# THE ALT-AZ INITIATIVE

## TELESCOPE, MIRROR, & INSTRUMENT DEVELOPMENTS

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## Chapter 22

# Replica Processes for Mirror Manufacturing

## Glass Slumping and Foamglas Backing

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### Introduction

During the last decade in the field of professional astronomy, the need grew to have larger optical telescopes, surpassing the present day 10 meter class telescopes (i.e. KECK I and II, VLT, Subaru, GranTeCan). An initial study to consider these large telescopes was accomplished by ESO (European Southern Observatory) with a project called OWL (Over-Whelming Large telescope): a 100 meter class primary mirror telescope. This sort of telescope is well beyond the technological capabilities that are now in the market or even the new ones under development. This project would require so much effort and development time as not to be affordable, if not impossible, today. Nevertheless, this study was an inspiration in both the U.S. and Europe. Consortia of research institutes began feasibility studies to address the problems related to telescopes with 20 to 40 meters of aperture. This new class of ground-based optical telescopes now under investigation is called ELT (Extremely Large Telescopes). There are three major telescopes that may be in operation around 2016-18: TMT (Thirty Meter Telescope), GMT (Giant Magellan Telescope), and E-ELT (European-Extremely Large Telescope).

Increasing telescope aperture permits astronomers to collect photons coming from the faintest sources located at the edges of the universe, to reduce the time needed for imaging, photometry, and spectroscopy, to improve knowledge in cosmology, and to study the early moments of the universe's birth just after the Big Bang. Another very interesting and challenging research topic that could be carried out with such telescopes will be the search for Earth-like exoplanets.

From the technological point of view, these ELTs are a considerable challenge from many aspects. Let's take the example of E-ELT and let us focus on the optics, in particular the primary and the secondary mirrors.

The primary mirror will have a diameter of 42 meters, about half a soccer field! It will be manufactured in many mirror segments that will be mounted and aligned together with an 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 gravitational force. Each segment will be of hexagonal shape, about 1.3 meters face-to-face: this implies a total number of segments of about one thousand! To produce such a large number of mirror segments, it will be mandatory to develop and use a technology that will be able to provide many mirrors with high optical quality that are lightweight in a short delivery schedule. All these requirements are in conflict with each other. The traditional optical manufacturing processes simply will not suffice. An attractive alternative is offered by processes that accurately replicate the shape of a master mold. In this way it is possible to reach a high production rate of identical mirror segments from each mold. Thus, with a limited number of optically figured molds, it is possible to achieve mass production of mirror segments.

The secondary mirror of E-ELT is also a sizable challenge. In the initial design of the telescope it was a 4 to 5 meter diameter mirror 2 mm thick having a fully integrated adaptive support. Flexures are induced by a matrix of actuators placed on the backface of the mirror that deforms its shape to compensate for the aberration introduced by atmospheric turbulence. The use of adaptive optics is fundamental to producing top level science with the present generation of telescopes, and it will be mandatory to realize the best performance of the ELTs.

This chapter will discuss an innovative technology based on a glass slumping process. The study was aimed at the secondary adaptive mirror for E-ELT, but with fascinating possibilities to translate it into the production of lightweight, stiff, and low cost primary mirrors for modest-aperture telescopes.

## The Hot Press Direct Slumping Approach

Currently, adaptive optics are systems added to telescopes as an upgrade to the original instrument. This implies one more reflection surface in the optical path; more reflections mean less efficiency of the overall instrument. A key breakthrough in this field is the Large Binocular Telescope (LBT), where both secondary mirrors of the two twin 8.4 meter telescopes will be fully adaptive from the very beginning. The secondary mirrors are two meniscuses 0.9 meters in diameter, each with [illegible] electromechanical actuators placed on their backface. Both mirrors are floppy enough to accept deformations; their thickness is only 1.6 mm.

The LBT mirrors were produced starting from a blank disk of material a few centimeters thick (Figure 1). Both surfaces of the blank disk were machined: the one that was the backface needed a surface precision

the meniscus was created from a thicker disk and the initial thickness was reduced to the desired one. These tasks took a long time to complete and they introduced a severe risk of breaking the mirror during the thinning phase. The costs for the production of such a mirror are very high, on the order of some hundreds of thousands of US dollars! It is clear this technology cannot be used in projects like the ELTs that are composed of many mirror segments, both for cost and production-time reasons.

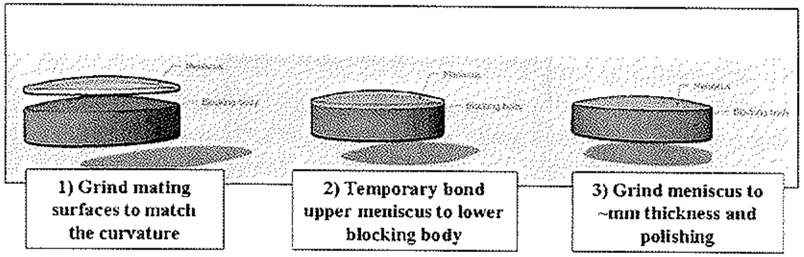


Figure 1: Conventional manufacturing technique for thin mirrors.

### *The slumping process*

A process able to deliver a thin mirror starting from a blank disk with the desired thickness (on the order of 1 to 2 mm) and based on the concept of a replicated master mold is a very attractive possibility to strongly reduce costs, production time, and the risk of catastrophic mirror damage. With these aims, a research team located in Milan, Italy, proposed and initiated a feasibility study based on the concept of glass hot slumping (Ghigo 2006). A thin, flat glass sheet is placed above a master mold previously optically figured and polished to the desired shape; then a suitable thermal cycle is applied. When sufficiently heated, the glass will soften enough to slump onto the mold surface and adapt to the mold's shape (Figure 2). When the system is cooled to room temperature, the slumped glass shell is released from the mold and coated with the proper reflecting layer.

Let's go into more detail. A mold having the complementary optical shape and the same surface micro-roughness quality desired for the optical segment is manufactured from a suitable material. In a clean-room environment, both mold and glass sheet are thoroughly cleaned of any residual grease from handling and dust; then they are placed into a muffle with the glass above the mold. The glass' surface touching the mold becomes the optical surface of the mirror.

The muffle is a stainless steel box designed to maintain a vacuum seal at high temperature. The air is removed, making use of mechanical vacuum pumps. The use of this muffle helps the process in many is essential to avoid creating stresses in the glass shell. Also, the muffle protects the mold and the glass from the dusty environment of the oven. In fact, dust particles can be named as one of the possible show stoppers for this technology: a dust grain trapped between the mold and glass surfaces during the slumping process prevents a correct copy of the mold's shape in an area of some square centimeters.

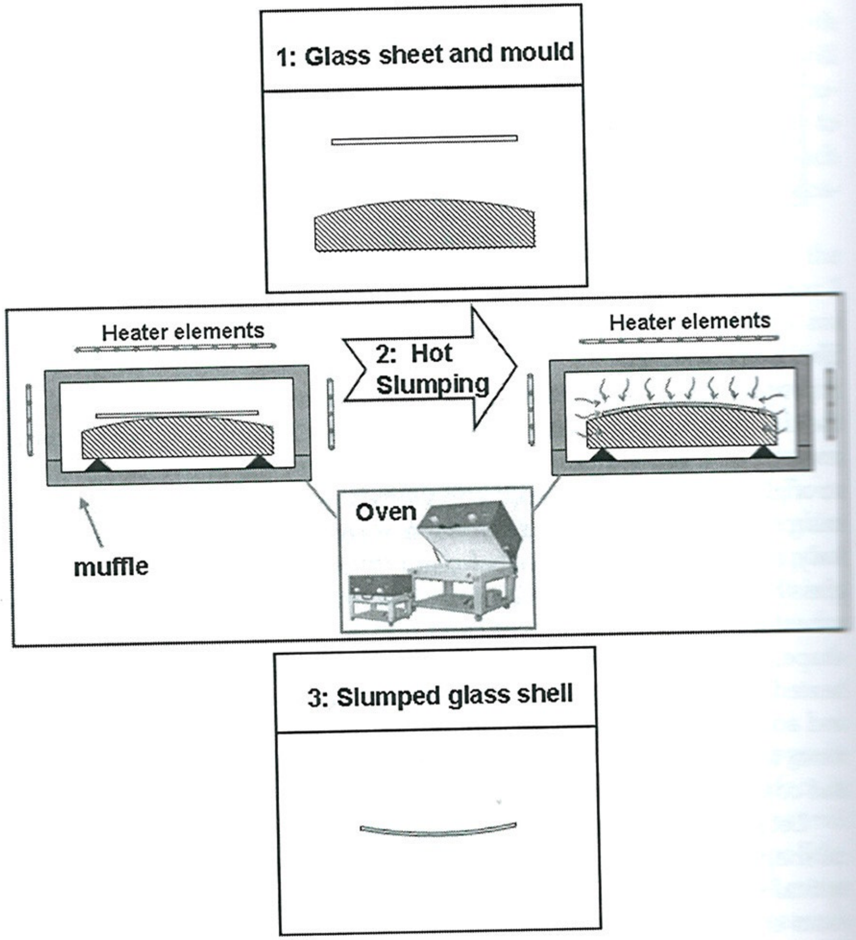


Figure 2: The hot glass slumping process studied in Italy.

The muffle is then placed inside the oven and a suitable thermal cycle is applied. The maximum temperature reached during the process is about 650° C. The speed in heating and cooling of the overall system is not simply limited by the power input to the oven used, but must

glass. The presence of 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, $T_g$. This kind of error is typically in the low spatial frequencies range affecting the optical figure of the slumped glass shell.

Bending a surface from a flat geometry to a spherical one is quite a complex task and it requires a long time if the slumping is assisted simply by gravity (it is the same for parabolic and hyperbolic shapes). To ensure the full (optical) contact of the glass against the mold, a pressure is applied during the slumping process when it reaches the maximum temperature. It forces the glass against the mold, helping both to bend the initially flat glass sheet and to speed up the procedure. This gives the process the capability to copy the overall geometry and part of the surface micro-roughness of the mold. For this last reason it is important to have a mold with a micro-roughness level consistent with a surface for optical application, otherwise the mirror will mostly scatter the light instead of reflecting it.

At the end of the thermal cycle, the thin glass shell will ideally have the same shape and micro-roughness of the mold. Its optical quality can be measured with an interferometer. Due to the floppy nature of the slumped shell (the thickness is only a few mm), it is necessary to use an astatic support to measure its shape. This device is able to support the shell, simulating a weightless condition in order to remove the gravity induced deformations.

*Some related problems*

One critical aspect is defining the best material for the mold and the glass type for the segments. To this end, it is useful to compare the theoretical thermo-mechanical parameters of suitable materials for the mold and, in parallel, to gain experience regarding the problems related to the slumping of different types of glass onto different types of molds (i.e. using test samples). The critical parameters we have identified can be summarized and grouped as follows in Table 1:

Table 1: Parameters for mold material and glass type.

| Mechanical | Physical | Structural | Fabrication | General |
|---|---|---|---|---|
| Young's modulus | CTE and CTE homogeneity | Voids, inclusions | Machinability | Availability |
| Hardness | Thermal conductivity | Max appl. temp. | Polishability | Scalability |
| | Density | High temp. stability | Optical microroughness | Costs |
| | Glass adhesion | | Mould charact. | |
| | Transparency | | | |

A consideration that must be kept in mind is that the choice of a mold material cannot be considered only in terms of thermo-mechanical material properties. Both the slumping process under development and the final application for which the technology is addressed could in principle affect or be affected by the mold and/or glass properties. Indeed, it must also be considered part of the selection. For example, if the sample for the study is a mirror segment of X size with a requirement on the scalability up to 10X, the choice of the mold must take into account the possibility for larger dimensions.

The selection of the type of glass is close to some of the characteristics of the mold itself. For example, finding a good match in CTE between glass and mold helps reach the desired shape on the final glass segment; the temperature necessary to slump the glass must be in the range of application of the mold; the chemical composition of the glass results in different behavior in glass-mold adhesion.

The thermo-mechanical properties of the glass itself are also important. In particular they are related to the final application of the slumped segments. For example, the actuators for the adaptive support heat the segments during the operation, hence the glass shells must be able to dissipate the heat with sufficient efficiency. Different glass types are produced/sold in different size ranges (depending on the technology used and the market they are addressed to), so the linear dimensions and the thickness of the glass sheets must be compatible with the application and possible scaling-up.

To choose the best material for the mold and the glass type, all these considerations must be properly weighted in a merit function to reach an acceptable trade-off between the many input parameters in the effort. The materials tested for the mold were Alumina, Silicon Carbide, Technical Quartz, and ZERODUR K20. A detailed analysis of the materials investigated has been presented Ghigo, 2007. The choice for the mold was the ZERODUR K20 material, while Borofloat was chosen for the glass. Both materials are produced by Schott.

Another crucial point is the heating and cooling rates for the 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. The graph in Figure 3 shows an example of an optimized thermal cycle. However it differs, it always includes ramps and plateaus. The exact timing is strongly dependent on the type and size of the material used as well as the oven. In general, the heating can be relatively fast up to the required slumping temperature; then a holding time ensures that no temperature gradients are present and the glass has time to slump against the mold. The cooling down is slower

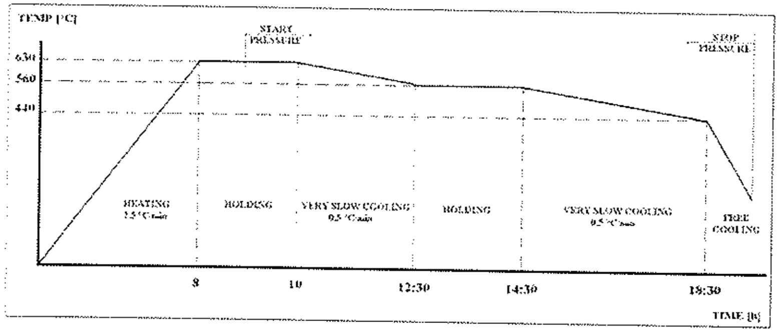
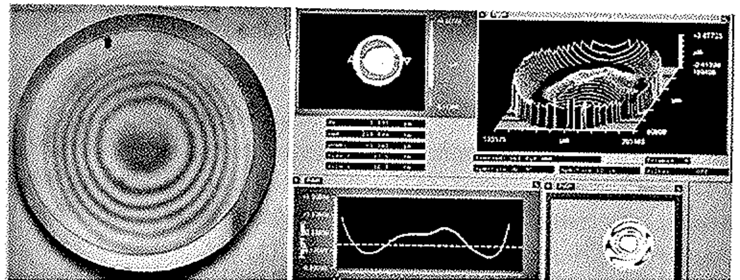


Figure 3: Optimized thermal cycle for slumping process.

*State-of-the-art*

Initial tests were performed on a small mold with a diameter of 150 mm and a convex spherical shape of about 4 meters radius of curvature. A number of glass disks having a thickness of 2 mm were slumped.

A representative measure of these shells is shown in Figure 4. On the left side, the shell is still in place on the mold just after the cooling down of the oven and is illuminated with sodium light. The periodicity in light and dark coronas is the interference fringes between glass and mold due to their shape difference. This evaluation is qualitative, but it permits us very quickly to assess the results of the experiment. The fringes are well rounded, smooth, and centered, meaning a good copy of the mold. There is some shape difference due to thermal effects (CTE variation from room to slumping temperature). On the right side, an interferometric measure of the entire surface is visible. The values range from $\lambda/11$ to $\lambda/3$ (where $\lambda = 632.8$ nm typical of the HeNe laser). The slumped shells so far have shown values of optical accuracy very similar to each other. This indicates a good repeatability for the process. Moreover, the surface features' pattern visible in the measures is present in all the segments slumped so far. These features are very likely present on the mold and are simply replicated onto the segment surface; on these tests the mold shape is limiting the performances obtainable with the slumping technique (Ghigo 2007).



Recently, a scaled-up process has been performed to slump glass mirror shells with more representative dimensions. The larger ZERODUR K20 mold with a diameter of 700 mm and thickness of [illegible] mm was used. The radius of curvature was about 10 meters, while the surface finish was on the order of 2.5-4.5 nm rms. This mold 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 require an overall figure of about 4λ rms, but more stringent values at higher spatial frequencies. The slumped glass disks have a diameter of 500 mm and a thickness of 1.7 mm.

From the thermal point of view, the time to reach the slumping temperature and to cool down the system minimizing the thermal gradients is longer than those shown in Figure 3. A complete slumping cycle takes up to four days (Canestrari 2008a).

In Figure 5, the small circular and concentric paths of fringes are due to dust grains or particles that prevent the glass from having full contact with the mold. Only a few number of dust grains can be counted on the whole surface, thanks to the cleaning tools and the meticulous procedure used. On the right side is the measurement of the shell: only the central part of the glass has a shape close enough to a sphere to be interferometrically measurable. This central part is about 22 mm wide (half diameter). It shows an error deviation from a mathematical sphere of about λ/2.

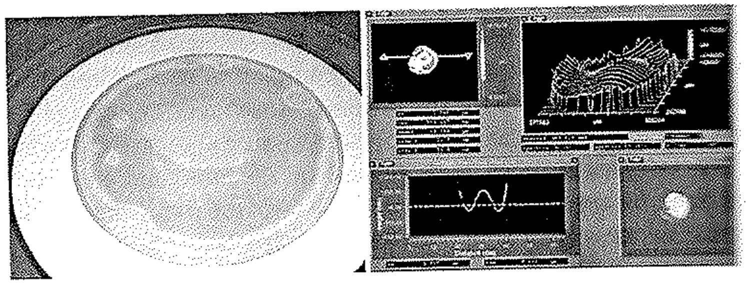


Figure 5: More representative (larger) slumped shell and measurements.

## The Foamglas backing

*The experience gained from telescopes for Cherenkov light*

INAF-Osservatorio Astronomico di Brera, in collaboration with Media Lario Technology, has developed a new technique for the production of mirrors that specifically addresses the production of segmented [illegible] mirrors for the Cherenkov telescopes (Figure 6). It is based on the [illegible]

a thin sheet of glass (1 to 2 mm thick). This concept works in the regime in which the glass is elastic and it accepts small deformations without introducing distortions of higher orders. At room temperature, by means of a vacuum suction, the initially flat glass sheet is bent and forced into contact with the mold. A honeycomb structure is then bonded with glue to the back face of the glass and sandwiched using another glass sheet on top of it. At the end of these steps, we have a good replica of the master mold in a stiff and lightweight mirror panel ready to be coated with a suitable reflecting film. The implementation of a symmetric sandwich-like structure helps achieve the desired stiffness of the panel and improves the thermal behavior of the mirror segments. This approach is very attractive since mass production with short manufacturing times is possible (e.g. one mirror per day per master mold), maintaining very low costs and weights, but with only modest angular resolution (Pareschi 2008, Vernani 2008). Cost for a 1 square meter mirror is about 2 to 3 thousand Euros; weight for a 1 square meter is about 10 kg.

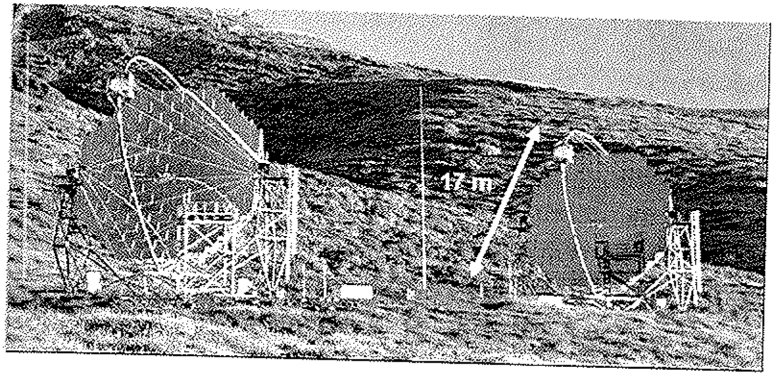


Figure 6: The MAGIC Cherenkov telescopes sited at the Canary Islands

*Stiffening a floppy glass slumped shell*

To permanently freeze the shape of a curved slumped glass, it is forced into full contact with a mold through air suction; then a suitable foamed substrate is bonded with glue to the mirror shell, forming a sandwich-like structure. One side of the foam substrate must be machined in advance to accept the curvature of the slumped glass segment. This also maintains as constant as possible the thickness of the glue (Figure 7) (Canestrari [illegible]b). The foams typically show good performance in stiffness and weight when compared with bulk materials of the same density.

Attention must be paid to the choice of the foam and glue. In particular, it is important to minimize the CTE mismatch between the foam gradients. For the glue, a very low-percentage shrinkage is mandatory to minimize local stresses during the curing phase.

With these steps, the optical shape of the shell is frozen and the final mirror panel has a low weight while maintaining the good optical quality obtained from the slumping process. In addition, with this approach the cost of a finished segment can be quite low and the production rate can be fast.

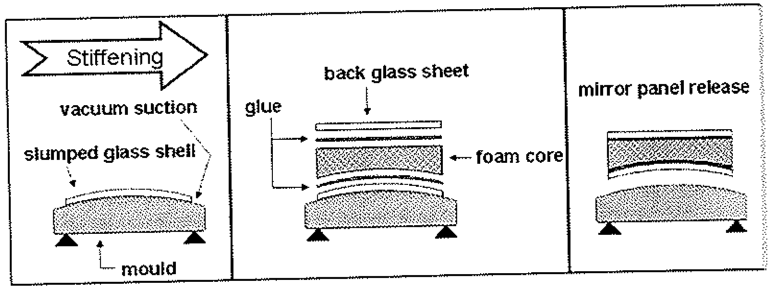


Figure 7: Bonding to maintain shape of slumped shell.

*Preliminary results of the investigation*
The substrate used for this development was Foamglas from Pittsburgh Corning. The CTE of this foam is different from that of the glass [illegible] Corning. To minimize the effect of the CTEs mismatch, the curing of the glue and the interferometric measurement were made at the same temperature. The use of foam with a better match in CTE (with respect to the glass shell) is a step that will be implemented in future development. The glue used is a two-component epoxy product that has very low percentage shrinkage, on the order of .037%, and the same quantity of epoxy was used in both of the foam substrate faces. We also tested for the capability of the foam to withstand a vacuum without breaking. This permits the panels to be vacuum coated.

The left side of Figure 8 shows the stack during the curing of the glue. Visible is the mold with the slumped glass kept in full [illegible] by vacuum suction. The foam substrate, with a thickness of 40 [illegible] placed above the slumped glass with the glue in between. At [illegible] of the stack is visible a weight used to spread the glue over the [illegible] surface. The right side of Figure 8 is a picture of the final mirror panel after the aluminization of the optical surface.

After curing, the mirror panel was measured interferometrically. Figure 8 (bottom) shows the results. Compared with the measurements of a standard slumped shell (Figure 4), it might be noted that [illegible] all surface shows essentially the same optical quality of about [illegible]

confirms that the implementation of the sandwich structure does not appreciably degrade the overall optical quality (Canestrari 2008b).

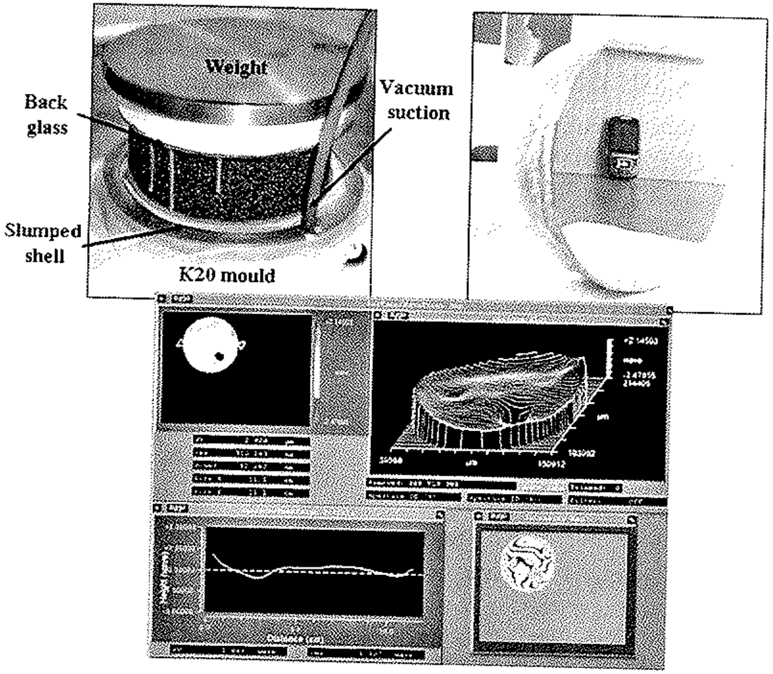


Figure 8: A mirror panel formed through slumping and stiffening, with measures.

## Author's Note

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