Novel direct slumping glass technology for making the XEUS mirror optics

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Progetti
s.r.l.

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Summary of the presentation

Why use of the Direct Slumping

- Direct slumping concept
- Our approach for XEUS:
  - Hot press slumping and shaping of very thin glass shells
  - The problem of the integration. The proposed approach

Technological Tradeoff and ongoing developments of a two year study for ESO concerning the slumping

Future work for XEUS
Direct Slumping Concept

With “Direct Slumping” of glass segments we intend a replication process from a convex mould, in which the glass optical surface and the mould are directly in contact.

Initially the thin glass sheet is conformed to the desired shape by means of a suitable thermal cycle and application of a uniform pressure. Afterwards the conformed segment is integrated in the petal by means of an handling vacuum chuck.

In the case of XEUS it is crucial the use of an integration process using a robotic system with a 3D positioning feedback.
Process description for making a petal (I)

- Glass segment coating with antisticking/reflecting layer like Platinum

- Hot Press Direct Slumping of the segment onto a superpolished mould using a suitable thermal cycle and pressure

- Characterization and compliance acceptance of the slumped segment, mounted in an astatic support, by means of an optical profilometer
**Process description for making a petal (II)**

- Mounting of the segment onto a handling porous graphite mandrel with vacuum suction

- Gluing of reinforcing ribs onto the back of the segment to conform to the required vibration specifications

- Robotic positioning of the slumped segment in the petal starting from the outer ring. Use of a 3D measuring machine for the fine alignment of the segment

- Gluing of the segment onto the previous one (the first segment will be glued onto a backplane)

- Gluing of the external walls of the petal
With the **Hot Press Direct Slumping** approach the optical surface of the glass is placed in contact with the mould surface so to copy its shape and partially its microroughness. Hence the mould surface must have a very low microroughness, comparable to that of the finished x-ray segment. Thickness variations of the glass are not an issue with the Hot Press Direct Slumping.
Integration of the slumped segments into the petal

The reference points are used for segment alignment with a 3D machine.

Porous graphite handling tool with suction capability.
Hot press development: present status

Study on thin glass sheets for the adaptive optics of the ESO-Extremely Large Telescope

NB: this study has been financed under the OPTICON FP6 program for E-ELT adaptive optics
INAF-OAB Hot Press Direct Slumping

This is an ongoing study. Goal: to produce a 50 cm concave spherical mirror, 1.6 mm thick, for adaptive optics, having a radius of curvature of 5 m.

Small oven used for initial tests. Large oven used to produce the full size mirror.

In this larger oven it is possible to slump optics up to 1.1 meter in diameter, fully compatible with the XEUS segments. Slumping of thinner glass sheets is easier. Glass sheets as thin as 150 microns are commercially available in large sizes for LCD.
Mould materials investigation

The materials considered for the mould were the following:

- Alumina
- Silicon Carbide
- Technical Quartz
- Zerodur K20

A quantitative analysis was performed to compare their thermo-mechanical parameters.

Informations were acquired to establish with vendors other relevant manufacturing informations

All the informations were integrated in a merit function to find the best trade-off material for the study
# Properties of possible mould materials

<table>
<thead>
<tr>
<th>Property</th>
<th>HP Alumina</th>
<th>HP SiC</th>
<th>Quartz Technical</th>
<th>Zerodur K20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>90</td>
<td>476</td>
<td>72</td>
<td>83</td>
</tr>
<tr>
<td>Knoop Hardness (HK 0.1/20)</td>
<td>1900</td>
<td>3000</td>
<td>580</td>
<td>620</td>
</tr>
<tr>
<td>CTE (RT to 1000°C) (1/K x 10^-6)</td>
<td>8.2</td>
<td>4.0</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>CTE homogeneity</td>
<td>Good but quantitative data not available</td>
<td>Good (\Delta=0.01*10^{-6}\text{K}^{-1})</td>
<td>Probably not very good</td>
<td>Very good (\Delta=0.004*10^{-6}\text{K}^{-1})</td>
</tr>
<tr>
<td>Thermal Conduct. (W/mK)</td>
<td>24</td>
<td>102</td>
<td>1.31</td>
<td>1.60</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>2.85</td>
<td>3.21</td>
<td>2.21</td>
<td>2.53</td>
</tr>
<tr>
<td>Glass adhesion (from tests performed)</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Transparency</td>
<td>NO-White</td>
<td>NO-Black</td>
<td>YES</td>
<td>NO-White</td>
</tr>
<tr>
<td>Voids, inclusions</td>
<td>NO</td>
<td>NO</td>
<td>Possible</td>
<td>NO</td>
</tr>
<tr>
<td>High temperature stability (cycles)</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Max application temperature °C</td>
<td>1900</td>
<td>1450</td>
<td>1200</td>
<td>850</td>
</tr>
</tbody>
</table>
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</tr>
</thead>
<tbody>
<tr>
<td>Machinability</td>
<td>In green body</td>
<td>In green body</td>
<td>Very good</td>
<td>Good</td>
</tr>
<tr>
<td>Polishability and figuring</td>
<td>Slow</td>
<td>Very slow</td>
<td>Fast</td>
<td>Slower than quartz</td>
</tr>
<tr>
<td>Microroughness</td>
<td>10-20 A</td>
<td>&lt; 5 A</td>
<td>&lt; 5 A</td>
<td>&lt;10 A</td>
</tr>
<tr>
<td>Mould characterization</td>
<td>3D machine + Patch map</td>
<td>3D machine + Patch map</td>
<td>Interferometer surface map</td>
<td>3D machine + Patch map</td>
</tr>
<tr>
<td>Material availability</td>
<td>Many producers</td>
<td>Many producers</td>
<td>Many producers</td>
<td>Only Schott</td>
</tr>
<tr>
<td>Scalability to 1.5 m</td>
<td>Sectors brazing</td>
<td>Sectors brazing</td>
<td>Possible but difficult</td>
<td>Several meters pieces</td>
</tr>
<tr>
<td>Mould Cost (Ø 0.7m)</td>
<td>~ 60 K€</td>
<td>~ 90 K€</td>
<td>~ 60 K€</td>
<td>~ 70 K€</td>
</tr>
</tbody>
</table>

A good trade-off material for the mould of the ESO study was identified in the Zerodur K20.

**For the hot slumping applied to XEUS segments** it will be preferable to change the mould material and use the SiC (we will see later the reasons). The thermomechanical and surface finishing properties of the SiC are very good, better than those of the K20.
Slumping tests on Borofloat33™ glass sheets with K20 mould

The use of a vacuum muffle with the capability to apply on the glass a uniform controlled pressure (~150 g/cm²) provided the best results.

The muffle protects the glass from the dust of the oven and the vacuum avoids convection. The metal walls spread evenly the heat.

No dust specks
Circular fringes very sharp up to the edge of the glass

Fringes between mould and glass

Slumping (λ/11 on 80 mm 50 nm rms) limited by the mould accuracy
Results of slumping tests on small diameters
Borofloat33™ glass sheets

In all the small segments slumped it is visible a pattern of features that repeat itself with a good approximation indicating that the opposite of this pattern is very likely also present on the small mould used for these tests.

The process is able to deliver a good copy capability and the results till here obtained are limited from the quality of the mould optical surface and not from the slumped segments, that limit themselves to copy its surface.

57 nm rms $\rightarrow \lambda/11$ rms over 80 mm diam.
The results obtained with the slumping of small borofloat disks have been obtained with the following thermal cycle, employing a vacuum muffle with the capability to apply on the glass a uniform controlled pressure (~150 g/cm²).

With K20 the thermal cycle foreseen for the slumping of a 500 mm diameter segment is of about 4 days. With a thinner glass (150 microns) and SiC mould this time can be reduced at least of a factor of 2.
Large muffle for slumping of 500 mm Borofloat33™ glass sheets

Stainless steel AISI 310  
Weight=190 Kg

External Diam=816 mm  
Height =516 mm

Vacuum seal at about 650 °C
K20 mould (700 mm diam.) under figuring and test

Low spatial frequencies characterization in SESO

K20 Mould in INAF
In February we have started to use the 700 mm diameter mould to slump a full size segment and to tune the parameters of the scaled-up slumping procedure. The initial results are very encouraging.
Ongoing experience

Last tests performed and dedicated to the XEUS issue
Why the SiC for the moulds of XEUS

| MOULD MATERIALS |
|------------------|-----------------|-----------------|-----------------|-----------------|
| Property         | HP Alumina      | HP SiC          | Quartz Technical| Zerodur K20     |
| CTE (RT to 1000°C) | 8.2             | 4.0             | 0.5             | 2.0             |
| (1/K x 10⁻⁶)      |                 |                 |                 |                 |
| Thermal Conduct. (W/mK) | 24              | 102             | 1.31            | 1.60            |
| Microroughness   | 10-20 A         | < 5 A *         | < 5 A           | <10 A           |
| Glass adhesion (from tests performed) | YES             | YES             | YES             | NO              |

* with SiC-CVD coating
The glass above the SiC moulds stick to the material. For this test was used Borofloat33 glass. The CTE of the Borofloat (3.3) and of the SiC (4.0) are quite similar and the forces acting on the glass are insufficient to broke it.

Anyway, it was impossible to detach the two pieces. In the left picture is visible an air bubble surrounded by the area of sticking. In the right picture is visible a second stucked sample.
SiC-Glass antisticking test with a layer (40nm) of Pt on glass

Square glass above a SiC mould after a thermal cycle up to 630 °C.

The glass was in very high contact with the mould surface and was separated only using a burst of compressed air.

After the separation of the two components the Pt layer was still stuck on the glass. It acts like:

- A release agent for mould separation
- X-ray reflecting coating (like gold for the electroforming replica process)
- The thermal cycle enhance the Pt adhesion on the glass
The SiC mould microroughness was copied very well from the Pt coated glass.
Hence its microroughness will need to be of the order of 5 Å or less
Proposal of future work for XEUS
Development scheme for Demonstrative Petal manufacturing (over two years)

- Optical system design for the demonstrative petal
- Manufacturing of the moulds and chuck pieces (3+3 pieces)
- Definition of the Integration procedure
- Segments manufacturing with hot slumping and metrology
- Construction of the integration system with 3D feedback
- Integration in the demonstrative petal of the segment
- X-ray tests in Panter facility

Products and deliverables:

Petal prototype with 3 representative mirror shells (30x15 cm - 150 micron thick - F.L=10 m (to be tested at Panter). Dummy shells: 30 (tbc)
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Final remarks....

“Mirror, mirror on the wall, Who is the lightest of them all?”

“The lighter ones, though light I be, are the slumped ones of OAB !”