m, one made by the considered material (SiC or quartz) and the other realized by Ni.

SiC and quartz can be adopted for the production of thin shells both by epoxy replication approach and by direct polishing approach. The production of thin shells by epoxy replication technology has already been proved some years ago using SiC carriers [3,4]. It was demonstrated how the replication approach can meet the WFXT requirements of 10 arcsec across the FOV of 1 deg. To further improve the technology and to achieve the goal of 5 arcsec resolution, the direct polishing method of quartz shells is under investigation. Quartz is adopted because of costs and production time reasons. Tubes of quartz glass to be used as raw material for shells production are available on the market. Learning from past experiences such as Chandra, and ROSAT, our approach is to follow a deterministic direct polishing method. On the other hand this approach presents challenging aspects, since it is applied for shells with much thinner walls (a factor 5-10 less) and a much lower length/diameter (L/D) ratio. However in the last few years, new machines and polishing techniques have been developed with performances very promising in the perspective of directly optical machining thin mirror shells. A number of FEM analyses have been carried out to evaluate the implication of the two parameters (thickness and L/D ratio) on the different production steps. In particular, the effects on optical performances due to deformations introduced by edge loads representative of the supporting systems loads have been considered. A total of 8 prototypes have been produced during the last year of activity to investigate the direct grinding and polishing of thin quartz shells. The capability of grinding procedure to produce thin shells with the required accuracy in terms of out-of-roundness and profile accuracy has been demonstrate. The first results will be presented in this paper, together with a description of the adopted metrology set up and of the developed jigs necessary to handle the shell during all the production steps until the integration into the final structure. Precise optical machining of the mirror shells will be performed in the next months.

2. TELESCOPE DESIGN

Focusing telescopes for X-ray astronomy are usually built in the Wolter I configuration, constituted by two mirror segments (the first parabolic and the second hyperbolic) joining at the intersection plane. This design guarantees a perfect image along the telescope optical axis but the image quality rapidly degrades for large off-axis angles. Being WFXT a mission for survey purposes, it is necessary to act on the mirror design in order to increase the off-axis response and optimize the performances over the entire field of view. The present design is based on shells with polynomial profiles [5]. Polynomial mirror profiles are described usually by forth or third order polynomial and optimization techniques can be implemented to optimize the angular response over a desired field of view [6]. Then, to optimize the whole mirror assembly for X-ray surveys, further improvements can be introduced, as the butterfly-like shape for the mirrors, to guarantee that each mirror has the same curvature of the focal plane, and a small displacement with respect to the intersection plane, in order to focus each spot on a non-curved CCD detector. In practice, each nested mirror shell presents a different length dependent on the radius, decreasing from the outermost to the innermost shell in such a way to keep the same curvature of the focal plane. A displacement of few mm between the intersection planes of the mirror shells is introduced to compensate for the different focal plate scale of the shells that causes focusing of X-ray in slightly different positions at any off-axis angle.

The proposed design consists of three telescopes with focal length of 5500 mm and diameter ranging from 330 mm for the innermost to 1100 mm for the outermost mirror shell. Shells thickness ranges from 1.2 to 2.2 mm. The total length of each shell is different because of the butterfly-like adopted design. The main characteristics of the optical module are summarized in Table 3.

Table 3: Characteristics of the proposed WFXT surveying telescope.

Focal Length	5500 mm
Number of Optics Modules	3
Material	Quartz
Numbers of Shells	78
Radius [min – max]	165 – 550 mm
Total length [min – max]	200 – 440 mm
Thickness [min – max]	1.2 – 2.2 mm
Total on-axis Effective Area* (1 keV)	9,236 cm^2
Total on-axis Effective Area* (4 keV)	2,565 cm^2
Total Weight (3 modules) Mirror+mirror mech. structure	930 kg

*this area refers to the total mirror area for the three modules and accounts for a 10% obstruction from the support structure.

The present design has been obtained following an optimization process. In order to fulfill the stringent angular resolution requirement, the thickness trend of the mirror shells along the series of diameters has been selected in such a way to maintain almost constant stiffness for all the shells.

The choices of small thickness and L/D ratios considered during the optimization process led to select the present optical design which needs to be proved on a manufacturing point of view [7]. A number of tests have been performed to verify the technological feasibility to produce such thin mirror shell. Two approaches are possible: the production by epoxy replication or the direct polishing. The epoxy replication with SiC carrier has already been proved in the past to reach TRL of 5. For completeness, it is summarized in the fourth paragraph of this paper. In order to further improve the performances and reach the angular resolution goal of WFXT, the direct polishing of thin quartz shell is being evaluated. Tests started with the production of demonstrative parts whose characteristics have been selected considering past experience, raw available materials, grinding and polishing machines, available measuring tools, and transportation and handling. Nevertheless, they are significant for the entire telescope design being intermediate dimensions as shown in Table 4.

Table 4: Geometrical characteristics of the realized quartz glass prototype shells.

	Shell 1	Shell 2	Shell 3	Shell 4	Shell 5	Shell 6	Shell 7	Shell 8
Diameter [mm]	620	620	490	490	490	490	490	490
Length [mm]	200	200	270	270	270	270	200	200
Thickness [mm]	1.5	1.5	2	2	2	2	2	2

3. THERMO-MECHANICAL ASPECTS

The technological challenge is therefore to produce thin and short mirror shells. Several aspects have to be considered, in particular:

- Deformation during the machining and the metrology phase
- Propagation of deformations in thin and short shells
- Resistance to launch conditions

A number of FEM analyses have been carried out to address these aspects and results are presented hereafter together with the implemented solutions

3.1 Effects of the support structure during the metrological measurements

It was expected (and confirmed by metrological tests) that an astatic support is needed to measure the real shape of the thin shells, since relevant deformations are caused by gravity. The measured values of the out-of-roundness of a shell standing on a plane can be different, depending on the three effective points of contact that causes different deformations in the shell. An astatic support takes care of the gravity loads giving the possibility to measure the intrinsic shape of the shell without relevant deformation. Two astatic supports are available at INAF-OAB, one with 12 and the other with 16 sustaining points. A number of FEM analyses have been carried out for thin shells in order to evaluate the effect of the support on the shell. The case of a mirror shell with diameter 600 mm, height 200 mm and thickness 1.5 mm is reported as an example in figure 1 and Table 5; the 16 points support is considered. It is verified that with the available astatic support, the deformations introduced on the shell are negligible, in the order of 0.5 arcsec HEW.

Table 5: FEM analyses and ray-tracing results computed on a thin 600 mm diameter mirror shell sustained at one edge by different numbers of supports.

Support number	Radial displ. PtoV [μm]	Nominal HEW [arcsec]	Best focus HEW [arcsec]
3	189.5	23.32	20.28
6	8.2	1.64	0.99
9	0.39	0.49	0.19
12	0.05	0.65	0.19

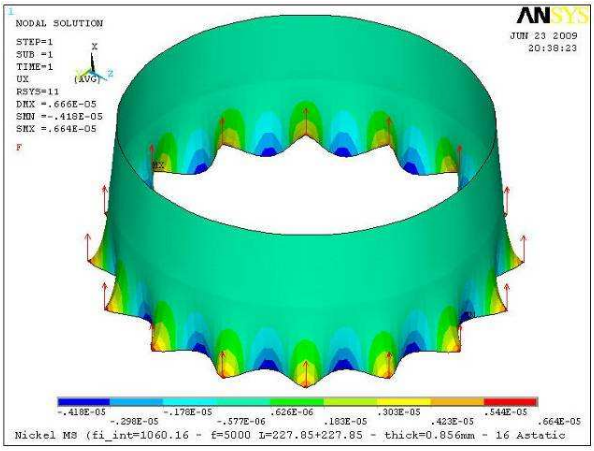


Fig. 1: Example of FEM simulation of the thin shell positioned on the astatic support.

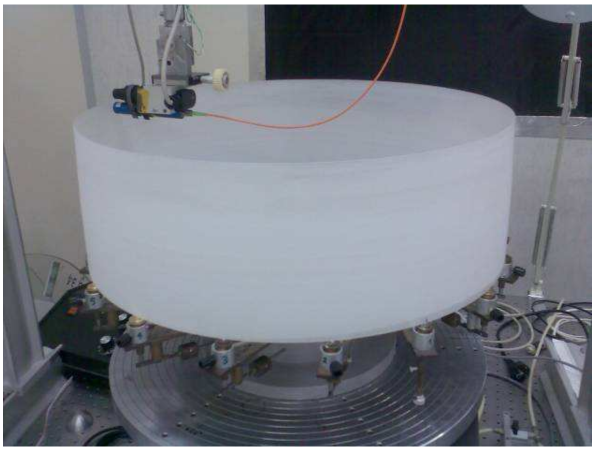


Fig. 2: 600 mm diameter shell supported by the astatic support during out of roundness measurement carried out with an optical sensor at the INAF-OAB metrology laboratory.

3.2 Effects due to the small L/D ratio

The effect of small L/D ratios on the angular resolution has also been investigated. Short mirror shells are difficult to be manufactured without introducing shaping errors. The angular resolution is strongly affected by the slope errors caused by azimuthal errors, which for a determined out-of-roundness error is inversely proportional to the mirror shell length. The case of out-of-phase azimuthal errors is less critical since the effects on the optical performances are smaller, also if the displacements can be of higher value. Considering that the mirror shells are normally fixed to the mirror module structure by spot connections at the one or both end sections and that, during metrology and integration, they rest on concentrated astatic supports at one-end section, distortions introduced by concentrated loads applied at the free edge have been evaluated. The results confirmed that short mirror shells are more sensitive to perturbing effects related to edge loads since the shell has a belt like rather than a tube like behavior. In particular, under the same perturbing edge loads, related to large spatial scale deformed shapes, very short mirror shells show degradation 6-16 times larger with respect to long mirror shells and this ratio becomes even larger in case of perturbing loads producing very local deformed shapes (see figure 3). For comparison, an example of radial displacement due to different loading conditions is reported in the following figure 4 for short and long shell.

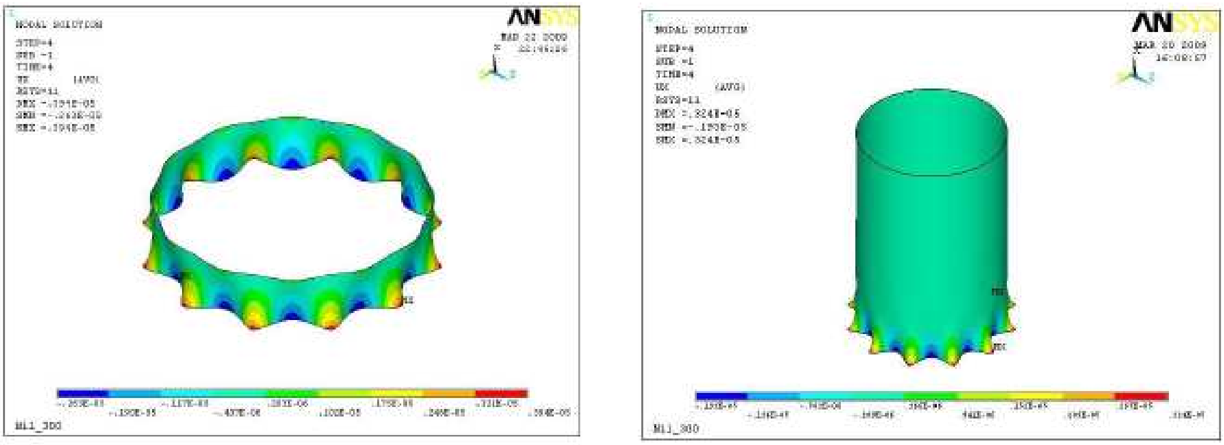
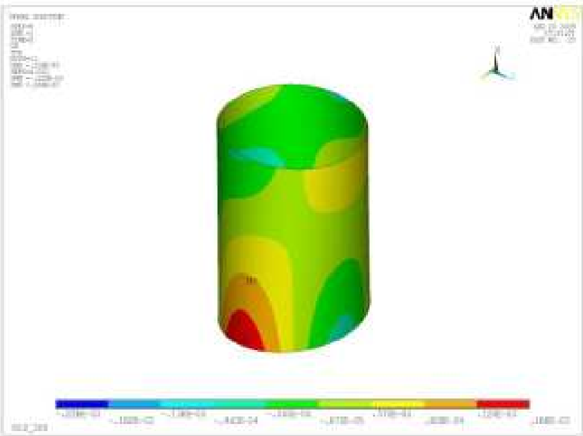


Fig. 3: FEM simulation results in the case of 12 concentrated loads (in this case 12 radial forces of equal intensity and spaced 30°) applied at one edge of a thin shell of same diameter but different height. It is clear how the deformations affect a larger portion in the case of short mirror shell. The performances degradation of short mirror shells can be 6-16 times larger with respect to that of long mirror shells.



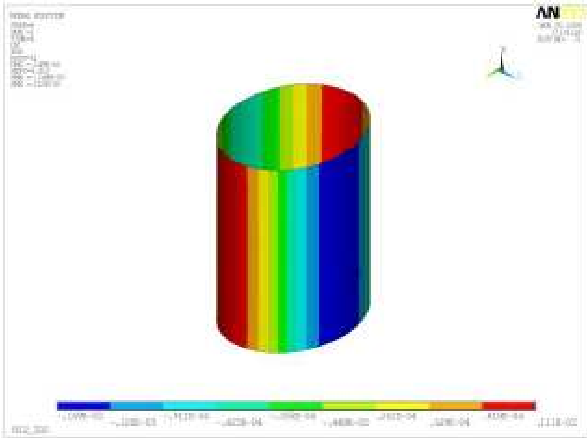


Fig. 4: Different deformations and out-of-roundness errors caused by different loads. In one case the azimuthal deformation is out-of-phase at the top and at the bottom of the shell (left) in the other case is on phase (right).

3.3 Effects related to the launch loads

Preliminary FEM analyses have also been carried out in order to estimate a value for stress peaks in the quartz glass mirrors during launch, even if at this stage of the project, exact load levels, and operative and survival temperatures are not yet available and need to be evaluated in near future. A complete check of quartz components will require some more information, relevant to the characterization of the specific material, which are not known at the moment. Nevertheless, simple preliminary consideration can be performed based on engineering evaluations and past experiences.

Considering a traditional X-ray telescope, the single mirror shells are connected to the telescope structure just at the end sections (one or both) through spokes wheel elements. Point connections between each mirror shell and the spokes wheel are realized by adhesive contacts. If such a configuration is adopted during FEM analyses, the maximum stresses in the glass might exceed the tensile stress limit in points of stress concentration. Qualitative considerations confirm the criticalities related to quartz glass usage. Local refinement of the analyses and the design is much more demanding when brittle materials like quartz are used. Revised design criteria with respect to the traditional approach will allow obtaining surviving loads conditions, while the use of special treatment of the shells in order to reduce the microcracks cause by the grinding will be envisaged to improve the intrinsic stiffness of the quartz.

4. REMARKS ON THE EPOXY REPLICATION APPROACH

The epoxy replication approach has been demonstrated to be a viable method to obtain rigid, light-weight X-ray mirrors [3, 4]. This technique has been developed by INAF-OAB some years ago with the support of Rhom & Hass and Zeiss. In this context SiC carriers were produced by Chemical Vapor Deposition (CVD) process. The carrier, after a grinding to obtain a roundness error of a few tens of microns P-V, was then positioned on a gold coated mandrel and the gap of about 200 μm between the two elements was filled with epoxy resin. After the resin was cured, the mandrel was cooled to separate the shell. Finally, the shell was integrated in a suitable stainless steel case for X-ray metrology. The diameter of the realized SiC shells was 600 mm, the height 200 mm and the thickness 2 mm. The shells were tested at both Panter/MPE (Munich) and the X-ray Calibration Facility (XRCF) of NASA/Marshall Goddard Space Flight Center obtaining, for the best one, an almost constant HEW of 10 arcsec at 0.108 keV on the entire field of view up of 1 deg in diameter, meeting in that way the WFXT angular resolution requirement.

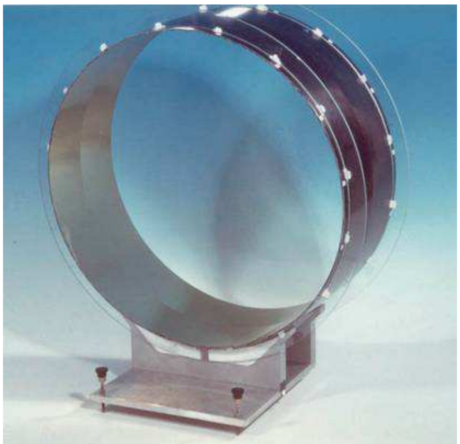


Fig. 5: Prototype shell realized in SiC by epoxy replication technique and successfully X-ray calibrated. The diameter is 600 mm, the height 200 mm and the thickness 2 mm.

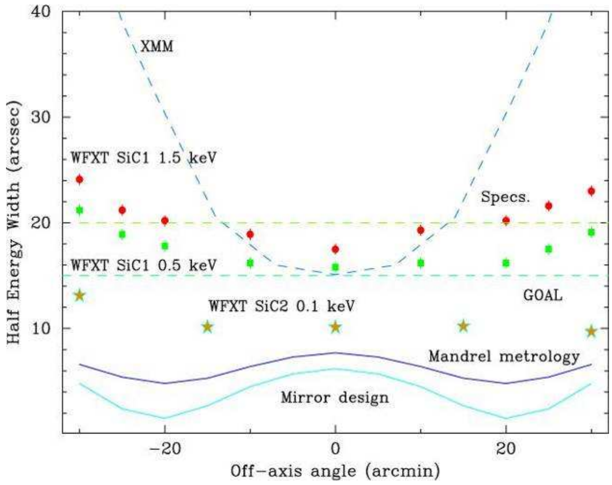


Fig. 6: Measured performances of the SiC prototypes shell manufactured by epoxy replication performed at the NASA/MSFC X-ray facility.

5. DIRECT POLISHING APPROACH

The epoxy replication approach is already able to fulfil the WFXT requirements but, in order to further improve the technology and achieve WFXT goals of 5 arcsec HEW across the FOV of 1 deg diameter, a direct polishing approach on the thin mirror shells is under study. The proposed method foresees the direct figuring and polishing of mirror shells after grinding. The monolithic mirrors are made of materials with good mechanical properties (but easy to polish) like quartz. Quartz is indeed a well known material and its thermo-mechanical and polishability properties make it ideal for the realization of high precision optics, also for space application. It offers a number of advantages such as low density (2.203 g/cm^3), low thermal expansion coefficient (0.5x10^{-6} /K), high modulus of elasticity (70 GPa). Quartz was also selected for reasons of costs, time and availability of the raw material. The main drawback related to quartz is that the material is quite brittle. However, this does not represent an unsolvable problem since it can be overcome with suitable surface treatments (as chemical etching) in order to eliminate, or at least reduce, the surface damages coming from the machining steps, that tend to originate the cracks. On the other hand the direct polishing of X-ray telescope mirror shells made by quartz or glass material is a technology that has been proved since many years for the manufacturing of very high angular resolution X-ray telescopes (like Einstein, with 4 arcsec HEW, ROSAT, with 3 arcsec HEW, or Chandra with 0.5 arcsec HEW). The challenge now is to obtain a good angular resolution on the entire FOV but for considerably thinner (a factor 5-10 less) mirror shells.

In the last years, CNC polishing machines, able to perform a precise figuring also on thin substrates have been developed. The production flow here envisaged foresees to start from a quartz glass tube already available on the market. The tube is firstly ground with a double cone profile at the required thickness of a few millimeters. Then, it is figured and polished to the final polynomial profile making use of a “deterministic” figuring method and then superpolished. This implies that after the measurements of the actual profile of the mirror shell to be polished, a corrective matrix is determined and supplied to a computer numerical control (CNC) polishing machine which provides the corrective action according to the given error matrix. In a few iterations it is possible to reach the required specifications once we start from an acceptable profile after grinding with P-V roundness errors of a few tens of microns. Between the grinding and the polishing step it is necessary to integrate the shell in a suitable jig structure able to allow the metrology, machining and all the necessary steps before the assembling of the shell into the final structure (i.e. reflective coating deposition and X-ray characterization at an X-ray facility, at least until the telescope structure with spiders is not developed). This jig structure is also necessary for handling and will be used for the shell integration into the final mirror module structure. After that, it can be removed and used for another shell. The entire proposed production flow is depicted in figure 7.

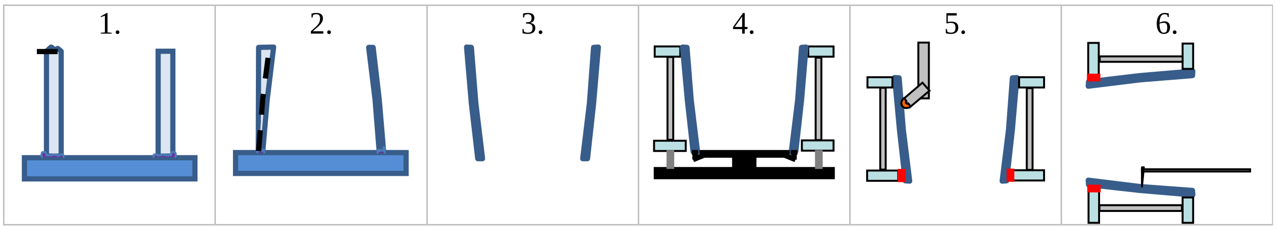


Fig. 7: Scheme of the production method under development for the manufacturing of thin quartz shells based on the direct figuring and polishing. 1) The raw material is given by a quartz glass tube available on the market. 2) The tube is positioned onto a suitable support and firstly ground to the required double-cone profile. 3) When the shell is ready, it is detached from the support and 4) by means of an astatic jig it is measured and integrated in a support structure. 5-6) The support allows the positioning of the shell in both vertical and horizontal positions whit respect to the optical axis without introducing deformations.

For the purpose of this study, 8 quartz glass shells have been realized to set the best parameters of the grinding phase and get useful hint on surface treatment to reduce surface imperfections that degrade the mechanical characteristics of the material. Two of these shells have been integrated in the suitable structure appositely designed to allow polishing, metrology, and all the necessary steps before the integration in the final structure. One of the integrated shells has been used for polishing tests. More details on the production of these demonstrative parts are presented in the following paragraphs, together with the present obtained results.

5.1 Grinding results

The grinding of the raw quartz tube has been pursued by Heraeus Quarzglas GmbH & Co KG. The requirement was to obtain a thin quartz shell with double cone profile and out of roundness in the range of 10 micron. The raw material is represented by the high purity HSQ 300 quartz glass produced by the same company. Heraeus Quarzglas normally produces tubes with diameters up to 900 mm and wall thicknesses between 0.5 – 13 mm, mainly used for the semiconductor and solar energy applications. Several options have been tested to optimize the grinding set-up, studying parameters like the abrasive grain type and size, the tool diameter and speed, and the quartz tube supporting during the grinding procedure. In particular, three runs have been performed. During the first run the process parameters have been selected. The other two runs have been pursued to optimize the support system of the quartz tube during the machining. In fact, during the first and the second runs, high out-of-roundness errors were present in the produced shells (see Table 6) and a thorough analysis of the problem confirmed that the deformations were originated by a wrong supporting method adopted for the quartz tube on the grinding machine that has been afterwards corrected. The selected approach foresees a two-step grinding process: first the external and internal surfaces of the quartz glass tube are machined, by means of a rough grinding machining; then the internal surface undergoes a finer grinding step. The purpose of this second step is to reduce the surface damage depth left by the initial grinding. Even if the polishing removes the subsurface damage on the internal surface, however residuals still remain on the external surface and this make the material quite brittle. To address this problem a treatment of chemical etching has been investigated. The chemical etching of the whole surface has been performed by Heraeus on two of the produced shells after the grinding, to demonstrate the feasibility and to test the compliance with the requirements in terms of shape. The tuning of the process will be subject of further studies in the near future.

As already mentioned, a total of 8 quartz glass carriers have been produced during this year. Two of them have a diameter of 620 mm, length of 200 mm and thickness of 1.5 mm. Two have a diameter of 490 mm, a length of 200 mm and a thickness of 2 mm. The others four have a diameter of 490 mm, a length of 270 mm and a thickness of 2 mm. They have been ground by Heraeus Quarzglas firm and characterized both by Heraeus Quarzglas at their site and by INAF-OAB after the delivery. Heraeus Quarzglas performed the metrology with a 3D Coordinate Measuring Systems supporting the shell on three points, providing absolute values for diameters and measurement profiles; INAF-OAB performed the shells metrology with an optical sensor mounted on a rotational table while the shell were supported by an astatic system. The measured values are reported in the following Table 6.

Table 6: Out Of Roundness (OOR) and longitudinal profile P-V error values for the eight prototypes shells developed in the present study. Lessons learnt from each of the realized shell are also reported in the table.

Grinding run	Shell #	P-V Out of Roundness Error [µm] (OAB)	Longitudinal Profile accuracy (P-V) [µm] (Heraeus)	Lesson learnt
1	1	76	-	Feasibility of the grinding process. Definition of metrology and support systems. Polishing test.
1a	2	73	-	
2	3-6	45, 61, 61, 305	11, 10, 16, 10	Analysis of the grinding process. Chemical etching tests on shell 6.
2a	3	-	-	Broken during re-grinding tests to improve the fixation.
3	7,8	9, 5	8, 6	Improvement in the fixation of the shell during grinding. Requirements are met.

1 average of 4 to 6 OOR values from roundness profiles at different height
2 average of 8 PV values (4 parabola, 4 hyperbola) at azimuthal distances of 90°

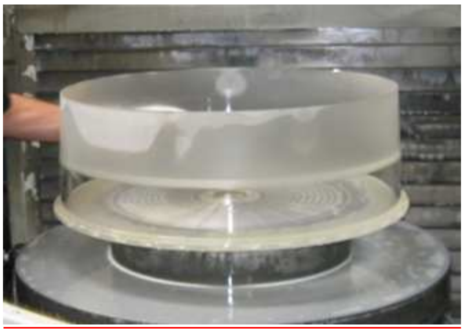


Fig. 8: Raw quartzglass tube mounted on the grinding machine at the Heraeus Quarzglas facility.

Fig. 9: Side view of the astatic support system used during the metrology phase in order to avoid deformations in the shell.

5.2 Development of suitable jigs and interfaces for polishing and metrology

A suitable jig has been designed and manufactured to allow the handling of the shell during all the production steps, i.e. polishing, metrological tests, reflective coating deposition, X-ray characterization, and integration into the final structure. The main requirement for the jig was to have a system able to maintain the shell intrinsic shape in both the vertical (intended with respect to the optical-axis) and horizontal positions without introducing deformations due to gravity or thermal loads. The shell polishing was performed mounting the shell in vertical position, while profiles measurements and X-ray calibrations need to position the shell horizontally. The jig has been called "Shell Supporting Structure" (SSS) and it is shown in figure 10 and 11, where the metrology equipment used for profilometry is also presented.

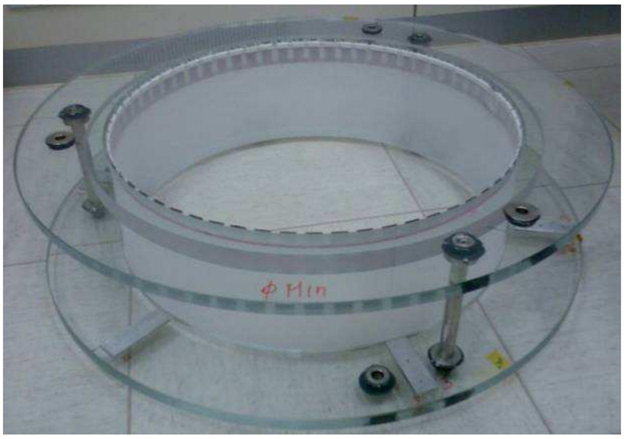


Fig. 10: The first integrated shell in its own SSS jig.

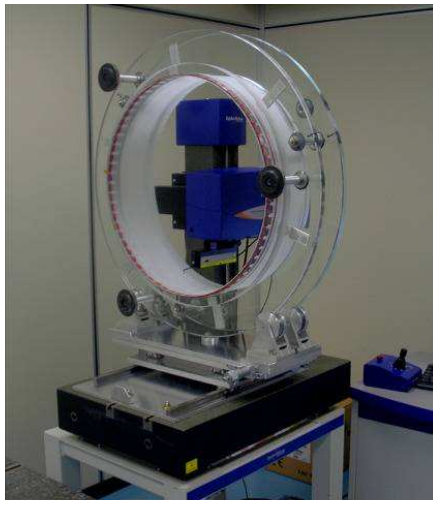


Fig. 11: Shell integrated in the SSS jig and positioned horizontally on the metrology machine by means of a suitable mechanical interface developed for alignment purposes.

The SSS is the result of an optimization process carried out after FEM simulations and analyses aimed at the evaluation of stresses, deformations and related optical performances degradation introduced in the thin shell by the supporting structure. Different configurations have been considered before selecting the final design. In particular, it was evidenced how a direct connection between the mirror shell and the supporting structure (through bonding with beeswax or glue) would introduce important degradations of the optical performances in the case of large CTE and adhesive cure shrinkage. Also, a direct connection between the shell and the SSS would cause deformations of the structure to propagate into the shell. The possible optical degradation is related to the mirror shell distortions induced by the radial movement of the connection. The phenomenon can be mitigated to an acceptable level (HEW degradation less than 0.5 arcsec) by introducing a radial flexure (realized by thin metal foil) at the connection between the mirror shells and SSS.

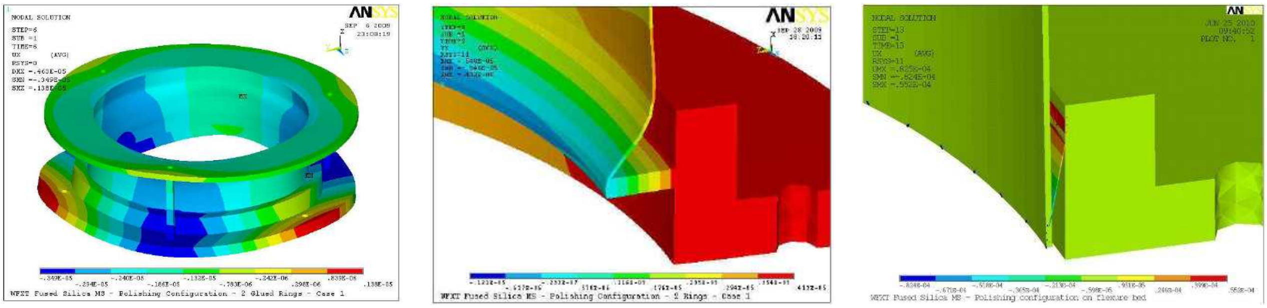


Fig. 12: Left: FEM simulation carried out to verify the effect on the shell due to SSS deformations in the case of direct connection between the shell and the SSS jig. It is clearly visible how radial deformations of the SSS are transmitted to the shell. Center: Detail of radial displacement isocontour at the connection between mirror shells and lower SSS ring. It is evident the effect of the adhesive expansion due to thermal effects and therefore the need of a radial flexure at the connection between the shell and the SSS. Right: The use of a metal foil introduces a radial flexure; in such a way the thermo-mechanical deformations of the glue contacts and SSS structure are not transferred to the shell.

The final SSS is composed of two rings made of glass that allocate three couples of metallic inserts (120° separated in azimuth). One insert of each couple is used to connect the two glass rings through metallic bars; the other inserts are used for the interface with the axial support when the shell is positioned in vertical position, i.e. with the gravity parallel to the optical axis. The shell is connected only to the bottom ring through a metallic comb flexure that introduces a radial flexure at the connection between the mirror shells and SSS. The upper ring, adjacent to the mirror shell front section, is not directly connected to the shells.

Several options have also been analyzed for bonding. Beeswax was disregarded because of contamination reasons. Since the SSS will be used for all the production steps until the final integration in the mirror module structure, a space-qualified glue has been selected in order to avoid problems in the vacuum chamber during coating deposition or X-ray tests (performed under high vacuum). A removable adhesive has been selected that guarantee acceptable values of shrinkage and CTE in normal conditions and a low outgassing. It has also been considered the possibility of an easy removal at the end of the manufacturing, after the integration of the shell into the final mirror module structure, preventing from any possible contamination.

Two of the manufactured shells have been already integrated in different SSS jigs. The first shell has been broken, due to an incorrect handling, after the delivery at OAB. However, it was possible to repair the mirror and to use it as a dummy shell to optimize the SSS design and integration process, even if the out-of roundness value resulted to be strongly degraded (see Table 7).

The critical points of the SSS design and of the integration process were verified and the design opportunely modified. The first integration led to an increase of the out-of-roundness, while the final integration procedure, tested with the second shell, allowed to maintain the shell intrinsic shape and also to reduce the error. Minor modifications are foreseen to be implemented to simplify the integration of the third shell.

Table 7: Comparison of the Out Of Roundness (OOR) measurement performed on shell 1 and 2 before and after the integration into the SSS. The progress in the integration procedure is clearly visible comparing the values for the two shells. Note that the values of shell #1 are high because a small part of the shell was broken during the test; nevertheless it has been used to test integration procedure.

Shell #	OOR before SSS integration [μm]	OOR after SSS integration [μm]	Lesson learnt
1	600	800	Prototype of SSS and definition of integration procedure.
2	73	28	Improvement in SSS and fixation procedure.

5.3 The Figuring and Polishing process

The polishing process is performed by the Zeeko firm by means of a IRP600 machine. The Zeeko Company not only makes use of an innovative figuring and polishing approach, but also it developed the capability of machining shells with diameter up to 1100 m and height up to 440 mm. The equipments of the Zeeko IRP-Series are CNC polishing systems, controlled on 7-axis, that use a patented tool to provide a distributed pressure and variable area head for the polishing of aspheric and complex forms [8]. In the Zeeko-Classic process, also called Bonnet polishing, a spinning, inflated, membrane-tool is compressed against the surface of the part to be machined, creating an area of contact that define the removal footprint. The membrane-tool effectively moulds itself around the local contours of the surface under the internal air-pressure, maintaining an excellent contact over the removal footprint also in the case of aspheric surfaces. The tools operate in the presence of polishing slurry. Standard Bonnets of different diameters can be exchanged on the polishing machine, ranging from 20 mm to 480 mm of radius of curvature. The diameter of the footprint can be changed by varying the axial position of the Bonnet with respect to the surface of the part to be machined or by varying the internal pressure of the tool, which is strictly related to its hardness. By acting on the process parameters, such as tool pressure, precession angle, compression offset and head speed, it is possible to select the desired influence function, i.e. the 3D depression left by the spinning precessing tool as it is pressed onto a piece of the material to be polished. The influence function is generated to determine the best volumetric removal rate in dependence of the specific materials and requirements.

Fig. 13: Thin shell mounted on the IRP600 polishing machine at the Zeeko facility. The SSS supplies the suitable interface to the machine, keeping the shell at the right vertical position necessary for the polishing.

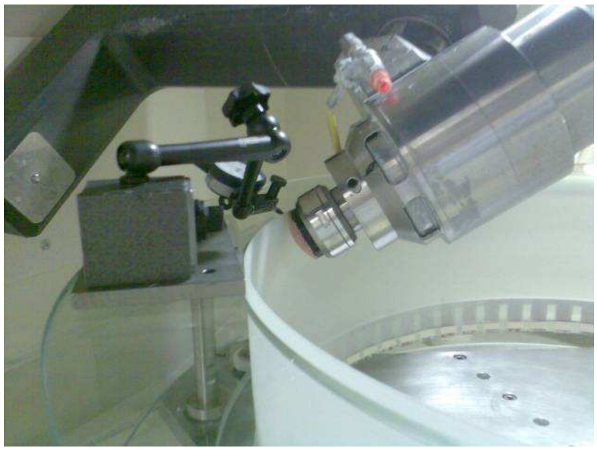


Fig. 14: Particular of the Bonnet polishing tool during one of first grolishing tests, performed to evaluate the suitability of the SSS jig as interface to the polishing machine.

A number of tests have been performed during the study, in order to evaluate the applicability of this process for the manufacturing of the WFXT quartz glass shell. The effort was in particular focused on the problems caused by the deformations of the thin walls by effect of the tool pressure. The shell used for these preliminary tests was the first ground dummy shell used to test integration into SSS that presents high out of roundness values (800 μm). The possibility of performing an intermediate coarser step ("grolishing") before the polishing was investigated. Grolishing is needed to correct possible residual errors coming from the grinding step and to remove the external layer of surface damaged at a microscopic level.

Different process parameters were investigated in order to define the best influence (or removal) function. Faster influence functions are used for bulk material removal. While slow removal functions provide better results in manipulating smaller scale errors. At first, selected segments have been raster "grolished": the machined area was 225 mm long x 100 mm wide (from top edge to transition zone). Three different radial segments have been treated in such a way to compare different tool speed and cloth. It is worth noting that the final shell process will be carried out following a spiral path and not in a raster configuration. For the performed tests, a raster configuration has been preliminary used taking into account the large azimuthal error of the first dummy shell available and to avoid performing major time-consuming software modifications. The behaviour of the raster scan could be slightly different from the one achievable with a spiral path. Using this preliminary configuration an entire half of the shell surface has been machined and important information have been obtained regarding the effects of vibration and deformation introduced during the Bonnet machining.

Moreover, these results achieved so far are very promising and useful parameters were inferred to carry out future activities. In particular, the out of roundness errors have effects on the radius of curvature of the Bonnet tool to be used and on the removal coefficient. For out of roundness errors less than 10 μm P-V the grolishing process can be skipped ad only the polishing phase should be performed. On the contrary, if the out of roundness error ranges between 10 to 60 μm P-V a pre-phase of grolishing should be considered, in order to remove defects coming from the precedent phase. The polishing phase will start in the next weeks on the second shell integrated in the SSS. Those new tests will be important to evaluate the possibility of obtain a proper polynomial profiles starting from the double-cone shape.

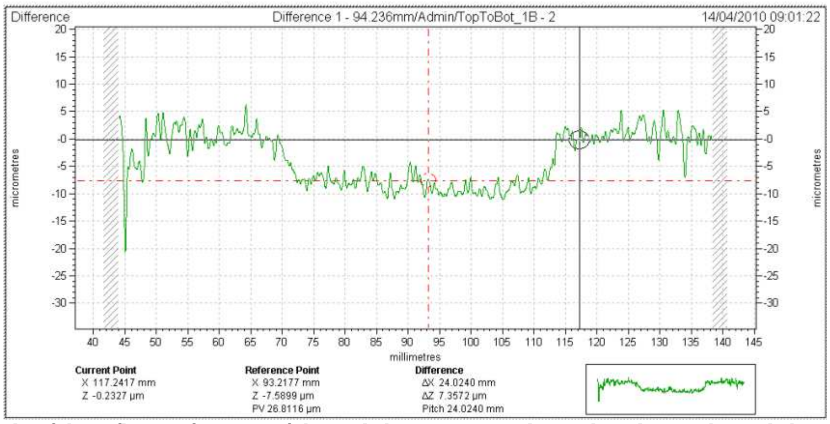


Fig. 15: Example of the influence function of the grolishing process. The circle indicates the grolishing starting point.

It should be mentioned that it has been also necessary to define and partially realize the metrological tools needed to monitor the surface during the polishing phase. Profile measurements have been performed with a PGI 1200 Thomson system, while the surface texture and roughness have been checked with a CCI Taylor and Hobson instrument. Custom interfaces and jigs for the connection to the polishing machine and to the metrology tools have been specifically developed at the Brera Observatory.

6. CONCLUSION

We presented here the first results of the tests performed to evaluate the deterministic direct polishing technique for the realization of thin quartz glass mirror shells, to be implemented aboard the WFXT mission. We showed that, adopting a suitable choice of materials, it is possible the design and the manufacturing of thin (less than 2 mm) mirror shells, able to meet the mass and area requirements of the mission. The development aims at achiving the angular resolution goal level of the mission of 5 arcsec HEW across the FOV of 1 deg in diameter. Several quartz glass shells with double cone shape and diameters of 490 and 620 mm, lengths of 200 mm and thicknesses of 1.5-2 mm have been produced for the scope. Three grinding runs have been performed to improve the process and, at the end, the tolerances expected after grinding (out of roundness error < 10 µm P-V) have been achieved. Two of the produced carriers have been integrated in a suitable jig, specifically designed for all the steps in the shell manufacturing. In particular, the jig was developed for allowing the handling of thin shells, giving the possibility of positioning the mirrors in both horizontal and vertical directions without the introduction of deformations. The horizontal position is required during metrology and X-ray characterization phases; the vertical position is used during polishing, coating deposition and assembly into the final structure steps. It has been verified that the integration process in the jig is able to maintain or improve the original shape. One of the integrated shells has been used for the preliminary polishing tests performed by Zeeko using an innovative optical machining based on the Bonnet tool. Preliminary grolishing results suggest that the process can meet the angular resolution requirements if the mirror shells after grinding is characterized by an out of roundness error < 60 µm. Future activities include the evaluation of chemical etching to remove the sub-surface damages on the surface of ground shells and the integration of the third shell in its own SSS. Polishing tests will start soon to evaluate the feasibility of obtaining mirror shells with a correct polynomial profiles. The mirror prototypes realized in this way will be X-ray tested in full illumination mode.

ACKNOWLEDGENTS

We are very grateful to the WFXT collaboration and, in particular, to Riccardo Giacconi, Steven Murray and Martin Weisskopf for supporting this work and for many useful discussions. This activity is funded by the Italian Space Agency (ASI) and by INAF.

REFERENCES

[1] S. Murray, et al., “Wide field x-ray telescope mission“, Proc . of SPIE Vol. 7011, (2008)

[2] WFXT Mission Web Site, http://wfxt.pha.jhu.edu/

[3] O. Citterio, S. Campana, P. Conconi, M. Ghigo, F. Mazzoleni, H. Brãuninger, W. Burkert, A. Oppitz, “X-ray optics for the WFXT telescope”, Proc. of SPIE Vol. 3766, 198 (1999)

[4] M. Ghigo, O. Citterio, F.Mazzo1eni, J.J. Ko1odziejczak, S.L. O'De11, R.A. Austjn, G. Zirnstein, “X-ray measurements of a prototype WFXT SIC mirror at the MSFC X-Ray Calibration Facility”, Proc. of SPIE Vol. 3766, 207 (1999)

[5] C.J. Burrows, R. Burg, R. Giacconi, Burrows, “Optimal grazing incidence optics and its application to wide-field X-ray imaging”, ApJ 392, 760 P (1992)

[6] Conconi, P., et al., “A wide field X-ray telescope for astronomical survey purposes: from theory to practice”, MNRAS, 509 (2010)

[7] P. Conconi, G. Pareschi, S. Campana. O. Citterio, M. Civitani, V. Cotroneo, L. Proserpio, G. Tagliaferri, G. Parodi, “Design optimization and trade-off study of WFXT optics” Proc. of SPIE Vol. 7437, 7437D (2009).

[8] D. D. Walker, A. T. H. Beaucamp, D. Brooks, R. Freeman, A. King, G. McCavana, R. Morton, D. Riley, J. Simms, “Novel CNC polishing process for control of form and texture on aspheric surfaces”, proceding of SPIE, vol. 4451, 267 (2002)