Development of hot slumping technique and last optical performances obtained on a 500 mm diameter slumped segment prototype for adaptive optics

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ABSTRACT

In the framework of the E-ELT Design Study financed by the European Community under OPTICON-FP6, the INAF Astronomical Observatory of Brera (INAF-OAB) has developed a technique for the manufacturing of thin optical segments. Thin glass segments are produced by mean of an hot slumping technique that makes use of an optical quality ceramic mould and a precise thermal circle to impart the desired shape to a glass sheet. In the present paper we summarize the results obtained during this study and report the last results of the effort in scaling-up the procedure: in particular the overall process has been refined in order to optimize the parameters (such as time, maximum temperature and amount of pressure) used to slump a 500 mm diameter glass segment. The thickness of these glass segments is of about 1.7 mm, making the optical surface very floppy and easy to be deformed. For this reason optical tests have been performed using a astatic support implemented into a vertical optical bench.

Keywords: Hot slumping, mould, Zerodur K20, Borofloat, astatic support

1. INTRODUCTION

The next class of ground-based optical telescopes now under development is called ELT (Extremely Large Telescope). Nowadays there are three big projects foreseen to be in operation around 2016-18: TMT (Thirty Meters Telescope), GMT (Giant Magellan Telescope), E-ELT (European-Extremely Large Telescope).
From the technological point of view these ELTs are a big challenge in any aspect, optical and mechanical. Taking as example the E-ELT, its primary mirror will have a diameter of 42 m. It will be manufactured in several mirror segments that will be mounted and aligned together with a proper active system to form a large monolithic-like astronomical mirror. The active system will also manage and minimize, during the observations, the shape distortions due to the gravity force. Each segment will be of hexagonal shape, about 1.3 m face-to-face, bringing the total number of segments around one thousand. The manufacturing and the metrology of these segments, all pieces of out-of-axis parabola, is a challenge in itself. The secondary mirror of E-ELT is a big challenge, too. In the initial design of the telescope it was a 4-5 m diameter segmented mirror composed by 2 mm thick hexagonal shells placed on a fully integrated adaptive optic support. These optics, able to flex very quickly and change shape, are an essential part of the optical systems of the modern optical ground telescopes and are used to remove the blurring effect of the atmosphere from the images acquired. The present manufacturing technique of thin and flexible optical surfaces for adaptive mirrors is a process that foresees the tinning of conventional thick blanks (Fig. 1). This process is very expensive and time consuming. In the first step of the process a thick glass meniscus is grinded until its surfaces have the same radius of curvature of a substrate material that will act as a blocking-body. In the next step the two pieces are glued together by means of a very thin layer of pitch. When the two pieces are glued is then possible to continue the grinding of the upper surface of the meniscus and to reach the desired thickness, typically in the range of 1-2 mm. When the grinding and figuring of the surface is done it is then possible to detach the two pieces by heating and hence softening the pitch as required. The convex thinned meniscus is then used as reflective surface of the optic. Experience gained with this technique has shown how complex and prone to difficulties is the technique, used for example in the production of the secondary mirrors of the LBT telescope, having a diameter of 911 mm and a thickness of 1.6 mm. An investigation in an alternative technique for the production of these shells has been proposed and based on a glass slumping process. In the next pages it will be described the technique and the results obtained during its development.

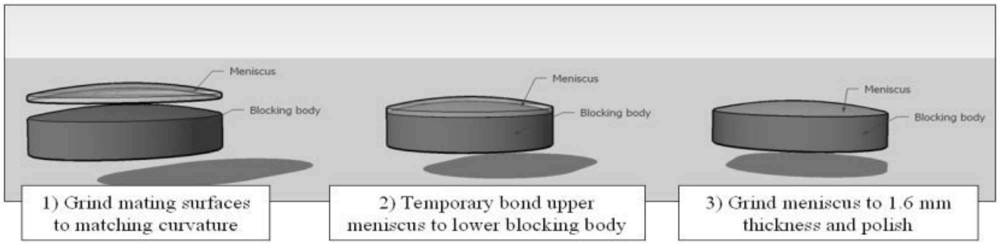


Fig. 1: Classical production of thin glass shells

2. THE HOT PRESS DIRECT SLUMPING APPROACH

A process able to deliver a thin mirror shell starting from a flat sheet of glass having the desired thickness (in the order of 1-2 mm) and based on the replica concept of a master mould is a very attracting possibility to strongly reduce costs, production time and mirror's damages risks. With this goal a research team of INAF-OAB is pursuing a study based on the concept of the glass hot slumping [1,2]. A thin and flat glass sheet is placed above a master mould previously optically figured and polished at the desired shape; then a suitable thermal cycle is applied. When sufficiently heated the glass will soften enough to slump onto the mould surface and adapts to the mould's shape (Fig. 2). When the system is cooled down to room temperature, the slumped glass shell is released from the mould and coated with the proper reflecting layer.

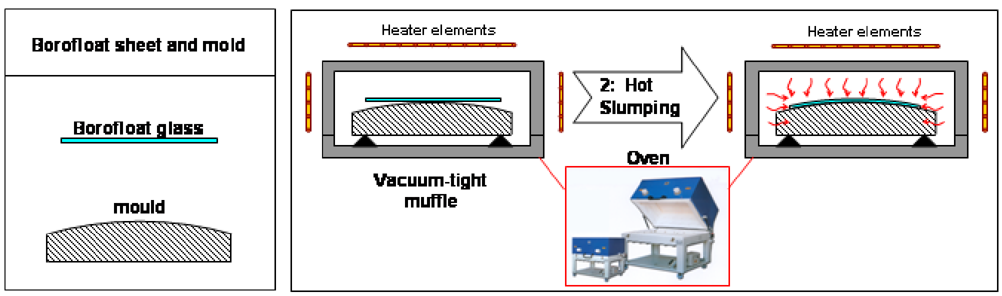


Fig. 2: Slumping process

Due to the fact that the optical surface of the glass will go in direct contact with the mould, the latter must have a surface microroughness very low so to avoid to ruin or change that of the glass. Further, the dust trapped between the mould and glass during the process could be an obvious problem and hence a clean room environment is necessary during the preparation of the process. During the slumping the pieces are placed into a muffle with the glass above the mould. The muffle is a stainless steel box designed to maintain a vacuum seal at high temperature and the air is removed making use of mechanical vacuum pumps. The use of the muffle helps the process in many ways. It reduces the air convection: heating the system just through irradiation makes easier to reach a better temperature distribution homogeneity, this is essential to avoid inserting stresses in the glass shell. Also, it protects the mould and the glass from the dusty environment of the oven. In fact, dust's particles can be considered as one of the main issues for the technology: a dust grain trapped between the mould and glass surfaces during the slumping process prevent a correct copy of the mould's shape in an area some cm^2 wide. The muffle is placed inside the oven and a suitable thermal cycle is applied. The maximum temperature reached during the process is of about 650 °C. The heating speed and cooling of the overall system is not simply limited by the power of the oven used, but much more by the thermal conductivity of the materials used for mould and glass. The presence of large thermal gradients during the slumping process can introduce shape errors on the glass optical surface. This is due to stresses arising mainly during the cooling-down phase of the process and in particular when the glass approaches its Transformation Temperature T_g. At this temperature the glass start to revert to the solid state. If it pass this threshold not homogeneously stresses will build up giving errors typically in the low spatial frequencies range that affect the optical figure of the slumped glass shell.

To ensure the full (optical) contact of the glass against the mould, a pressure is applied during the slumping process, when it reaches the maximum predetermined temperature. It forces the glass against the mould permitting both to bend the initially flat glass sheet and to speed up the procedure. This gives to the process the capability to copy the overall geometry and part of the surface microroughness of the mould. At the end of the thermal cycle, the thin glass shell will have ideally the same shape and microroughness of the mould. Due to the floppy nature of the slumped shell (the thickness is of few mm), to perform its optical shape measurement it is necessary to use an astatic support. This device is able to support the shell simulating a weightless condition, in order to remove the gravity induced deformations.

A critical aspect concerning the process was to define the material of the mould and the glass type for the segments. To this purpose, a comparison of the theoretical thermo-mechanical parameters of suitable materials for the mould and glass were performed. A detailed analysis of the materials investigated is presented in(4). For the mould it was chosen the K20, a special crystallization form of the Zerodur (3) able to withstand to high temperatures, while for the glass was chosen the Borofloat. Both materials are produced by the Schott company. Another crucial point was the heating and cooling rates for thermal cycle. The slumping is done at temperatures between the annealing point and the softening point in order for the glass to slump without loosing its original good surface properties. In Fig. 3 is shown an example of an optimized thermal cycle. Depending from the size of the segment and mould, the best cycle may be different but always include ramps and plateaus. In general, the heating can be relatively fast up to the required slumping temperature, then an holding time ensure that no temperature gradients are present and the glass has time to slump against the mould. The cooling down is slower to give the glass the possibility to reach the annealing point without internal stresses, since below this point the glass is no longer able to relax them.

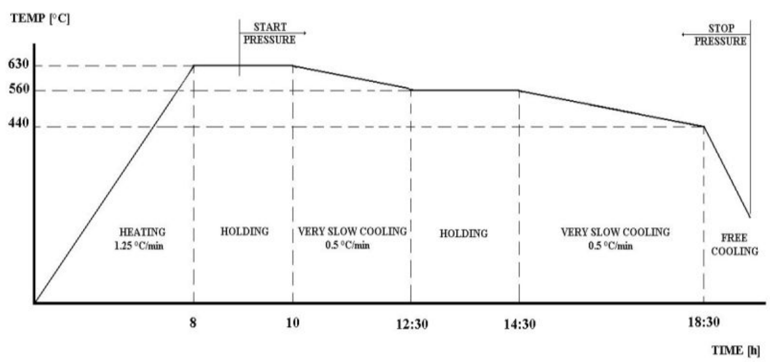


Fig. 3: Example of thermal cycle

3. STATE OF THE ART

Initial tests were performed on small moulds having diameter of 150 mm and a convex spherical shape of about 4 m radius of curvature. A number of glass disks having thickness of 2 mm were slumped.
A representative measure of these shells is shown in Fig. 4. On the left side, the shell is still placed onto the mould just after the cooling down of the oven and enlighten by Sodium light. In this configuration are visible bright and dark coronas that are the interference fringes between glass and mould due to their shape difference. These fringes permits a qualitative quick evaluation of the copy of the mould shape so to assess the results of the experiment. The fringes are quite round, smooth and centered meaning a good copy of the mould but with a small shape difference (a change of radius of curvature) due to thermal effects (different CTEs between the mould and glass). On the right side, it is visible an interferometric measure of the entire surface. The value for all the surface is of $\lambda/3$ (where λ= 632.8 nm typical of HeNe laser). All the slumped shells having this diameter have shown values of optical accuracy very similar to each other. This indicates a good repeatability of the process. Moreover, the surface features patter visible in the measures was present in all the segments slumped. These features are very likely present on the mould and are simply replicated onto the segment surface; on these tests the mould shape was limiting the performances obtainable with the slumping technique (5).

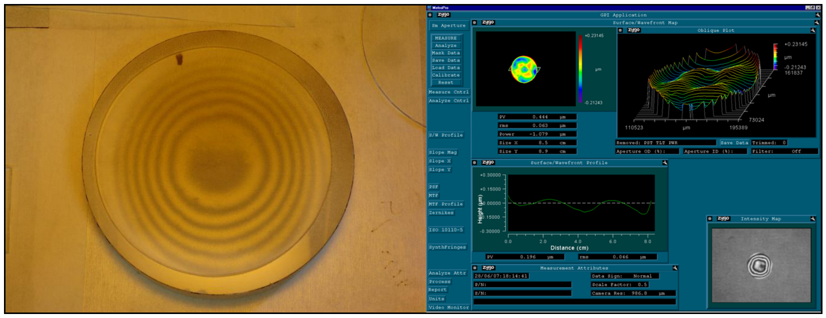


Fig. 4: Fringes under Sodium light and interferometric measure

In the last year a scaling-up of the process has been performed to slump glass mirror shells with more representative dimensions and with the aim to produce a demonstrative 500 mm diameter, 1.7 mm thick, concave spherical mirror in Borofloat33 glass. Initially a large Zerodur K20 convex mould having a diameter of 700 mm, thickness of 110 mm and radius of curvature of about 5 m was manufactured, having a surface finishing in the order of 2.5-4.5 nm rms. This mould has a constant thickness for thermal reasons and hence its bottom surface is concave. The optical figuring of the upper surface was performed following the specifications related to the project that requires an overall figure of about 4λ rms but more stringent values at higher spatial frequencies.. After a certain number of slumping tests it was clear that the slumping (or bending) of a 500 mm diameter glass disk onto the radius of 5 m of the spherical mould was not doable at the maximum temperature possible to avoid the sticking of the glass. The Borofloat flat glass infact (even if at 640 °C) did not accepted to bend smoothly on the sphere but started to warp optically its surface especially on the outer parts of its area. Hence, after these tests, it was decided to refigure the mould surface changing its radius of curvature from 5 to 10 m to permit a better copy capability.

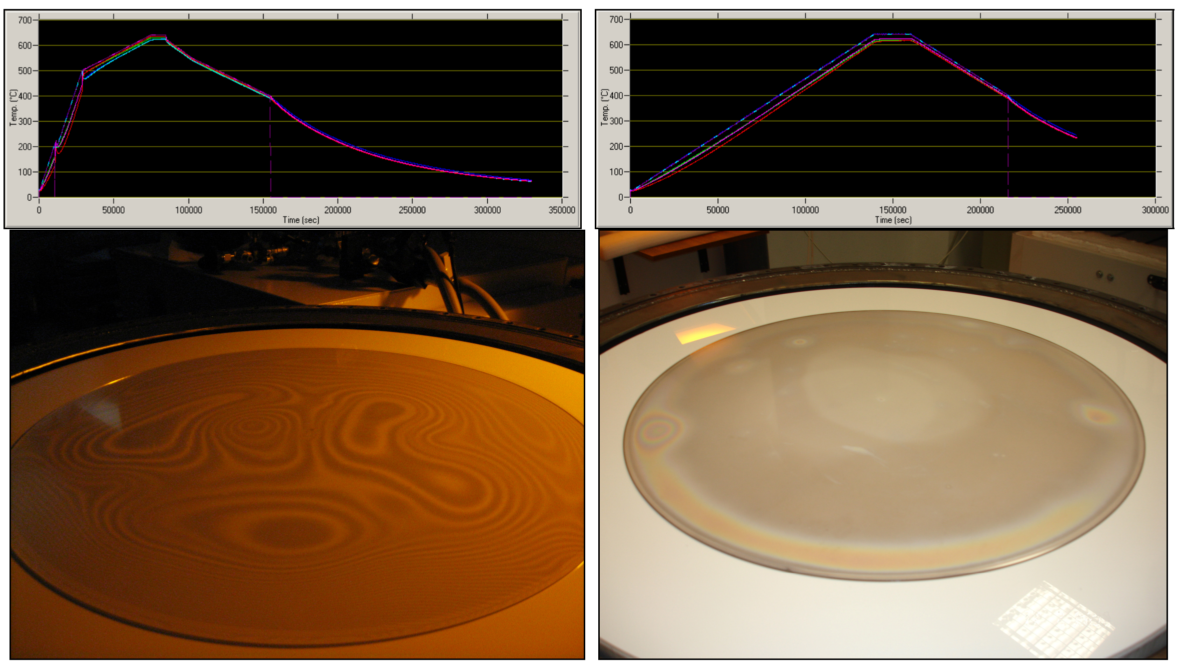


Fig. 5: Slumped glass disks with two different thermal cycles

With the new surface of the mould and using a maximum temperature of 640 °C a number of thermal cycles has been applied in different slumping tests. In Fig. 5 are visible two glass disks slumped and the relative thermal cycles. The best result obtained so far is that on the right of the figure.

The relative thermal cycle was very long (about 4 days) and symmetric, having a slow heating, a long holding time and cooling. With the glass placed above the mould very few interference fringes were visible indicating a good copy of the mould. On the contrary, the use of a faster thermal cycle (3 days), with a faster heating, a short holding time and a faster cooling provided a glass segment having stresses, as visible by the pattern of interference fringes on the left of Fig. 5.

For what concern the control of the dust, the circular and concentric patches of small fringes visible on the glass disk at right of Fig. 5 are due to dust grains or particles that prevent the glass to have a full contact with the mould. As it is visible only a small number of dust grains can be counted on its whole surface, thanks to the cleaning tools and the accurate procedure used. The same is true for the glass disk at left, the fringes visible are due to difference in shape respect to the mould surface, not to the presence of dust.
The best slumped disk shown in Fig. 5 (right) has been optically measured using an interferometric setup comprising an astatic support developed during this study and a solar tower located in the building of the institute so to have a vertical optical bench of about 10 m. The first step foresaw to put the slumped disk in the astatic support and to inject the correct amount of air to sustain its weight. The injection of the air has been done using a precise air flow controller and monitoring the load cell reading. At the end of the procedure the weight of the glass disk was almost totally sustained by the air cushion, each load cell touched the glass returning a value of few grams. This provided a reference plan for the interferometric measure avoiding the glass to float or vibrate. Once aligned the optical axis of the glass disk with the one of the interferometer a series of measures have been taken. The Fig. 6 below shows the measuring setup and the measure obtained.

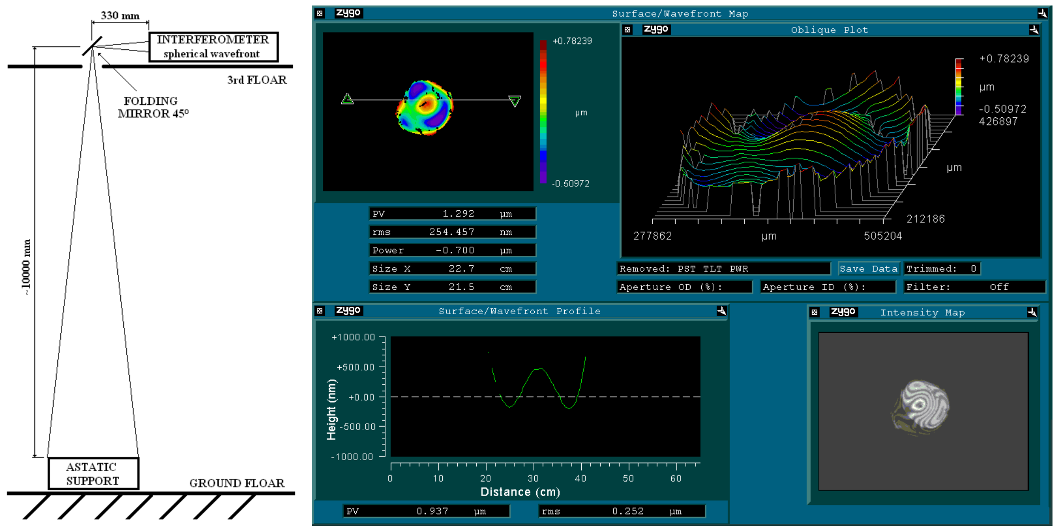


Fig. 6: (left) Sketch of the10 m vertical optical bench used to measure the slumped disk shape. (right) Interferometric measure of the central part of the slumped disk

The disk was measurable interferometrically in a central part having a diameter of about 250 mm, half in diameter respect to the total glass sheet. On this part it has been measured an error deviation from a mathematical sphere of about $\lambda/2$ (254 nm rms). The area of the mirror outside this part has an axial symmetric shape, without warping, that can be divided into coronas with different radii of curvature. In Fig. 7 is a list of the radii distribution and a profile sketch.

Diameter on the glass shell (mm)	Radius of curvature (mm)
0 < d < 250	10000
250 < d < 300	11500
300 < d < 400	11000
400 < d < 500	10500

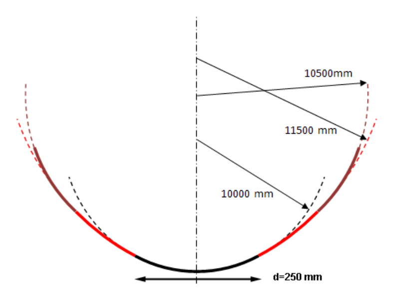
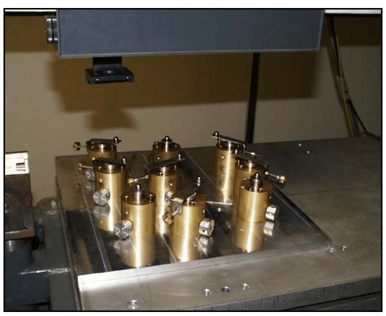


Fig. 7: Measured radius of curvature and profile of the slumped shell

A likely explanation of the overall shape obtained during this slumping is that it is due to a joint effect between the radial thermal gradient on the mould and the way (the timing) in which it has been applied the pressure to force in contact the glass to the mould. During the experiment we applied the pressure when the system reached the maximum temperature (640 °C) and then maintained it until the system was completely cooled down to room temperature. During this phase, a radial thermal gradient on the mould occur so that the edges of the mould cools down more quickly than the centre. This imply that the outer part of the glass "froze" its shape, passing through the Transformation temperature (T_g), earlier than the central one. Since the pressure was continuously applied during the cool down till to room temperature, the glass disk in this test was continuously constrained on the mould by the pressure applied above it. Stresses hence build-up that were released after removing the pressure, bending the wings of the glass disk profile. Probably, in next slumping tests it will be necessary to release the pressure applied on the glass earlier, when above the T_g so to avoid these particular stresses.

4. ASTATIC SUPPORT DEVELOPED

The problem of sustaining adequately very thin optical shells so to measure their intrinsic shape, not influenced by the gravity, is generally solved by means of an astatic support. This kind of support generally consist of a number of supporting points (their number is determined by FEM computations) placed in a grid pattern. Three of these supports are fixed meanwhile the others can slide up or down. The fixed points act as a reference plane meanwhile the moving points can be preset to apply locally pre-computed forces, obtained with a finite element simulation, that permits to obtain a situation in which the deformation of the segment is lower than a certain acceptable value and hence its shape is similar to that that it would have without gravity. An example of "classical" astatic support having only 9 points is visible in Fig. 8. In it is visible also a FEM computation made to determine the forces to be applied and the deformations introduced.



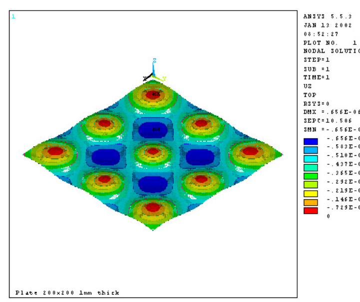


Fig. 8: Example of "classical" astatic support and FEM simulation

This kind of support became quite complicate to build as soon as the number of supporting points grow up as it is the case for thin and large optical shells. This increment of points (that must be active in the sense that it should be possible to set the pre-computed forces quickly) becomes a factor of complexity and cost. In INAF-OAB we have developed an alternative design for an astatic support that does not make use of a large number of support points. The force that sustains the weight of the glass segment is due to an air cushion and only the fixed support points are necessary. The prototype that has been built was produced during this study for the slumping of segments. As visible in Fig. 9 a circular container having a diameter almost equal to the glass to be measured, contains four load cells movable up and down and placed at 90°. These provide the fixed points on which the glass will come into contact with a predetermined pressure. Also, three movable hard stops are present (the blue elements). Placed along the inner circumference of the container is a magnetic strip having a magnetized zone large few mm. When the circular glass segment is inserted into the circular aperture, it is placed into contact with the hard stops that maintain it at the height of the magnetized zone. The tip of the four load cells will be just below the glass but not in contact with it. In this position the glass edge will face the magnetic strip along all the circumference and a small gap (of 0.5-1 mm) will be present between them. This gap will be filled with a Ferro-fluid liquid that will act like a seal. This fluid is maintained in place thanks to the magnetic strip and does not tend to flow downwards due to its magnetic field. To perform a measurement, air is injected in the bottom cavity until its pressure starts to make the glass to float. The air cannot escape from the bottom cavity due to the Ferro-fluid that closes the gap between the magnetic strip and the glass. At this point, the hard stops are lowered since the glass is suspended on the air cushion. To provide a stable reference plane, the four load cells are lifted toward the glass until their outputs reach predetermined values obtained with a previous FEM analysis. In this configuration, the glass segment shape can be measured in an interferometric way or by means of a profilometer. This kind of astatic support is much cheaper to be manufactured than the classical one. Since the air is sustaining the optical surface (except where there are the four points with load cells) there are no significant local deformations like those visible in Fig. 8 and due to the mesh of points in the "classical" case.

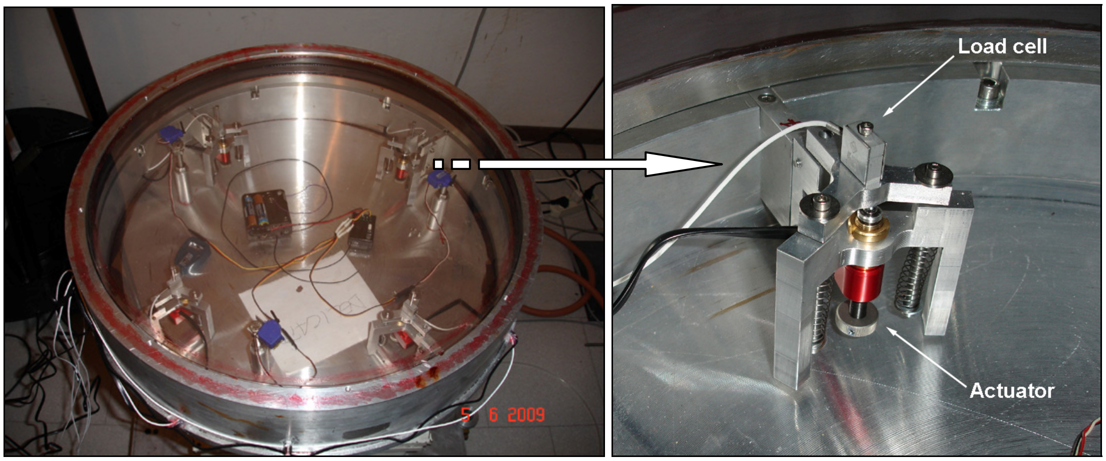


Fig. 9: Astatic support with air cushion during measurements

5. FINAL CONSIDERATIONS AND FUTURE WORK

At this point of the investigation on the slumping technique of thin shells to be used as mirrors for DM some considerations can be drawn:

The slumping of a flat glass onto a spherical mould can be done (for optical purposes) only for certain range of sagitta, diameters and thickness of the glass. The experience has shown for example that there are problems slumping a 500 mm Borofloat disk having a thickness of 1.7 mm onto a mould of 5000 mm of radius of curvature. A warping of the outer part of the optical surface was visible because the requested sagitta of 6.2 mm of bending was too large for the glass.

It has been found that changing the radius of curvature of the mould from 5000 to 10000 mm and hence reducing the bending sagitta to 3.1 mm has permitted a slumping that shows no sign of warping on all the surface of the 1.7 mm thick glass shell.

The Zerodur K20 material of the mould is a good trade-off between the Silicon Carbide (that offer excellent thermo mechanical properties) and the Quartz (that, as the K20, is also very poor thermal conductor). The main advantage of the K20 is that it doesn't stick to the Borofloat 33 up to 660-670 °C permitting to avoid the use of an anti sticking layer necessary anyway for the Quartz and the SiC.

The issue of the dust trapped between the glass and mould during the slumping can be solved with a careful procedure during the thermal process preparation. A good degree of cleanliness has been obtained but few dust speck were always present at the end of the tests. A more stringent cleanliness is in principle possible.

In the future the slumping activity of thin glass sheets will further focus on improving the copy capability of the mould shape. During the next slumping test we will remove the pressure on the glass shell during the cooling-down before reaching the Transformation Temperature T_g so to avoid the stresses previously described.
It could be interesting also to make a number of tests (and a smaller K20 mould has been already done) to find the relation between the diameter of the shell, its thickness and the available Sag that permits to slump without warping of the glass surface at a certain temperature. The results from these tests will permit to know if a certain shell is within the possibility to be manufactured by slumping successfully or not.
Finally, the shape of the present large mould is not known with high accuracy. Its overall shape has been measured with a 3D machine and using a concave master so to look at patches of its surface. An interferometric map of the mould

(made for example using the stitching technique) could permit to have a real map to be compared directly with the slumped shells. A number of firms able to do this measure on a convex surface has been found.

6. CONCLUSIONS

In INAF-OAB we have developed an hot slumping process based on the replica concept. This process slumps a thin (1-2 mm) glass sheet copying with good accuracy the shape of an optically polished mould made in ceramic material. The results obtained with shells having diameter of 130 mm have shown a very good copy capability of the master mould, permitting to obtain optical surfaces whose accuracy was limited only by the mould shape accuracy. The scaling-up of the process has introduced difficulties linked to the initially too strong sag of the mould when trying to slump 500 mm diameter shells with 5 m of curvature. This problem has been solved giving to the mould a larger radius of curvature passing from 5 to 10 meters. With this radius of curvature it is possible to slump without warping of the optical surface and a last slumping attempt has produced a shell with a good inner part on 250 mm diameter but an outer mirror part having an axial symmetrical shape, without warping, having coronas with different radii of curvature. An interpretation to this behavior has been found and a further slumping of another 500 mm glass shell is planned to verify the hypothesis and try to further improve the shell optical quality.

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ACKNOWLEDGEMENTS

This study has been financed by the European Community in the frame of OPTICON-FP6 for the ELT Design Study (WP9300) contract n° 011863