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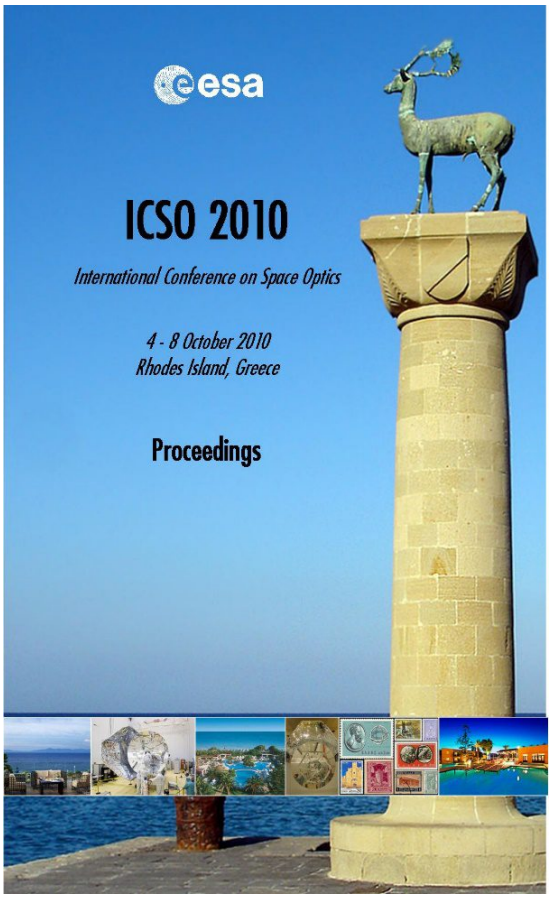

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DESIGN AND DEVELOPMENT BY DIRECT POLISHING OF THE WFXT THIN POLYNOMIAL MIRROR SHELLS

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ABSTRACT

The Wide Field X-ray Telescope (WFXT) is a medium class mission proposed to address key questions about cosmic origins and physics of the cosmos through an unprecedented survey of the sky in the soft X-ray band (0.2-6 keV) [1], [2]. In order to get the desired angular resolution of 10 arcsec (5 arcsec goal) on the entire 1 degrees Field Of View (FOV), the design of the optical system is based on nested grazing-incidence polynomial profiles mirrors, and assumes a focal plane curvature and plate scale corrections among the shells. This design guarantees an increased angular resolution also at large off-axis positions with respect to the usually adopted Wolter I configuration. In order to meet the requirements in terms of mass and effective area (less than 1200 kg, 6000 cm^2 @ 1 keV), the nested shells are thin and made of quartz glass. The telescope assembly is composed by three identical modules of 78 nested shells each, with diameter up to 1.1 m, length in the range of 200-440 mm and thickness of less than 2.2 mm. At this regard, a deterministic direct polishing method is under investigation to manufacture the WFXT thin grazing-incidence mirrors made of quartz. The direct polishing method has already been used for past missions (as Einstein, Rosat, Chandra) but based on much thicker shells (10 mm ore more). The technological challenge for WFXT is to apply the same approach but for 510 times thinner shells. The proposed approach is based on two main steps: first, quartz glass tubes available on the market are ground to conical profiles; second the pre-shaped shells are polished to the required polynomial profiles using a CNC polishing machine. In this paper, preliminary results on the direct grinding and polishing of prototypes shells made by quartz glass with low thickness, representative of the WFXT optical design, are presented.

I. INTRODUCTION

The WFXT X-ray mission foresees an X-ray Telescope Assembly that will be 2-order-of-magnitude more effective than previous and planned X-ray missions in carrying out large area sky surveys. Focusing telescopes for X-ray astronomy are usually built in the so called 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 adopt a mirror design capable to maintain across the entire FOV (i.e. for off-axis angles up to +/- 30 arcmin and beyond) the same angular resolution behavior achievable for paraxial rays. The current WFXT design is based on thin nested shells with polynomial profiles [3], radius-dependent length, and with the intersection planes between the two pseudo-cylindrical reflecting surfaces shifted one with respect to the other for each mirror shell. The result of the entire set of assembled shells assumes a sort of "butterfly-like" configuration [4]. The WFXT optical assembly will be composed by three identical modules, whose characteristics are reported in Table 1.

Table 1. Characteristics of the proposed WFXT surveying telescope.

Focal Length	5500 mm
Number of Optics Modules	3
Material	Quartz
Numbers of Shells per module	78
Shells Radius [min – max]	165 – 550 mm
Shells Total length [min – max]	200 – 440 mm
Shells Thickness [min – max]	1.2 – 2.2 mm
Total on-axis Effective Area* (1 keV)	9236 cm^2
Total on-axis Effective Area* (4 keV)	2565 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 by the support structure.

Several tests have been performed to verify the technological feasibility to produce such thin mirror shells. Two approaches have been envisaged: a) the production by epoxy replication onto pre-formed carriers using a precisely figured and polished mandrel and b) the direct polishing of pre-machined shells. The epoxy replication technology using a SiC carrier (600 mm diameter) has already been proved in the past, able to meet an angular resolution of 10 arcsec HEW across a FOV of 1 deg [5], [6]. In order to further improve the performances and reach the angular resolution goal of 5 arcsec across the FOV, the direct polishing of thin quartz shells is now under evaluation. Quartz glass has been selected because of its very good thermo-mechanical properties (in particular low density, $\rho = 2.2$ g/cm^3; high rigidity, Young Modulus E = 72.5 GPa; low Coefficient of Thermal Expansion, CTE = 0.5×10^{-6} /K) and easy polishability. The proposed method foresees the direct figuring and polishing of monolithic quartz glass mirror shells. The production flow starts from a quartz glass tube, which is a standard item already available on the market. The tube is firstly ground to obtain a double cone profile at the required thickness around 1-2 mm. Then, it is figured and polished to the final polynomial profile making use of a "deterministic" figuring method. This implies that, after the measurements of the actual profile of the pre-machined 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 removal matrix. Starting from a profile after grinding with P-V roundness errors of a few tens of microns (in any case < 60 μm), it is possible to reach the required specifications with a small number of iterations. For passing from the grinding to the polishing step, it is necessary to integrate the shell in a suitable supporting structure, able to allow the handling during the metrology, machining and all the necessary operations before the assembling of the shell into the final structure (i.e. the reflective coating deposition and the X-ray characterization). The entire proposed production flow is depicted in Fig. 1. The technological challenge of producing thin mirror shells poses several issues to be taken into account. In particular, the deformations during machining and metrology phases and the resistance to launch conditions have to be considered.

I-A. Considerations on the deformations during machining and metrology of thin glass shells

As already mentioned, the wall thickness of WFXT shells is very small, in order to meet the effective area and mass requirements; the thickness is a factor of 5-10 less with respect to past experiences such as ROSAT or CHANDRA. The wall thickness is a function of the shell diameter, ranging from 1.2 mm (for the innermost shell) until 2.2 mm (for the outermost shell), to have constant stiffness behaviour across the whole series of mirror shells. In the last few years, new machines and polishing techniques have been developed with performances very promising, offering the possibility to perform the direct optical machining of thin substrates. The WFXT mirror shells are not only thin, but they are also characterized by a very small Length-to-Diameter ratio (L/D), 3 times smaller than XMM-Newton mirrors. For this reason, their realization is more difficult because short mirror shells are more sensitive to perturbing effects related to edge loads. Under the same perturbing edge loads, short mirror shells show degradation 6-16 times larger with respect to long mirror shells and this ratio becomes even bigger in case of perturbing loads producing local deformed shapes. Moreover the angular resolution is strongly affected by the slope errors caused by out-of-phase azimuthal errors, which are inversely proportional to the mirror shell length. It is worth noting that the consideration of concentrated loads at the free edges of the shells is really representative of the actual conditions. Indeed normally the mirror shells are fixed to the mirror module structure by spot connections at the one or both end sections and, during the metrology and integration operations, they rest on concentrated astatic supports at one-end section. An astatic support (see Fig. 2-A) is needed to measure the intrinsic shape of the thin shells, since relevant deformations would be otherwise caused by gravity. Two astatic supports are already available at INAF-OAB, one with 12 and the other with 16 sustaining points. It was verified by FEM and ray-tracing analyses that with the available astatic supports, the deformations introduced on the shells are negligible, in the order of 0.5 arcsec HEW.

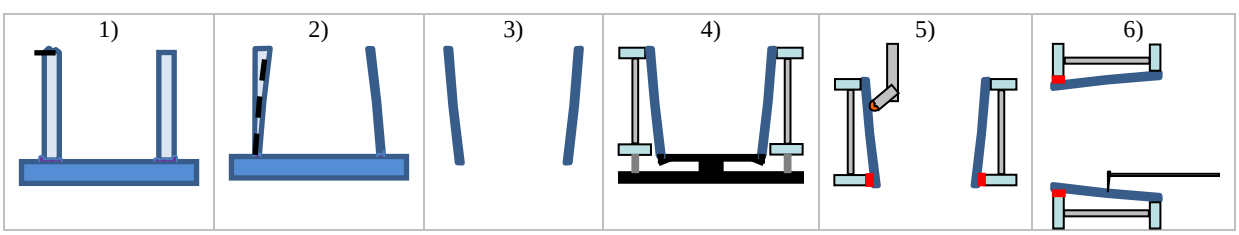

Fig. 1 Scheme of the production method under development for the manufacturing of thin quartz shells based on the direct figuring and polishing. 1) The raw starting material is a quartz glass tube, already available on the market; 2) The tube is positioned onto a suitable support and firstly ground to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

I-B. Considerations on the resistance to launch conditions of thin glass shells

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 considerations can be performed, based on engineering evaluations and past experiences. Assuming a traditional X-ray telescope, each single mirror shell is 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 using adhesive contacts. If such a configuration is adopted for the FEM analyses, the maximum stresses in the glass might exceed the tensile stress limit in points of stress concentration. Local refinement of the analyses and the design are needed considering the use of a brittle material like quartz. Revised design criteria with respect to the traditional approach will allow obtaining surviving loads conditions. In addition to that, the use of chemical etching treatment of the shell surfaces in order to reduce the micro-cracks cause by the grinding is under investigation to improve the intrinsic stiffness of the quartz.

II. TESTS PERFORMED AND RESULTS OBTAINED ON THE REALIZED PROTOTYPES

For the purpose of this study, 8 pre-machined prototypes have been realized. Three of them have been chemically etched in order to assess the effects of this treatment on the quartz stiffness. The results are currently under evaluation. Three shells have been integrated in the suitable jig structure that, as said before, has been appositely developed for a proper handling during the operations. One of the integrated shells has been already used to perform preliminary polishing tests. The characteristics of these produced demonstrative breadboards are reported in Table 2.

II-A. Grinding results

The grinding of the raw quartz tubes has been pursued by Heraeus Quarzglas GmbH & Co KG. The requirement was to obtain a thin quartz shell with double cone profile and an Out-Of-Roundness (OOR) error not larger than 60 micron. The raw material is represented by the high purity HSQ 300 quartz glass, produced by the same company. Several options have been tested to optimize the grinding set-up, studying parameters like the grains type and size of the abrasive slurry, the tool diameter and speed, and the quartz tube supporting configuration during the grinding process. In particular, three runs have been performed to study those aspects. During the first run the raw parameters of the process have been selected. The other two runs have been pursued to optimize the support system of the quartz tube during the machining (see Fig. 2-B). In fact, during the first and the second runs, high OOR 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 fixing 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, as already mentioned. The chemical etching of the whole surface has been performed by Heraeus on three 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 addressed by further studies to be carried out in near future. Heraeus Quarzglas performed the metrology with 3D Zeiss Coordinate Measuring Systems, supporting the shell on three points, providing absolute values for diameters and measurement of profiles. INAF-OAB afterwards performed the shells metrology with an optical sensor mounted on a rotational table, supporting the shell with an astatic system. The measured values are reported in Table 3. The capability to grind the thin shells with the required double-cone profile and accuracy in terms of OOR of a few tens of microns has been demonstrate during this first phase of the study.

Table 2. 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

Table 3. Out-Of-Roundness and longitudinal P-V errors for the 8 pre-machined prototype shells.

Grinding run	Shell #	P-V OOR Error [μm] (OAB)[1]	Long. accuracy (P-V) [μm] (Heraeus)[2]	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 4 and 6.
2a	3	-	-	Broken during re-grinding tests to improve the fixation to the grinding machine.
3	7,8	9, 5	8, 6	Improvement in the fixation of the shell during grinding. Requirements are met. Chemical etching on shell 7.

[1]Average of 4 to 6 OOR values from roundness profiles at different height. [2]Average of 8 P-V values (4 parabolas, 4 hyperbolas) at azimuthal distances of 90°.

II-B. Development of suitable jig for polishing and metrology phases

A suitable jig, called Shell Supporting Structure (SSS), has been designed and manufactured to allow the handling of the shell during all the production steps. 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 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. The SSS is the result of an optimization process carried out through FEM analyses aimed at the evaluation of stresses, deformations and related optical performances degradation introduced in the thin shell by the supporting method. A direct connection between the mirror shell and the supporting structure through bonding would introduce important degradations of the optical performances in the case of large CTE and adhesive cure shrinkage. It would also cause deformations of the supporting structure to propagate into the shell. 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 shell and SSS. The final SSS is composed of two rings made of glass that allocate metallic inserts for interface purposes with the polishing machine. The two rings are joined through metallic bars. The shell is connected only to one ring through the metallic comb flexure that allows a radial flexure at the connection between the mirror shells and SSS. Removable space-qualified glue with low shrinkage and low CTE has been selected to glue the shell to the metallic comb in order to avoid problems in the vacuum chambers during coating deposition or X-ray tests. The first shell integrated in the SSS has been broken after the delivery at OAB due to an incorrect handling. However, it was used as a dummy shell to test and optimize the SSS design and integration process, even if the OOR value resulted to be strongly degraded (see Table 4). With the other two integrated shells, it has been verified that the integration process in the jig is able to maintain or even improve the original shape.

Table 4. Comparison of the Out-Of-Roundness measurement performed before and after integration into SSS.

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.
7	9	11	Verification of the SSS design and fixation procedure.

2-A) 2-B) 2-C)

Fig. 2. A) Side view of the astatic support system used during OOR metrology. B) Raw quartz glass tube mounted on the grinding machine at the Heraeus Quarzglas facility. C) First shell integrated in its SSS.

3-A) 3-B) 3-C)

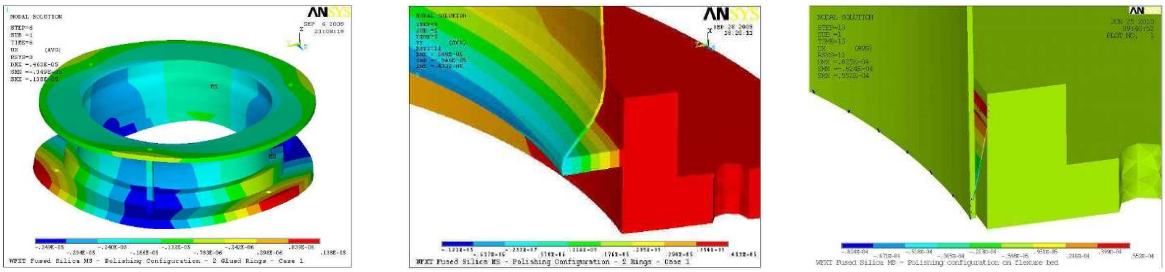

Fig. 3. A) FEM simulation carried out to verify the effect on the shell due to SSS deformations in the case of direct connection between the shell and the SSS. Deformations of the SSS are transmitted to the shell. B) Detail of radial displacement isocontours at the connection between the mirror shells and the SSS ring. The effect of the adhesive expansion due to thermal effects is evident. C) The use of a metal foil introduces a radial flexure, implemented in order to avoid the transmission of possible thermo-mechanical deformations into the shell.

II-C. Figuring and polishing results

The polishing process is being performed by the Zeeko firm (UK), using a IRP600 machine, a CNC polishing systems, controlled on 7-axis, that uses a patented process for the shells polishing, named “Bonnet polishing” [7]. The Zeeko IRP Serie machines have the capability of machining shells with diameter up to 1100 m and height up to 440 mm, as required for WFXT telescope. By acting on the process parameters, such as the 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 so called “influence” or “removal” function is generated, in order to determine the best volumetric removal rate in dependence of the specific materials and requirements. Several tests have been performed during the study, in order to evaluate 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 OOR values (800 µm). The possibility of performing an intermediate coarser step (named “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. An entire half of the shell surface has been machined and important information has been obtained regarding the effects of vibration and deformation introduced during the Bonnet machining. It should be noted that the results achieved so far are very promising and useful parameters were inferred to carry out future activities. In particular, it has been demonstrate that the OOR errors have effects on the radius of curvature of the Bonnet tool to be used and on the removal coefficient. For OOR 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 OOR error ranges between 10 and 60 µm P-V a pre-phase of grolishing should be considered, in order to remove defects coming from the precedent phase.

4-A) 4-B) 4-C)

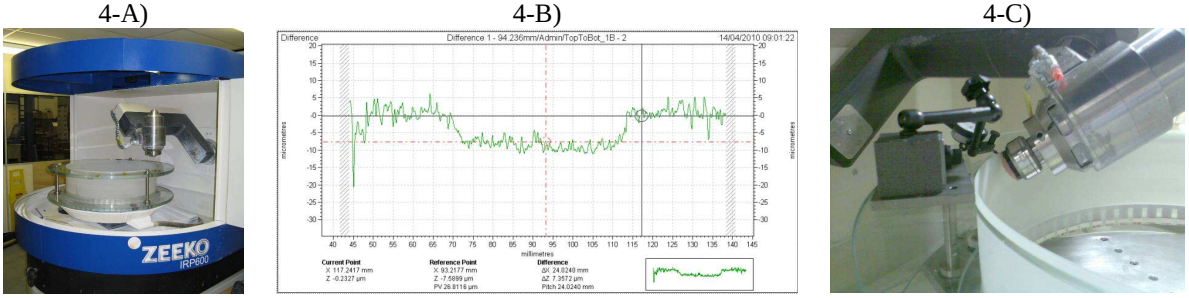

Fig. 4. A) Shell mounted on the Zeeko IRP600 machine. B) Example of the influence function of the grolishing process. The circle indicates the grolishing starting point. C) Particular of the Bonnet polishing tool during one of the first grolishing tests to evaluate the suitability of the SSS as interface to the polishing machine.

The polishing phase will start very soon on the second and third shells integrated in the SSS. Those new tests will be important to evaluate the possibility of obtain proper polynomial profiles starting from the double-cone shape. 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.

III CONCLUSION

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, have been presented. The development aims at achieving 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 (OOR error < 10 μm P-V) have been achieved. Three of the produced carriers have been integrated into a suitable jig, specifically designed for performing all the steps foreseen for the shell manufacturing, up to the integration in the final telescope structure. In particular, the jig was developed for allowing the handling of thin shells, giving the possibility of positioning them in both horizontal and vertical directions (with respect to the optical axis) without introducing 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 OOR error < 60 μm. The evaluation of chemical etching to remove the sub-surface damages on the surface of ground shells has started and analyses are in progress. Upcoming activities include polishing tests 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.

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