

COMPOSITE GLASS PANELS FOR STIFF AND LIGHTWEIGHT OPTICAL MIRRORS: A NOVEL APPROACH WITH PRELIMINARY RESULTS

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I. ABSTRACT

In the last years, INAF-Astronomical Observatory of Brera (INAF-OAB) has started to develop a glass slumping technology for the realization of thin and flexible mirror substrates for adaptive optical applications. In particular, the study was financed in the framework of OPTICON FP6 – E-ELT Design Study. With this approach we aim to reproduce with adequate accuracy the shape of an optically figured mould. At the end of the process we will have a thin, flexible and extremely lightweight glass mirror substrate. The shape of this glass shell will be of optical quality. In this paper we propose and discuss a technique for the manufacturing of stiff and lightweight mirror panels. Each panel shows a sandwich-like structure with two thin glass skins on both sides, the optical one being the substrate produced via glass slumping. This mechanical structure is ideal to limit the optics weight but keeping the quality of the substrate itself; key points for space-based applications. Moreover, the proposed phase of sandwich assembly is such that the glass shell does not lose its shape's quality. The approach here presented is derived from a previous development conducted by INAF-OAB for mirrors for Cherenkov Telescopes. We present the basic idea of the approach and some preliminary results obtained from tests realized.

II. TECHNOLOGICAL APPROACH UNDER INVESTIGATION

The process hereafter described produces composite glass mirror panels with a sandwich-like structure. Each panel is composed by two thin glass sheets glued as skins of a suitable material being the core of the panel itself (core's board). The front glass sheet is conformed to the desired optical shape using a two-step process based on the replication of a master, while the rear one is used to increase both the stiffness and the thermal stability of the panel when exposed to temperature variations.

This process has been already partially discussed in [1] and [2] and it is herein summarized for completeness. It can be divided into two separate steps shown in Fig. 1: the first one uses a thermal forming procedure to conform the shape of a thin glass sheet to a mould; while during the second step the sandwich structure is assembled.

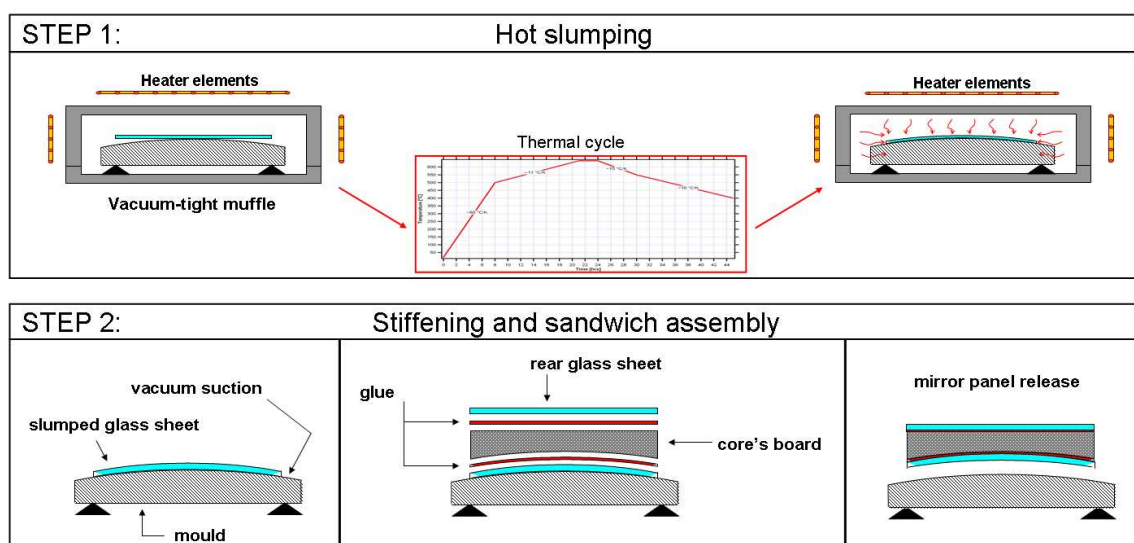


Fig. 1. Technological process under investigation. The first step uses a thermal forming procedure to shaping (up to optical quality) a commercial thin glass sheet. This procedure is completely developed in INAF-OAB.

The second step permits to assemble this glass shell in its final configuration without major optical degradations.

A. First step: hot glass slumping

The first step of this process is used to precisely shaping a common float glass sheet. Applying a thermal cycle up to temperatures above the glass transition temperature T_g , i.e. where the glass's viscosity becomes low enough, permits to the glass to slump and retain permanently the new geometry when it is cooled down.

This is derived from an ongoing R&D program started for an ESO FP6 activity for the development of a technique based on hot slumping of thin glass sheets to manufacture floppy glass shells for adaptive optics [3][4][5]. A mould, having as a shape the negative of the desired optical profile, is manufactured in a suitable material; it has to withstand high temperature with no major shape changes during the thermal cycle and after repeated ones. In addition, the CTE of the mould should be as similar as possible to the glass to be slumped to have a close replica. After having performed a trade-off, for the material of the mould it was chosen the ZERODUR K20 [6]. For what concern the glass, the BorofloatTM 33 was chosen due to its good quality and CTE match with the mould. Both these materials are produced by the Schott company. This decision was mainly supported by the following considerations:

- The ZERODUR K20 has not shown sticking attitude to the BorofloatTM 33 glass up to 660 °C, hence there is no need of an anti-sticking coating.
- The dimensions of ZERODUR K20 blank can be easily scaled-up to 1.5 meters in diameter.
- The ZERODUR K20 has a CTE near to that of the BorofloatTM 33.
- The CTE homogeneity of the ZERODUR K20 is the highest of all the other considered materials. This avoid local changes in height and shape of the mould.
- The cost of the finished mould in ZERODUR K20 is not far from that of the moulds made in other materials considered.

After a deep cleaning of the two components (mould and glass sheet), they are placed onto a muffle with vacuum capability. Roughly, the muffle is a stainless steel box that permits to remove the air convection, with advantages in terms of homogeneous heat distribution and cleanness from the dusty ambient of the oven.

The muffle is placed inside the oven. A suitable thermal cycle is applied up to 650 °C (depending on the glass type); during the slumping a uniform pressure of about 150 g/cm² is applied on the glass so to force it against the mould surface. This ensures the full contact of the glass against the mould. At the end, the glass sheet will have copied the shape of the mould.

The process is able to replicate with high accuracy the geometry of the mould profile, but also the features at higher spatial frequencies are copied and in particular part of the surface microroughness. For this reason a superpolishing of the mould is needed.

Based on the finite element analyses and experiments we have done using our facilities it is possible to reach the maximum temperature in about one day maintaining limited thermal gradients (< 1% over a mould diameter of 0.7 m). The total thermal cycle has a duration of about 3-4 days before the complete cool down to room temperature.

B. Second step: stiffening and sandwich assembly

After the thermal shaping phase it is possible to proceed with the second and final step where the glass shell will be assembled in its final configuration. This is accomplished exploiting a vacuum suction between the shell and the mould, and then gluing the core's board and an additional glass sheet on the rear.

This concept is derived from a R&D program funded by INAF-PRIN-2006 grant for the development of innovative mirrors for Imaging Atmospheric Cherenkov Telescopes. In particular, from this study came up the so called "cold slumping" technology successfully adopted for the production of more the 100 square meters of mirror panels [7][8]. These mirrors compose almost half of the optical surface on the MAGIC II Cherenkov telescope installed in La Palma, Canary Islands.

Following the scheme proposed in Fig. 2, the glass shell is uniformly pushed against the mould using a vacuum suction. This eliminates any geometrical errors between the mould and the glass, residual from the thermal forming phase and due to the CTE mismatch and/or thermal gradients. Anyway, if both the choice of the materials and the thermal cycle timing have been properly done, the geometrical errors are very small and in the order of tens of microns at most.

A thin layer of glue is uniformly spread on the glass shell and the core's board is assembled together with the rear glass sheet. The adhesive is cured following the proper thermal cycle, if needed, and then the sandwich is released from the mould.

At last, the sandwich panel can be coated with the proper reflecting layer.

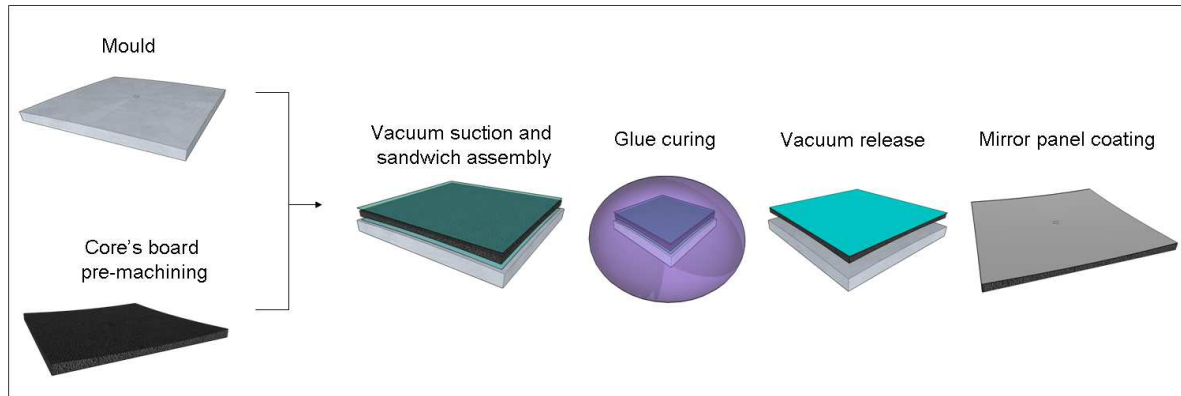


Fig. 2. Detailed scheme of the second step of the process. The glass shell thermally formed in step 1 is now placed in contact with the same forming mould by means of a vacuum suction. Then a core's board and a second glass sheet are assembled together to form the final sandwich structure.

III. CONSIDERATIONS ON MATERIALS FOR THE CORE OF THE PANELS: FOAM AND GLUE

The choice of the material for the core of the panels plays a very important role in the design. To obtain panels with areal density in the order of 20 kg/m^2 and with high stiffness, we use materials with a foam structure. In fact, they show good performances when compared with the bulk materials.

We are experimenting the use of Foamglas® boards [9] from Pittsburg Corning company as core of the mirror panels. However, this is probably not the best material to be used for this kind of applications, and in particular if we aim to deliver very high performance mirrors as usually needed in space-based applications. Foamglas® shows a quite fragile surface and a good thermal insulating behavior, meanwhile materials like Silicon Carbide or Fused Silica foams should be able to deliver mirror panels with better thermo-mechanical performances. However, the experience gained and the results obtained using Foamglas® are interesting and quite promising in view of further developments that we are scheduling with the above suggested materials.

In the following are reported some considerations we have drawn from the present experience we had with Foamglas®.

Foamglas® is an all-glass closed-cell structure material composed of millions of completely sealed glass cells. It shows a number of interesting characteristics that made it attractive for our development. It comes in lightweight boards produced in several thicknesses, from 40 to 120 mm, and density ranging from 120 kg/m^3 to 165 kg/m^3 , it is stiff and easy to work. Moreover, it is waterproof, stable in time with a low CTE of about $9 \text{ } \mu\text{m/K} \cdot \text{m}$ and, last but not least, the cost is below hundred of Euro per square meter.

Due to the limited dimensions of the boards commercially available and due to its intrinsic stiffness, a number of Foamglas® boards shall be assembled together so to form the tile shape. At this point we have a plano-plano panel, and this is machined on the front side following a profile that fits the curvature of the forming master. This plano-concave tile is then used as core's board of the final mirror panel. The machining of this blank panel has been done in the labs of INAF-OAB using a dedicated facility, a CNC milling machine similar to a pantograph, it is capable to work on pieces up to $1500 \times 1700 \text{ mm}^2$.

We think that exploiting this approach it will be possible to produce mirror panels with very good opto-mechanical characteristics. Some expected improvements are here summarized.

Since the panel's core is machined to match the shape of the curved glass sheet, the final mirror panel should results to be in a very stable condition. The spring-back effect is essentially absent or it is at most caused by the small bending that happens with the vacuum suction.

Using glass also for the core of the panel we realize essentially an all-glass mirror panel in which it is strongly reduced the CTE mismatch between the principal components of the panel itself, i.e. the two skins and the core. This should give a net improvement in the stability of the focal spot produced by the mirror when exposed to environmental thermal gradients, because of a very reduced differential expansion/contraction between the skins and the core.

The glue can be an epoxy adhesive showing adequate characteristics in terms of shrinkage, CTE and curing temperature. In particular, a very low percentage shrinkage is mandatory to minimize overall stresses during the curing phase, as well as the application of a thin bonding layer with a uniform thickness to avoid local stresses.

Also, milling or turning the foam boards on the front side (i.e. shaping them to match the curvature of the glass shell) helps to maintain as constant as possible the thickness of the layer of glue. This avoids differential shrinkages (i.e. from point to point) of the glue and hence it allows a better copy of the master's shape.

IV. PRELIMINARY RESULTS

In the present section are reported a number of results obtained measuring and testing some mirror panel prototypes realized by the authors. These prototypes have been realized using the approach presented in this paper.

All the measurements and tests here reported have been done using equipments installed in the labs of INAF-OAB. The metrology adopted is mainly aimed to show the focusing capability and the shape quality (through interferometric measurements) of the mirrors.

The prototypes presented in the following have been replicated from a mould already available in INAF-OAB from the ESO FP6 R&D program. It is made in ZERODUR K20, a ceramic material from Schott with a circular tile shape of 700 mm in diameter. Its surface geometry has been figured with a classical optical polishing process. It is a convex sphere of approximately 9700 mm radius of curvature with a figure RMS error of about 1 or 2 λ at 632.8 nm, while the microroughness finishing level is of about 3-5 nm RMS. The glass sheets used are disks of Borofloat 33 type from Schott, 500 mm in diameter and thickness of 1.7 mm.

In Fig. 3 are shown some phases of the prototype manufacturing. In particular, from left to right it is visible the preparation of the blank with Foamglas® boards, the slumped shell placed on the mould and the finished mirror panel after the vacuum release. In the central image the curved glass sheet is in contact with the mould through the vacuum suction distributed all around the glass circumference. In this condition a number of interference fringes should be visible. These are generated by the shape difference between mould and slumped shell. If no difference is present no fringes are visible, this means that the glass matches exactly the mould shape. The present situation returns an almost complete match on a wide central area covering more than 80% of the total, with just some islands due to not perfect cleaning of the glass surface. On the contrary, along the glass perimeter a corona of dense fringes is visible; it comes once again from a lack of adequate cleaning of the shell edge.

A preliminary evaluation of the optical performance of the mirror panel has been done through its capability to form images; in Fig. 4 are presented few of them. On the left panel it is shown a small, sharp and very intense disk of light generated pointing the mirror onto the Sun. The central photo is the focal spot derived from the concentration of a spherical laser wavefront placed on the radius of curvature. The bulge of the spot is contained in about 3 mm, while the measured radius of curvature is 9850 mm. At last, in the right panel there is the image of a filament lamp as generated by the mirror. As visible it is possible to recognize some features as the incandescent filament itself and the glass bulb.

The mirror has also been measured with a ZYGO GPI XP interferometer equipped with an optical reference sphere for the generation of the laser wavefront. Due to the long focal length of the mirror it was not possible to measure it using a vibration damped optical bench. The result of the measure is reported in Fig. 5. Almost the whole surface generates interference fringes with the reference laser beam, while the dark areas have a tilt respect to it. The overall figure error of the mirror is of about 1.5 λ , in complete agreement with the figure manufacturing specification of the mould.

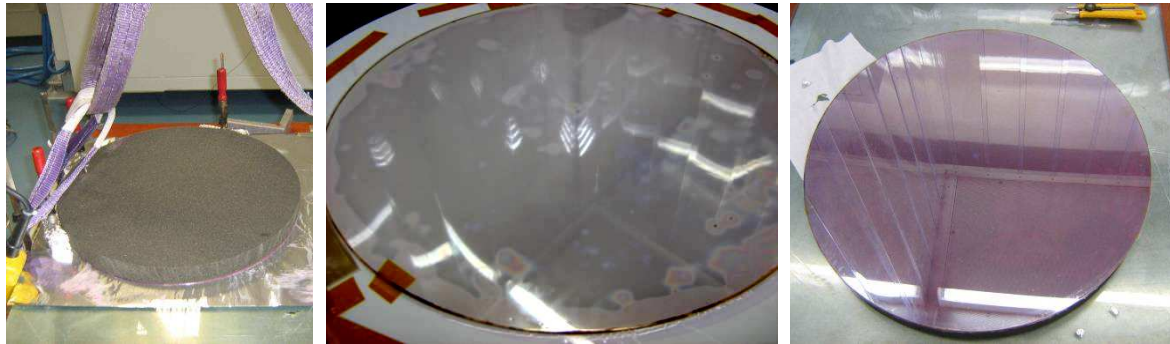


Fig. 3. (left) Foamglas® boards assembled to form the panel core. (center) Hot slumped glass shell in contact with its forming mandrel. Only a narrow corona along the glass circumference deviates from the mould shape. (right) Mirror panel after the curing of the glue and the vacuum release.



Fig. 4. Images generated by the prototype mirror panel realized: (left) an image of the Sun disk, (center) the focal spot on the radius of curvature and (right) a filament lamp.

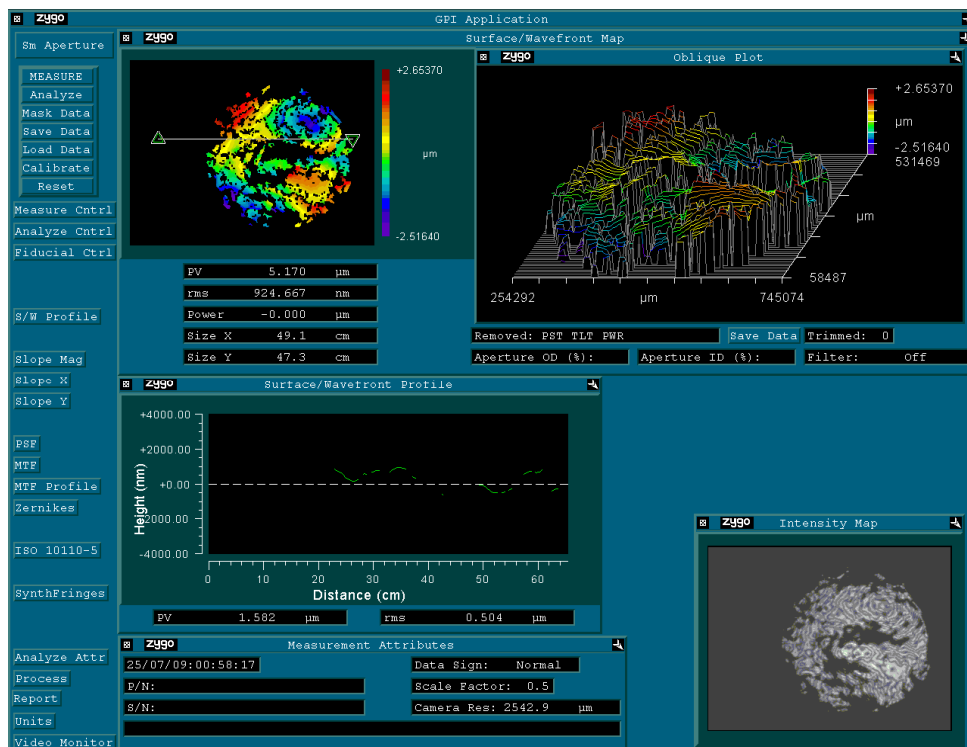


Fig. 5. Interferometric measure of the mirror panel prototype realized from a previously hot slumped thin glass sheet. The overall figure error is of about 1.5λ RMS respect to a perfect sphere. The higher frequencies contribution is attributed to a not optimized gluing procedure.

V. CONCLUSIONS

From this experimentation we summarize that in the low spatial frequencies domain the procedure here adopted permits to copy with good fidelity the overall geometry of the forming mandrel. Superimposed to this shape, there is an irregular set of fringes that degrades the surface quality of the mirror at the higher frequencies. In our understanding this contribution can be strongly attributed to the glue layer. In fact, we were not able to apply an adequately uniform layer of adhesive. This problem should be solved in the near future designing and using an ad hoc tool.

In the opinion of the authors, the use of this technique for the manufacturing of lightweight mirror segments for high quality segmented primary mirrors should be taken into account. Main applications can be searched in the upcoming ground-based projects, but this technique worth to be considered also in view of the advent of the new and large space-based telescopes such as the JWST. However, there are a number of improvements that have to be done in order to make this type of mirrors compliant with a sort of “standard requirements” for astronomical mirrors, in particular concerning the optical quality. Nonetheless, the very low areal density, the fast and cost production rates of such panels are all noticeable characteristics. In the future plans of the authors there is a strong intention to carry on a careful investigation of the presented approach.

Moreover, for high performance optical telescopes it is mandatory to use different materials, rather than Foamglas®, as well as higher optical quality moulds. In particular, concerning the core material the authors want to concentrate both on very low CTE open-cell structure Fused Silica foam and Silicon Carbide foam. Also the use of different glues will be investigated. In this ways, we think to be able to improve significantly the copying capability of the mould and hence the final optical quality of this kind of mirrors.

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