Lightweight optical segment prototype for adaptive optics manufactured by hot slumping

R. Canestrari [1,2], M. Ghigo [1], S. Basso [1], D. Spiga[1], L. Proserpio [1,2]

[1] INAF-Osservatorio Astronomico di Brera - Via Bianchi 46 23807 Merate (Lc) Italy
[2] Università degli Studi dell'Insubria - Via Valleggio 11 22100 Como (Co) Italy
Email: rodolfo.canestrari@brera.inaf.it mauro.ghigo@brera.inaf.it stefano.basso@brera.inaf.it daniele.spiga@brera.inaf.it laura.proserpio@brera.inaf.it

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. This study has the potential to fulfill the requirements of speed of production, contained costs and good optical quality for adaptive optics mirrors of the future. Following this approach these shells are produced by means of an hot slumping technique in which an initially flat thin Borofloat^{TM} glass sheet is placed onto a high quality ceramic mold, used as a master, to impart a precise shape to the glass by means of a thermal cycle. The thickness of these shells is of about 1.7 mm, making the optical surface very floppy and easy to be deformed. A previous investigation made on small size segments (diam. 130 mm) has shown quite encouraging results. The final goal of this study is to produce a concave spherical mirror prototype of 500 mm diameter. In this paper we report the last results of this effort in scaling-up the procedure and related problems concerning the optical testing.

Keywords: Segmented Optics, Glass Slumping, E-ELT, Borofloat^{TM}, Adaptive Optics

1. INTRODUCTION

The adaptive optics systems installed in current instruments have diameters less than 1 m and thickness in the range of few mm[1][2]. Adaptive surfaces with these thicknesses are nowadays manufactured using a technique that foresees the thinning of conventional thick glass blanks. A thick glass meniscus is grinded to have the same radius of curvature of a stiff support on which it is glued using a very thin layer of pitch. Then, the upper surface of the meniscus is also grinded until it reaches the desired thickness of about 1-2 mm, then it is removed from the support softening the pitch by heating. This is an expensive and time consuming process which it risks to break the thin segment under production. This procedure is useful for the manufacturing of a single piece optic, but it is not well suited for the production of a large number of segments like those foreseen for the adaptive optics of the next generation telescopes. In this context, we have investigate a new technique based on a replica process, that allow to obtain several identical segments saving money and time. For this reason we started to investigate the technique generally referred as "hot slumping"[3], in which a thin sheet of glass assume the precise shape of a master after a suitable thermal cycle in an oven. Fig. 1 illustrates the approach followed at INAF-OAB for the production of hot slumped segments.

A mould having the complementary optical shape and the same microroughness desired for the optical segment is manufactured in a suitable material. The mould used for our tests is made of ZERODUR K20, that has a CTE similar to that of the Borofloat^{TM} glass to be slumped. In a cleanroom environment, these two components are deeply cleaned and placed in a muffle with the glass above the mould. The muffle is used to remove the air and to reduce the convection in order to reach a better temperature distribution homogeneity. Also, it protects the mould and the glass from the dusty environment of the oven.

The muffle is then placed inside the oven and a suitable thermal cycle is applied, with predetermined warming-up, holding times and cooling rates. To ensure the full contact of the glass against the mould, a pressure is applied during the slumping process. This pressure force the glass against the mould giving to the process the capability to copy the overall geometry and also part of the microroughness.

At the end of the thermal cycle, the thin glass shell will have ideally the same shape and microroughness of the mould. Its optical quality can be then measured with an interferometer. Due to the floppy nature of the slumped shell, to perform its shape measurement it is necessary to use an astatic support. This device is able to support the shell simulating a

Adaptive Optics Systems, edited by Norbert Hubin, Claire E. Max, Peter L. Wizinowich,
Proc. of SPIE Vol. 7015, 70153S, (2008)
0277-786X/08/$18 · doi: 10.1117/12.790396

weightless condition, in order to remove the gravity induced deformations. The presence of thermal gradients during the slumping process can introduce some shape errors on the glass optical surface. This is due to stresses arising mainly during the cooling-down phase of the process. This kind of errors are typically in the low spatial frequencies range that can be corrected by the adaptive system support. For this reason the shape quality of the mould can be relaxed and consequently also the slumped shells to be produced.

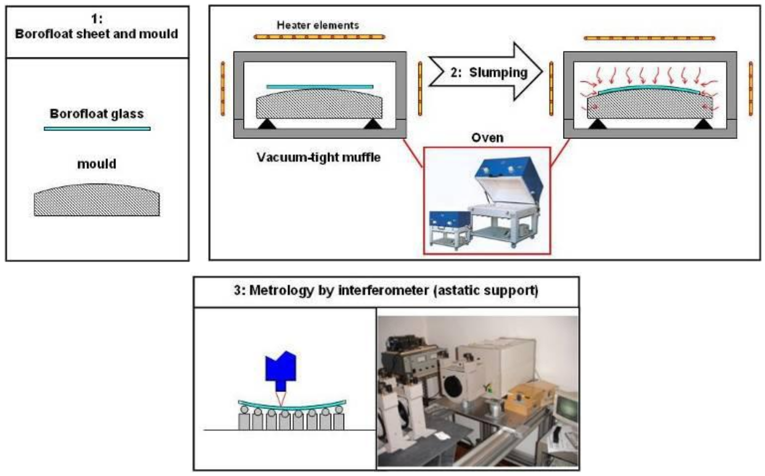

Fig. 1: Hot Slumping technique concept for the manufacturing of thin mirror shells.

The INAF-Astronomical Observatory of Brera (INAF-OAB) is developing this technique called “Hot Press Direct Slumping” for the manufacturing of thin glass optical segments to be used in adaptive optics systems. This study has been financed in the frame of OPTICON-FP6. The investigation here presented is part of a larger effort dedicated to the development of the European Extremely Large Telescope (E-ELT) that will have a segmented main mirror with a diameter of 42 meters. The aim of this study is to produce a thin concave spherical demonstrator in Borofloat™ glass, having a diameter of 50 cm, radius of about 5 meters and thickness of 1.7 mm. The process developed must be scalable up to the typical dimensions foreseen for the real segments of the secondary mirror for E-ELT. This size is of about 1.5 m in diameter.

2. OVERVIEW OF PREVIOUS RESULTS

Initially it was decided to investigate a number of materials either for the mould and for the glass. The materials tested for the mould were Alumina, Silicon Carbide, Technical Quartz and ZERODUR K20. A detailed analysis of the materials investigated is presented in a previous paper that compare the set of parameters taken into account (from thermo-mechanical to more general ones) and with a brief description[4].
After having performed a trade-off, for the material of the mould it was chosen the ZERODUR K20[5] shown in Fig. 2 (left). For what concern the glass, the Borofloat™ 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 Borofloat™ 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 Borofloat™.
- 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.

Fig. 2: **(left)** ZERODUR K20 mould used for tests. **(right)** Small oven for tests.

Using an oven facility installed at INAF-OAB (see Fig. 2 right) it has been developed a suitable procedure to obtain a good copy capability of the mould shape. Initial tests were performed on a small ZERODUR K20 mould having diameter of 150 mm and a convex spherical shape of about 4000 mm radius of curvature. An *ad hoc* muffle was also developed. It is made of AISI 310 stainless steel with the capability to maintain a vacuum seal at about 650 °C. With these equipments a number of tests were made in order to achieve the best performances in the slumping of thin shells.
A representative test performed during the past development of the slumping technique is shown in the following.
The Fig. 3 shows the optimized thermal cycle used to reduce the thermal gradients inside the muffle. Using it and applying an uniform controlled pressure to the glass, it has been possible to slump a number of glass disks having diameter of 130 mm and thickness of 2 mm. The interferometric measurements of these shells are shown in Fig. 4. On the left side it is valuated the optical quality in 80 mm of the central region, while, on the right side, it is visible the entire surface. The measurements return values of $\lambda/11$ and $\lambda/3$, respectively (where λ = 632.8 nm typical of HeNe laser).

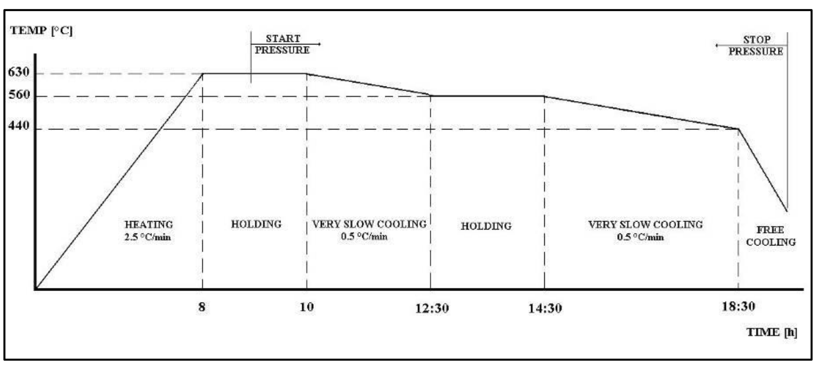

Fig. 3: Optimized thermal cycle used during the tests phase. With this timing it was achieved, so far, the best copy capability.

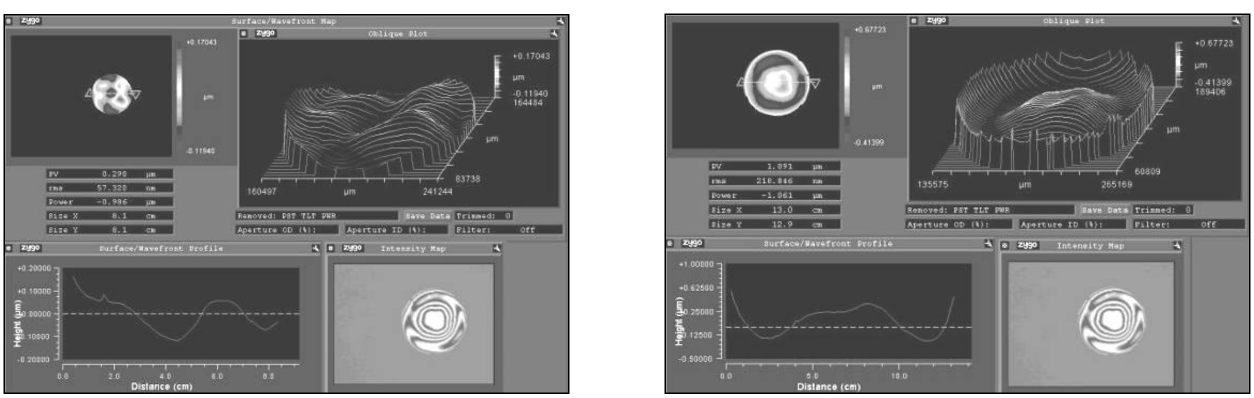

Fig. 4: Surface measurements of a typical slumped segment. **(left)** slumping on 80 mm ($\lambda/11$), **(right)** slumping on 130 mm ($\lambda/3$).

All the slumped shells so far have shown values in terms of optical accuracy very similar to each other, indicating a good repeatability of the process. Moreover, in all the segments till now slumped it is visible a pattern of features that repeat itself with a good accuracy. These features are very likely present on the mould and are simply replicated onto the segment surface. On these dimensions, the 150 mm mould is limiting the performances obtainable with the slumping technique. This is due to the fact that this mould was polished without addressing precisely its spherical shape because it was used only for the preliminary part of the study.

3. PROCESS SCALING-UP AND FIRSTS RESULTS

A new muffle has been designed to accommodate a larger ZERODUR K20 mould that was optically figured by SESO. The muffle can host up to 750 mm diameter moulds. To obtain the vacuum seal at the high temperature needed for the slumping procedure the muffle uses a braid of graphite placed along its perimeter and clamped between its body and cover. In Fig. 5-A and 5-B are shown a picture of the finished muffle and its mechanical drawing. The tubes visible are used to control the vacuum inside the muffle and to inject a stream of Argon gas. The latter flows in a circular cavity external to the braided graphite to protect it from the Oxygen of the atmosphere. In fact, as know, over 440 °C the graphite burns converting into CO_2 in presence of Oxygen.
For what concern the large ZERODUR K20 mould it has a diameter of 700 mm and thickness of 110 mm (see Fig. 5 C). The blank material was purchased from Schott. This mould has a constant thickness for thermal reasons and hence its bottom surface is concave, but not optically figured. The optical figuring of the upper surface was instead performed by SESO. The optical specifications for this mould were taken by an ESO “E-ELT Design Study” technical document[6]. These specs require an overall figure of about 4λ rms and more stringent values at higher spatial frequencies. The characterization of the mould has been performed by SESO using a precise 3D machine for the low spatial frequencies and the control of the radius of curvature. Meanwhile, the high spatial frequencies has been checked by means of a transparent *ad hoc* manufactured concave master having the same radius of curvature. The measured radius of curvature was 4808,29 mm with a figure error of about 5 μm PV. The surface finishing was in the order of 2.5-4.5 nm rms.

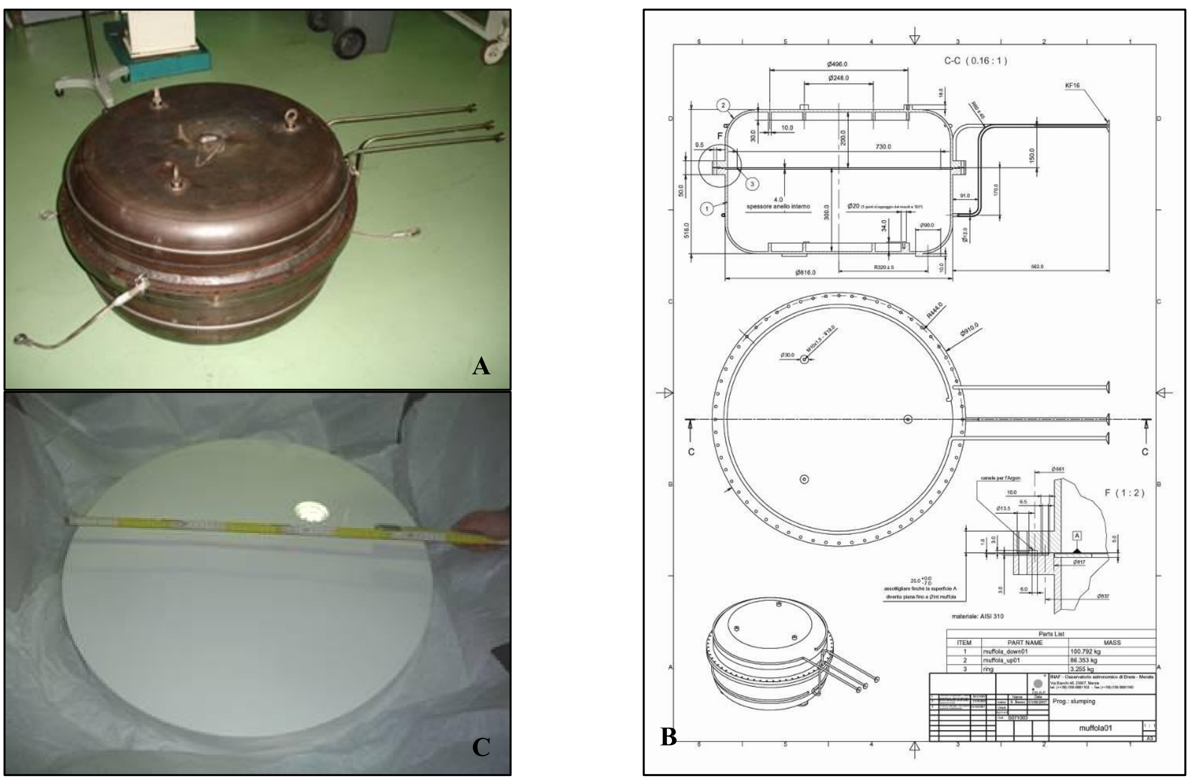

Fig. 5: **(A)** Large muffle used for the full scale slumping. **(B)** Mechanical drawing of the large muffle. **(C)** 700 mm diameter ZERODUR K20 mould figured by SESO.

For the scaling-up it was necessary to install a larger oven with an internal cavity of 1.45 x 1.45 x 0.65 m^3. The oven has five independent heater elements for a total power of about 70 kW and it is possible to have a remote computer control of the thermal cycles. For the handling of the muffle and of the mould a crane was also installed.
An initial test was made to setup a starting thermal cycle and to address the problems related to the new large size of the mould. From the thermal point of view, it is clear that the time necessary to reach the slumping temperature and to cool down the system minimizing the thermal gradients is longer than that of Fig. 3. For the larger oven a complete slumping cycle protracts up to 4 days. Since the K20 is poorly thermally conductive, it is necessary a long time to permits to the mould material to cool evenly. A possible way to speed-up the process could be the use of a mould made in a more thermal conductive material like the Silicon Carbide. Using this material, the total time needed for a complete thermal cycle could be much shorter.
In Fig. 6 (left) it is shown the mould when placed inside the body of the muffle with a tool used to position and remove the glass segment.
The glass disks to be slumped have a diameter of 500 mm and thickness of 1.7 mm. The difference in diameter between mould and glass has been implemented to keep the edge of the glass segment far from the edge of the mould. This is necessary to reduce the thermal gradients since the mould material is not a very good thermal conductor.
The result of the second test is visible in the right side of Fig. 6. The slumped shell is till placed onto the mould and enlighten by a Sodium light to show the shape differences with the mould. This evaluation is qualitative, but it permits very quickly to assess the results of the experiment. As visible in Fig. 6 (right), a pattern of circular fringes is present covering a large part of the surface. In this area, it is possible to count no more than 10 fringes that it translates in a figure deviation from the mould of about 3 μm.

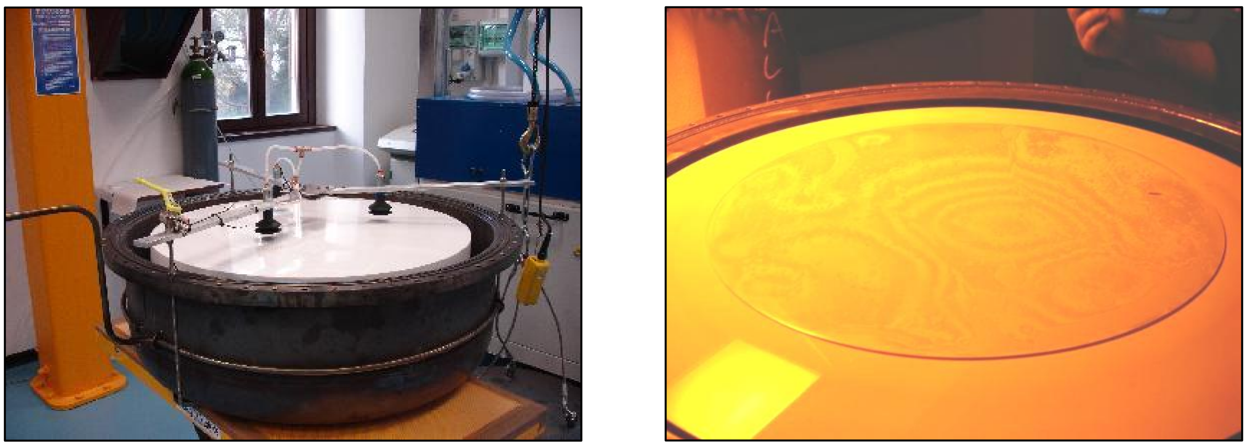

Fig. 6: **(left)** Mould placed inside the muffle during the preparation of a slumping experiment. **(right)** 500 mm diameter slumped shell above the mould after the cooling down and enlighten by a Sodium light.

To anticipate how a perfectly slumped shell looks like at the interferometer it has been done an exercise. The first step consisted in the creation of a synthetic mould surface using the specifications, in terms of spatial frequencies and rms, given by an "E-ELT Design Study" technical document[6]. Of course, the computed simulated surface is one of the many possible surfaces that have that set of specifications. Using this synthetic surface, the data were used to perform a ray tracing with the ZEMAX code. The used configuration matched the real interferometric setup so to understand if a real surface measurement was possible on a true slumped segment.
The results of this exercise are shown in Fig. 7. On the left side is reported the synthetic interferogram resulting from the ray tracing simulation. As visible, the number of fringes is very large, giving a total peak-to-valley of about 90 μm. This density of fringes is very high and behind the sampling capability of an interferometer. This means that, even if the slumped shell would had copied exactly the mould, its measure on the whole surface could be very difficult (if not impossible) using an interferometer. In any case, it could be possible to measure a sub-aperture of the entire shell surface by physically masking a sub-area and aligning properly that zone.
A more reasonable way to test the full aperture optical performances of these slumped shells could be the use of a different setup. For example, it could be possible to measure the PSF of the mirror segment to obtain its the angular resolution. A dedicated setup will be installed in INAF-OAB in order to evaluate this parameter. It is possible to have an

estimation of the expected angular resolution using the previous synthetic data. The ray tracing simulation returns the encircle energy plotted in Fig. 7 right. The 80% of the ray traced gave an angular resolution value of about 1 arcmin.

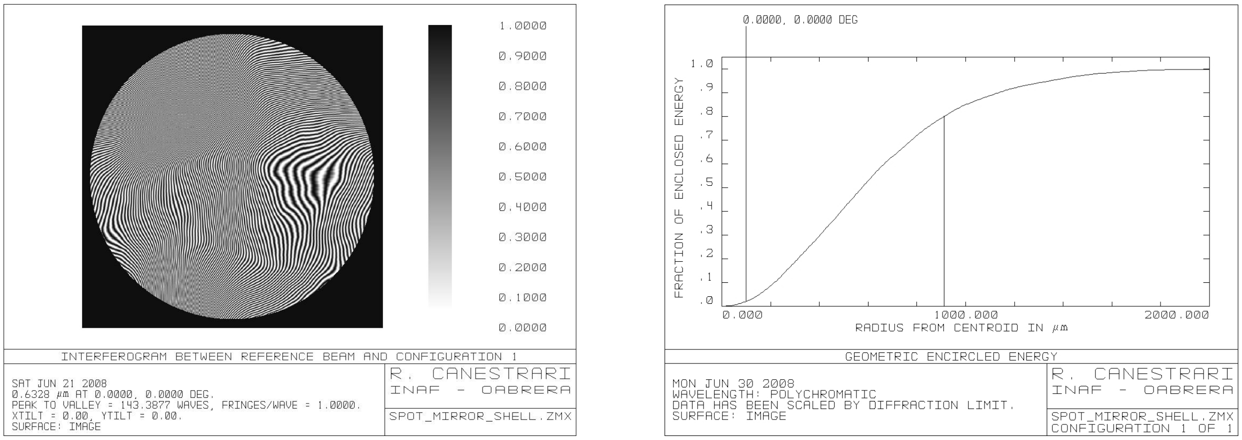

Fig. 7: **(left)** Synthetic interferogram of a mould surface computed following the "E-ELT Design Study" specs. **(right)** Geometrical encircled energy from a ray tracing simulating a slumped shell that copied perfectly the synthetic mould shape.

4. ASTATIC SUPPORT, A NEW CONCEPT

Since the slumped glass shells are quite floppy, it is necessary to foresee the use of an astatic support to measure their real shape. The astatic support has the capability to sustain a floppy optical surface in a near weightless condition.

The standard astatic support make use of an array of points on which the sample is supported. Each point pushes the sample with a pre-calculated force so to counterbalance the gravity force. These kind of supports are quite complex and expensive.

Another way to implement a device able to give a near weightless condition to a floppy segment has been developed and manufactured in INAF-OAB.

This support use an air cushion to sustain the glass sheet weight during the measurements. In Fig. 8 is shown the mechanical drawing of the support developed for the 500 mm diameter shells. The size of the container must be only a fraction of millimeter bigger than the shell to be measured. The gap between the edge of the glass and the walls of the support is filled with a ferrofluid seal that is maintained in a proper position by a magnetic strip. As visible in Fig. 9 (left), four load cells are mounted onto four actuators. These cells provide the fixed points on which the glass touches. When the ferrofluid closes the gap, the air is injected in the bottom cavity until the glass float completely sustained by the air. To adjust the predetermined values that must be read on the load cells it is possible to move up and down the actuators. In this condition the glass weight is supported by the air cushion with a small and known deformation due to the contact points. In this situation the glass shape can be measured.

We foresee to use this astatic support mounted into a vertical optical bench that is under construction in INAF-OAB. On the top of the bench can be accommodated a number of instruments like an interferometer generating a spherical laser beam as well a pinhole light source to illuminate the whole shell area for the measurement of the PSF.

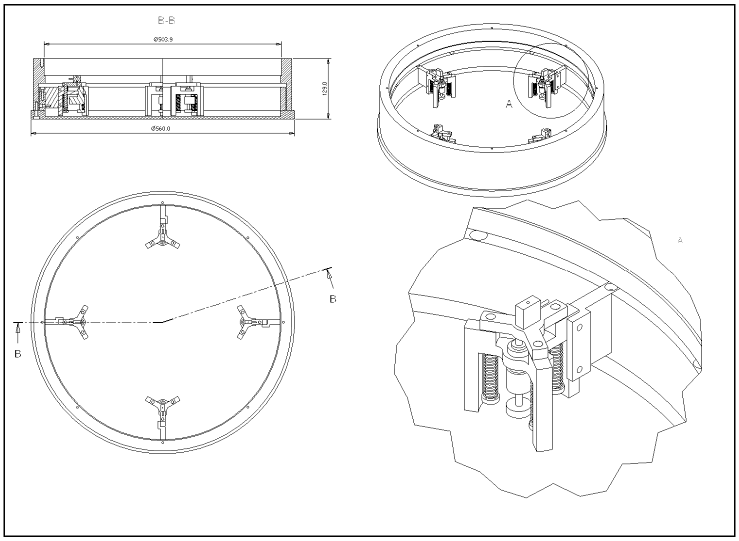

Fig. 8 Mechanical drawing of the astatic support developed by INAF-OAB

Fig. 9 **(left)** Overall view of the astatic support produced for the measurement of the 500 mm slumped shells. **(right)** Close view of the actuator supporting the load cell.

5. CONCLUSIONS

The slumping technique developed so far has the potential to reach a very high shape accuracy on the slumped segments depending on the mould accuracy. The Borofloat^{TM} glass is directly put in contact with the mould surface because the ZERODUR K20 doesn't stick to it up to 660°C. This allow us to avoid an antisticking layer. To ensure a full contact between glass and mould we make use of a uniform controlled pressure.

In the last months, a larger muffle and mould were realized. Also a dedicated oven and lab have been implemented. We have started the study of the scale-up process for the manufacturing of 500 mm diameter slumped segments. The results till here obtained in this investigation have given us confidence that it is possible to reach good copy capability of the mould. It is foreseen to continue this study to better optimize the scaled-up process and to solve a number of open issues like the optical testing. The last segment slumped has shown a shape difference from the mould of 3 μm. It is also visible that the fringes are not fully circular and in particular the edge is not completely in contact. This means that the overall process should be refined changing some parameters like time, maximum temperature and amount of pressure.

To fully understand the limits of this technique we want to perform a number of slumping tests using different small size moulds to find the maximum bending of the glass that can be obtained, maintaining a good optical shape.

We plan also to enlarge our experience on the hot slumping technique with the use of others moulds made in different materials.

Concerning the optical tests, we have found that using our 700 mm mould the interferometric measure of a slumped shell could be very difficult. For this reason we are implementing a vertical 5 meters long optical bench to perform a focal spot measurement of the angular resolution.
We have also developed a new concept of astatic support that use an air cushion to avoid bending of the shell due to its own weight. This device is quite cheaper respects to a standard astatic support.

REFERENCES

[1] A. Riccardi, G. Brusa, et al., "Adaptive secondary mirrors for the Large Binocular Telescope", Proc. SPIE 4839, 2003

[2] F. Wildi, G. Brusa, et al., "Towards first light of the 6.5m MMT adaptive optics system with deformable secondary", Proc. SPIE 4839, 2003

[3] M. Ghigo, S. Basso, O. Citterio, F. Mazzoleni, D. Vernani, "Manufacturing of lightweight glass segments for adaptive optics", Proc. SPIE 6272, 2006

[4] M. Ghigo, R. Canestrari, S. Basso, D. Spiga, "Development of lightweight optical segments for adaptive optics", Proc. SPIE 6691, 2007

[5] T. Doring, R. Jedamzik, et al., "Forming mandrels for X-ray telescopes made of modified Zerodur", 2004, Proc. SPIE v.5168, p. 148

[6] ELT-SPE-ESO-09300-0002

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