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Abstract. We present a method for the production of segmented optics. It is a process developed at INAF-Osservatorio Astronomico di Brera (INAF-OAB) employing commercial of-the-shelf materials. It is based on the shaping of thin glass foils by means of forced bending that occurs at room temperature [cold-shaping (CS)]. The glass is then assembled into a sandwich structure for retaining the imposed shape. The principal mechanical features of the mirrors are their low weight, rigidity and environmental robustness. The cost and production time also are competitive. We sum up the results achieved during research and development performed in the past years. We have investigated the theoretical limits of the structural components by means of parametric finite elements analyses; we also discuss the effects caused by the most common structural loads. Finally, the process implementation, the more significant validation tests and the mass production at the industry are described. [DOI: 10.1117/1.OE.52.5.051204]

Subject terms: segmented optics; glass slumping; glass, technology; optical fabrication; mirrors; astronomy.

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1 Introduction

Segmented optics are being used more often in astronomy because of their capability of coupling low-cost and low-weight together when compared with the monolithic mirror solution. Many different telescopes are already implementing these kind of optics, both ground- and space-based ones. They are either submillimeter radio antennas like ALMA, or optical telescopes like the Keck, GranTeCan, or the forthcoming E-ELT; both the infrared eye of the JWST satellite or the recently launched NuSTAR x-ray telescope mount segmented mirrors.

Despite the variety of the scientific topics addressed, the wavelengths of light observed and the technology adopted, there is a commonality between all of these (and possibly other) projects. Segmented optics typically require a manufacturing process with the capability to deliver tens or hundreds or even thousands of pieces in a well-defined time, cost, and requirement frame. Furthermore, each mirror, in general, is not a unique piece of high precision optic like in the past, but rather one in a series of identical pieces.

There is an additional class of telescopes, new in astronomy, that brings segmented optics into the domain of the extremely low-cost and low-weight, but with the discount of a moderate angular resolution requirement. They are called imaging air Cherenkov telescopes (IACTs).

These are instruments for studying astronomical sources that emit very high energy gamma rays. They operate from the ground using Earth's atmosphere as a calorimeter; energetic photons (γ) or charged particles (hadrons) coming from the most distant parts of the universe hit the atmosphere and interact with it. They lose energy by producing pairs that run faster than light (in air) and emit a bluish light by the Cherenkov effect. This propagates into the atmosphere, generating a so-called shower, whose light pool covers an area on the ground enclosed by a circle about 120 m in radius. The electromagnetic showers generated by γ are very faint relative to the night-sky background; they are also rare and last for only a few nanoseconds. This light can be detected by very large light collectors (of the order of hundreds of m^2) equipped with proper focal plane instrumentation and fast gigahertz electronics. From these images, both the incoming direction and the energy of the primary photons can be recovered. If many telescopes are used and more than one detects the same event, the angular resolution of the reconstructed incoming direction is improved. Such observations make it possible to understand the physics behind the extremely powerful acceleration mechanisms at work in the astronomical sources emitting the primary gamma photons, and to gather clues to the origin of the universe.

To better exploit this detection technique, IACTs are, in general, deployed in arrays of few telescopes (2 to 5 units) working in stereoscopic configuration. They are located on top of mountains, at about 2000 to 3000 m above sea level (asl). Hence, the sites can present aggressive environmental conditions where the telescopes operate; the temperature ranges from several Celsius degrees below zero to tens above; humidity can reach 100%; winds are very frequent and gusts can occur up to 200 km/h. Despite these conditions, IACTs are not protected by domes or enclosures. They are continuously exposed to the environment, including ultraviolet (UV) solar irradiation, terrain's dust, rain or

Fig. 1 The MAGIC II telescope during a strong winter season.

hail fall, frost, etc. An example is shown in Fig. 1. Moreover, the mirrors typically require a cost of simply few thousands of Euro for square meter and an area density of 10 to 30 kg/m^2.

2 Concepts of Cold-Shaping

The light collection of IACTs is typically achieved through one reflection. The collector is tessellated with many identical mirror segments; these are sections of a spherical surface. This design is called Davies-Cotton, and it has been adapted from early solar concentrators.[1] Moreover, as mentioned before, the collecting area of each telescope is very large, also in comparison with the most recent ground-based optical telescopes, and is composed by hundreds of mirror segments.

All of these aspects underscore the importance and advantages of developing proper manufacturing technologies capable of mass production. Processes exploiting the concept of replication of a master shape can be very attractive to strongly reduce the costs and production time while maintaining quality of the products in terms of repeatability. The cold-shaping (CS) technique presented here has been developed over the past years with the goal to address this problem. Throughout this process, a glass foil will copy, with a very high degree of fidelity, the shape of a mold. The mold can be reused to produce many substrates, identical to each other, without suffering evident surface deterioration.

A thin glass sheet, typically 1 or 2 mm thick, is bent by vacuum suction, and is made to adhere to a mold. The mold's profile is the negative of that desired on the mirror. This processing is done at room temperature without any heating of the glass. The elasticity of glass, although limited by the tensile strength of the commercial product, is the working principle of this technology. For this reason, clear limitations imposed by this method appear in the surface profiles of the mirrors, particularly the achievable radii of curvature. A detailed analysis is postponed to Sec. 3. Moreover, since the process occurs at room temperature, the glass permanently retains the tensile stresses resulting from bending. These stresses will also cause the glass to spring back to its original position when the vacuum suction is removed. To overcome this behavior, a sandwich-like structural configuration is realized by gluing a reinforcing core and a second glass skin. Aluminum honeycombs, having a few cm thickness, are typically used for the core structure. The chosen mechanical structure for the substrate of these mirrors confers stiffness and low areal density.

The connection of the parts is achieved through epoxy resin structural adhesive bonding with curing at the temperature required by the glue while maintaining the vacuum suction. After the glue is polymerized, the vacuum suction can be released and the substrate properly coated. Eventually, the mirror is then finished by sealing its edges to prevent damage from water infiltration and ensure its safe handling. Figure 2 shows the main steps as described before.

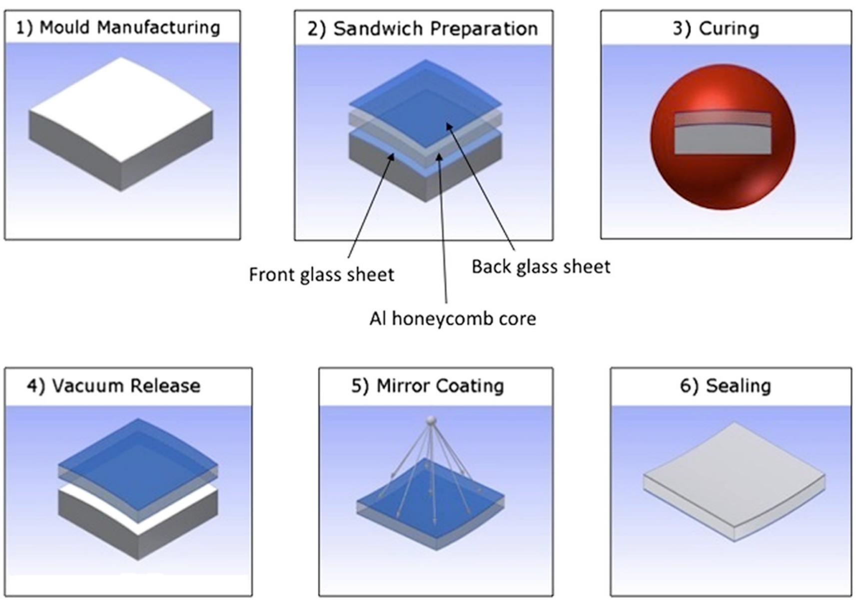

Fig. 2 Conceptual sketches of the main steps for the cold-shaping. Sandwich structural configuration is implemented having a honeycomb core few cm thick and skins made by glass foils.

Table 1 Mechanical properties of glass as used in the present analyses.

Mass density	2.49 g/cm^3
Young's modulus	73 GPa
Poisson's ratio	0.224
CTE	9×10^{-6} K^{-1}

Table 2 Main parameters investigated in finite elements analysis for the CS evaluation.

Tile shape	Square and hexagon
Tile area	0.6 m^2 and 1.2 m^2
Glass foils thickness	0.5–1.0—1.5–2.0 mm
Radii of curvature of the bending	from 7.5 m to 40 m

3 Structural Analyses

Sandwich mirror panels, which consist of two solid face sheets bonded to an inner and lighter core, represent a favorable structural scheme in case it is desired to increase the ratio between the bending stiffness and the panel aerial density.

The choice of commercial glass material for the sandwich faceplates is favorable in terms of cost, but it requires a careful evaluation in terms of mechanical strength. As a matter of fact, it is well known that the strength of glass is not an intrinsic property of the material, but on the contrary, it strongly depends on the whole processing method. In fact, strength depends on several parameters such as distribution of cracks (or surface flaws), entity of stressed surface area (or volume), stress distribution, residual internal stresses from manufacturing process, nature of the loads (static or cyclic), fracture toughness, humidity, and temperature. Furthermore, glass materials are susceptible to subcritical crack growth in monotonic tension due to the influence of moisture. Handling, glass cutting, and edge finishing can also affect the surface defects, and so the strength. Finally, further strength degradation can occur due to the exposition to the environment.

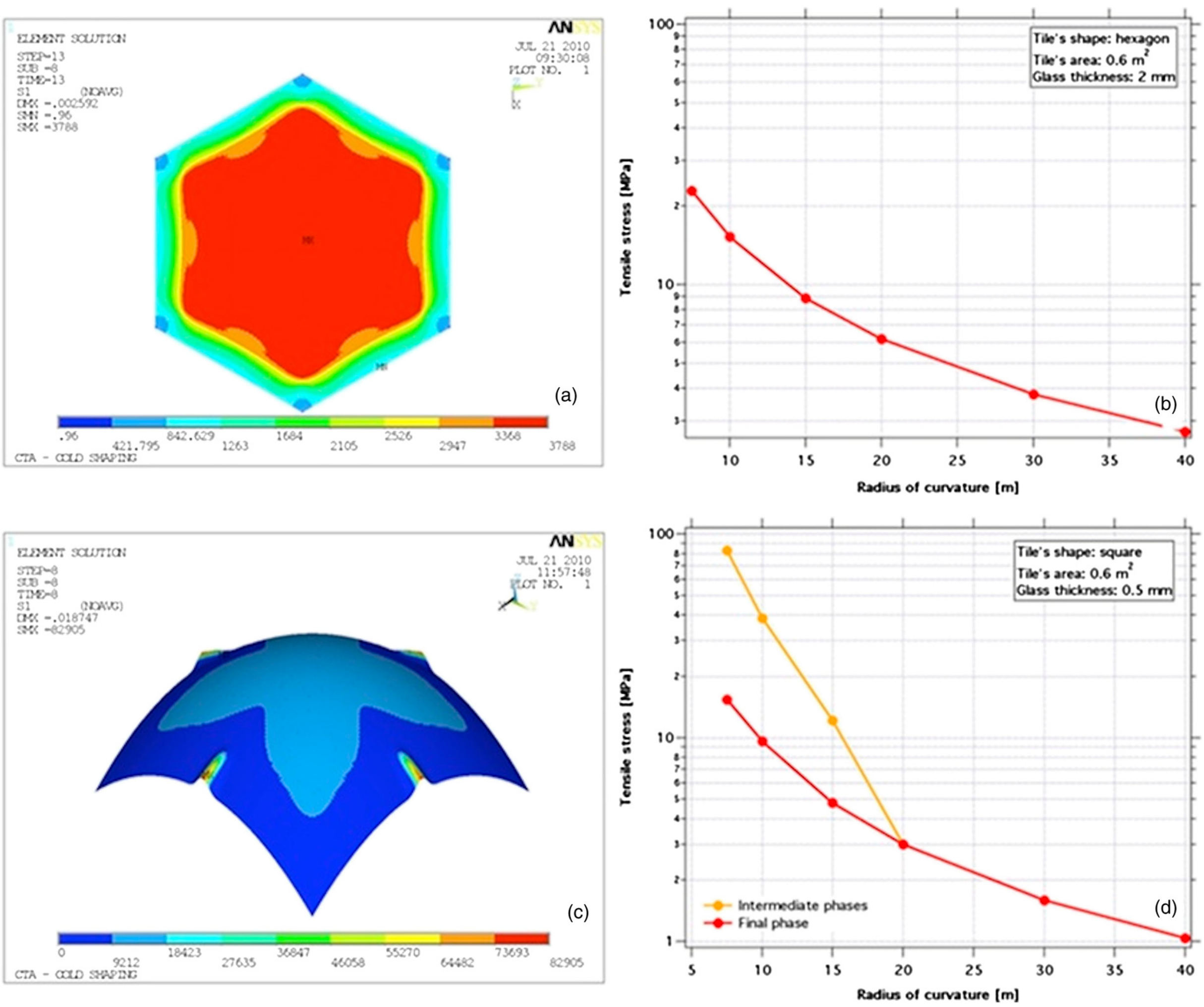

Fig. 3 Example of cold-shaping (CS) undergoing the regular configuration: (a) isocontours plot of the principal tensile stress; (b) principal tensile stress versus bending radius. Example of CS undergoing the corrugated configuration: (c) isocontours plot of the principal tensile stress; and (d) principal tensile stress versus bending radius.

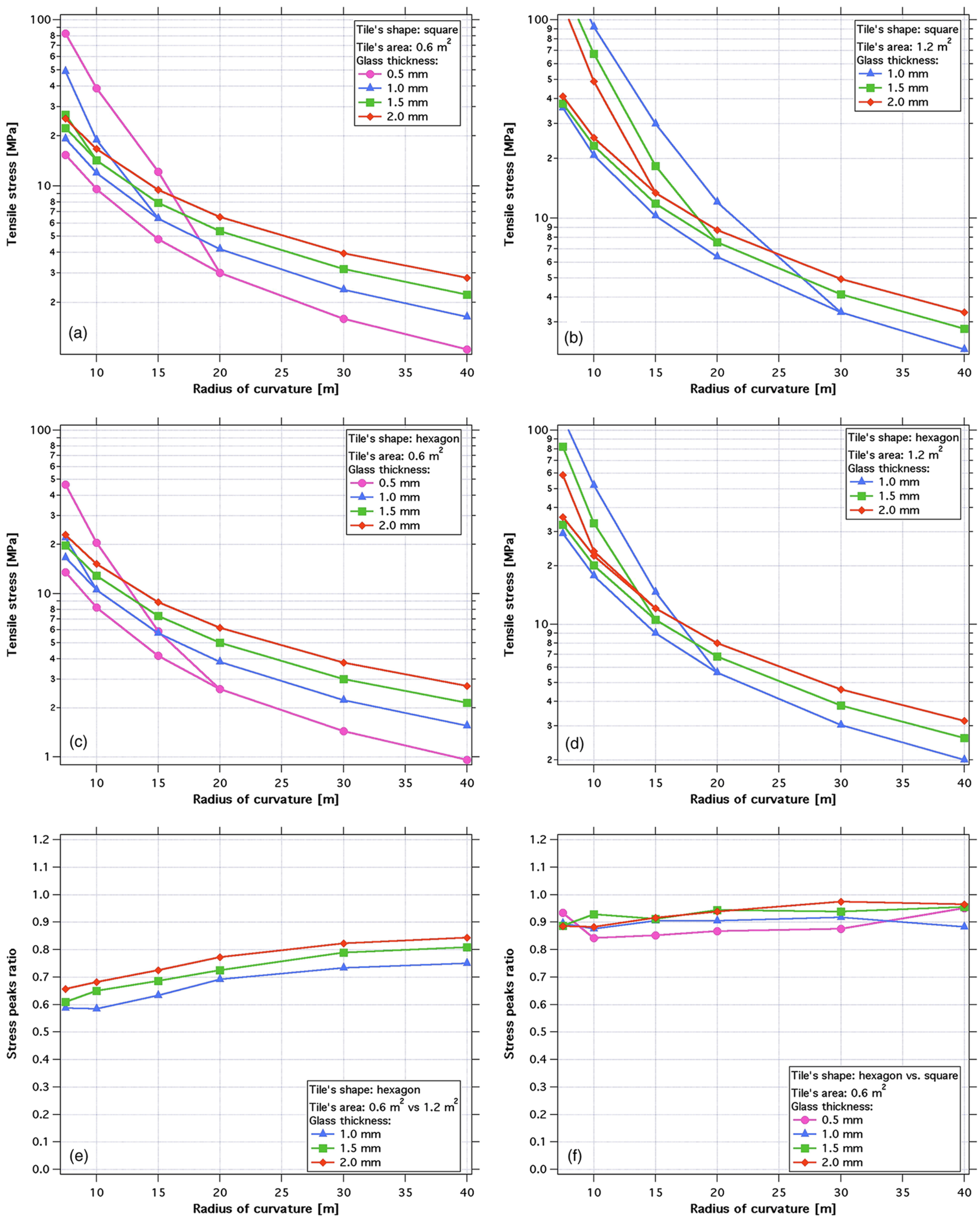

Fig. 4 Plots showing the behavior of the principal tensile stress versus bending radius for: (a) small square tile; (b) large square tile; (c) small hexagonal tile and (d) large hexagonal tile. Plots showing the relationship between: (d) small versus large tiles; and (f) hexagon versus square tiles.

The few above reported remarks point out that a deterministic value for glass strength is not available, so the approach to the glass safety is statistical, and in principle, a proper characterization campaign is necessary. Without this information, the main mechanical properties of glass refer to a commercial product; specifically, for the present analyses, we referred to annealed product as in Table 1.

By now, the characteristic value of the bending strength, 45 MPa, has been retrieved by engineering judgment as from the most updated draft version of the relevant prEN 13474-3 regulation, namely "Glass in building—determination of the strength of glass panels—Part 3: General method of calculation and determination of strength of glass by testing." Safety checks in mirror design have been performed following the same regulation.

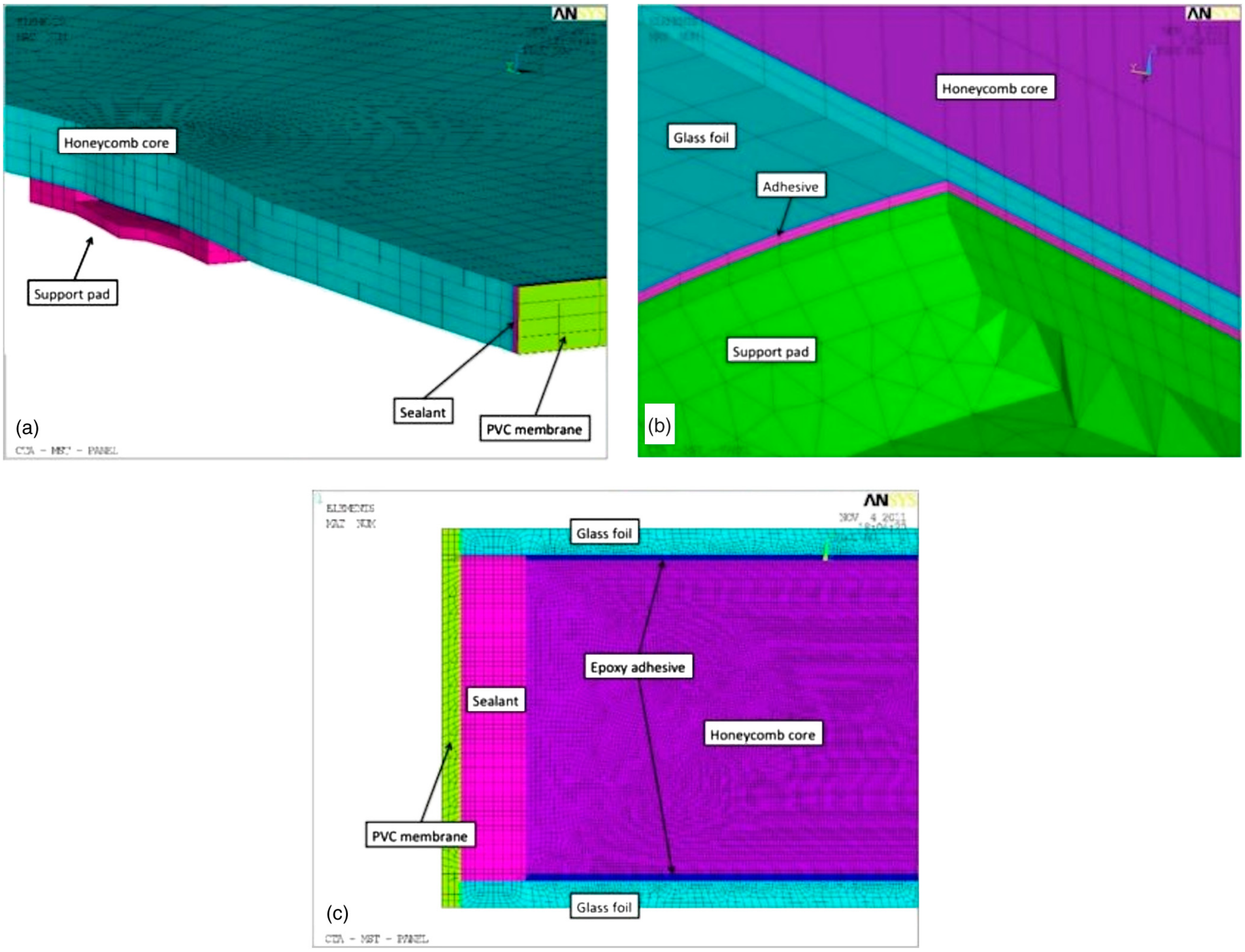

Fig. 5 Finite element models: (a) global model for the full panel; (b) local model surrounding the pucks locations; and (c) local model at the mirror edge.

We underline the point that in the following sections of the paper, we do not aim to present a design for mirrors; instead, we discuss some important aspects helpful to drive a design. Nevertheless, the methods applied and the finite element models developed give a reliable first order estimate for the stress behavior, and can be used for preliminary estimations.

3.1 *Understanding Bending Limits*

Given that glass is a brittle material often showing low tensile strength, the stress level in the face sheets become a critical parameter which has to be attentively checked. In the present subsection, we focus our attention on the tensile stresses induced by the CS procedure in order to assess the limits of the proposed manufacturing procedure. Structural analyses have been carried out by a nonlinear, finite element approach, by means of step-by-step analyses able to follow the stress behavior during the whole bending process as the applied load increases.

The purpose of the analyses is to evaluate how different design parameters affect the tensile stress induced by CS. The parameters considered are reported in Table 2. The analyses performed in Ref. 2 showed that two different configurations, namely regular and corrugated, of the deformed glass shape can occur during the CS process. The configurations will depend on the tile shape, size, and glass thickness, as well as on the imposed radius of curvature.

In the regular configuration, bending of glass proceeds smoothly and regular from the innermost zones to the outermost ones as the applied pressure increases. No significant folds in the glass are generated during the process. It is the most favorable case in terms of glass stress between the two possible evolutions observed. Figure 3(a) and 3(b) shows an example of the principal tensile stress developed in the glass during the CS process, and the corresponding stress trend as a function of the imposed radius of curvature.

On the contrary, in the second case, the glass assumes a corrugated configuration where some folds are generated. By increasing the pressure, it is, in principle, possible to bring the glass in contact with the forming mold to remove the folds; nevertheless, the intermediate corrugated configurations are very unfavorable in terms of stresses. It is observed that the maximum tensile stress occurs during the intermediate bending phases in correspondence of the folds, while at the end of the process the tensile stresses would be smaller. In any case, this is just a theoretical condition, because the higher stresses recorded could be sufficient to cause the failure. Figure 3(c) shows the principal tensile stress in the glass

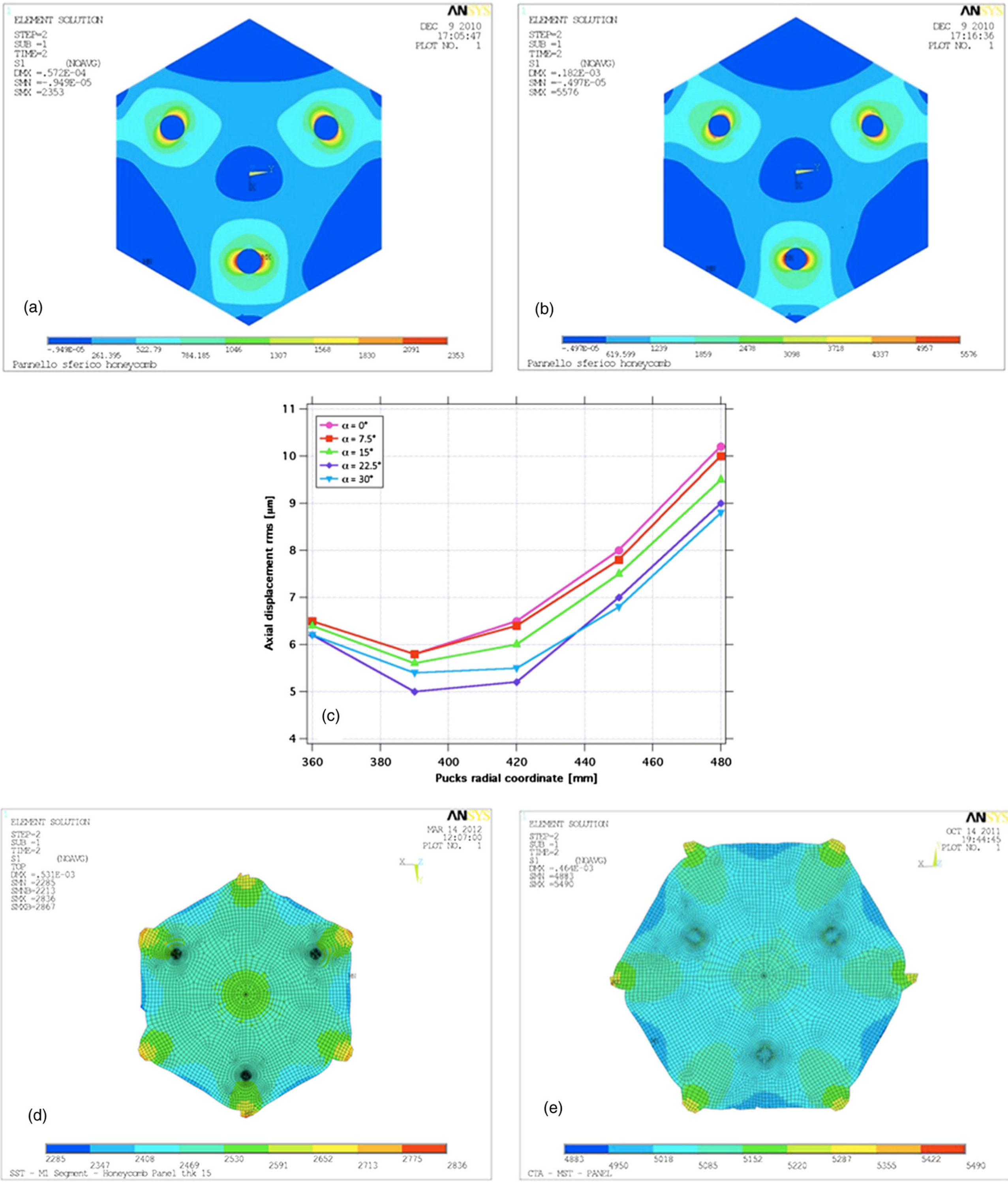

Fig. 6 (a) And (b) are examples of principal tensile stress in case of small (a) and large (b) mirrors (core thickness: 30 mm); (c) shows the influence of the pucks location for rms errors under normal gravity + moderate winds (α is the azimuthal position of the three pucks); (d) and (e) show the influence on the stress peaks of a temperature shift of +40°C in case of small (d) and large (e) mirrors. Stress isocontours quoted in kPa.

during an intermediate phase when the folds are generated. When corrugated configuration arises, a double curve is reported in the plot of Fig. 3(d).

In Fig. 4, we summarize the tensile stress peaks obtained in all the cases analyzed for the two geometries and sizes considered. From the plots, some considerations can be drawn. The formation of folds during the CS process is made easier by: a. reducing the foil thickness; b. increasing the foil size; c. reducing the curvature radius, and d. changing the geometry from hexagon to square (under the same panel area). In fact, by comparing the stress peaks for a given foil thickness and for an imposed radius of curvature, smaller foils seem preferred because stress could be reduced up to about 40% [Fig. 4(e)]; similarly, hexagons are slightly better than squares with about 10% less stress [Fig. 4(f)]. These considerations are worth mentioning in particular for the design of mirrors with a small radius of curvature.

Finally, we point out that in case of corrugated configurations the upper branch of the curves (intermediate phase) has to be considered just as a first evaluation of the maximum stress, because these analyses only provide results at discrete load steps. It follows that, in principle, there could exist intermediate levels of peak stress that are not revealed by the end case analysis. The same concept is applicable to the bifurcation point of the curves. Nevertheless, because the upper branch of the curve is often related to a high and nonallowable stress level, the meaning related to this zone of the curve is almost academic.

3.2 *Additional Effects*

It is evident that the manufacturing process induces stresses in the glass face sheets and possibly in the core material. These stresses are frozen by the bonding between the elements, and so any additional stresses induced by other loads will act on a non stress-free panel. In case the structural behavior of the panel can be considered linear, new stresses induced by any loads will be simply added to the initial stresses related to the CS phase.

With reference to the present structural configuration (i.e., sandwich), the influence of the mirror size, core thickness, and pucks location have been also investigated with particular attention to:

(1) additional stresses due to environmental conditions (i.e., strong winds, large temperature shifts); and
(2) elastic deformations due to operative conditions (i.e., axial gravity, moderate wind, and temperature gradients across panel thickness).

Long term effects caused by stress relief in the glass could, in principle, lead to figure changes. In applications well below the glass transition temperature, as in our case, these have been judged negligible since long-term strains are just a few percent of the instantaneous elastic deformation, and so the impact is negligible. Only hexagon tiles have been considered.

The deformed shape and stress state in the panels were evaluated by means of global finite element models relevant to the whole mirror segment [see Fig. 5(a)]; more detailed ones have been also implemented to investigate local stress states generated into sensible zones of the mirror as shown by Fig. 5(b) and 5(c) (i.e., pucks location and mirror edges). A comprehensive selection of the results illustrating the different aspects is reported and discussed in the following.

Mirror size and core thickness play a substantial role in the stress peaks. The stress state into the panel structural components obviously depends on the mirror size [see Fig. 6(a) and 6(b)]. Wind loads are also important; in particular, the survival wind load represents the prominent contribution. Thus, the entity of the induced stresses poses some limits to the technology. However, in order to keep stresses within the allowable range, different solutions can be adopted. For example, the core thickness could be augmented to a certain extent, or as an alternative, a more complex support system could be required.

Results also show that adopting the simplest support system consisting in three circular pucks placed at azimuthal distance of 120 deg., the pucks location does not play any prominent influence on the stress peaks values, while it does in the elastic deformations that concur to deteriorate the optical prescription. The minimum values for peak-to-valley and rms errors are reported when the radial position approaches 2/3rds of the panel radius [see Fig. 6(c)].

Large temperature shifts, for example, caused by daylight direct sun heating or winter frosting, are also demanding in terms of stress loads (noting that stresses generated by thermal loads must be considered over extensive time periods), and can also generate tensile stress on the order of a few MPa. Examples are shown in Fig. 6(d) and 6(e).

The mirror edges finishing can have a major impact on the mirror because of the generation of stress caused by large thermal shifts coupled with differential CTE between the materials. Important peak values can appear for particular implementation choices; an example is shown in Fig. 7.

A more extensive description of the results can be found in Ref. 3; moreover, comprehensive and detailed analyses applied to real mirrors designs are reported in Refs. 4 and 5.

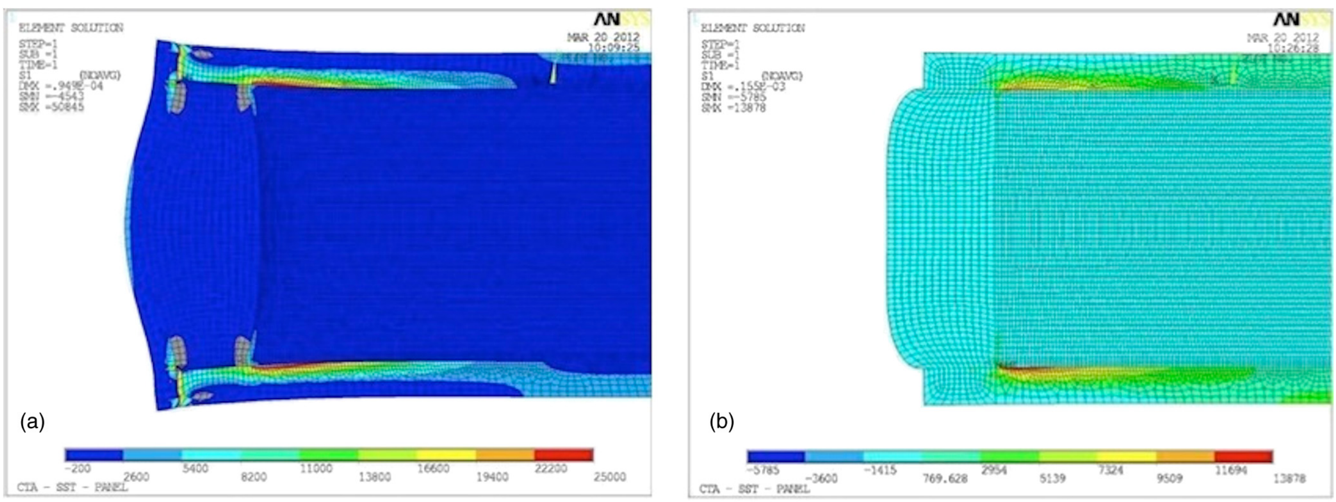

Fig. 7 Two examples of possible stress behavior at the edges of the mirror in case of: (a) edges finished with silicone rubber sealant and a protecting polyvinyl chloride (PVC) rim; (b) edges without the PVC rim. The stress peaks differ considerably in the two implementations. Stress isocontours quoted in kPa.

Fig. 8 Main steps of the manufacturing: (a)–(c) sandwich preparation; (d) polymerization of the glue; (e) sandwich release; (f) coating; (g) and (h) mirror's interfaces fixation and edge finishing.

4 Technological Readiness

4.1 *Cold-Shaping Implementation*

The CS process has been developed by Media Lario Technologies under the scientific supervision of INAF-Osservatorio Astronomico di Brera (INAF-OAB).[6]

The mold has to be machined only once, and needs to have the same profile precision as needed for the mirrors, but be the negative. The microroughness is not an issue since the CS process is not going to replicate it. The molds can be made out of metal (i.e., aluminum or steel) through (diamond) turning/milling machining, or more performing processes depending on the shape accuracy requirements.

The remaining steps sketched in Fig. 2 are hereafter described:

(1) A pair of glass foils and one sheet of aluminum honeycomb for the sandwich are prepared by cutting out from larger blanks. The cutting can be easily done by using shape templates and cutters. Glass is then carefully cleaned.

(2) The first glass foil is positioned, bent, and fixed over the mold; then it is made to adhere by vacuum suction. In this way, the shape of the mold is replicated; afterwards the sandwich is assembled. The connection between the honeycomb sheet and the glass foils is achieved by bonding the parts together with epoxy resin structural adhesive. Photographic images of the sandwich preparation are shown in Fig. 8(a) to 8(c).

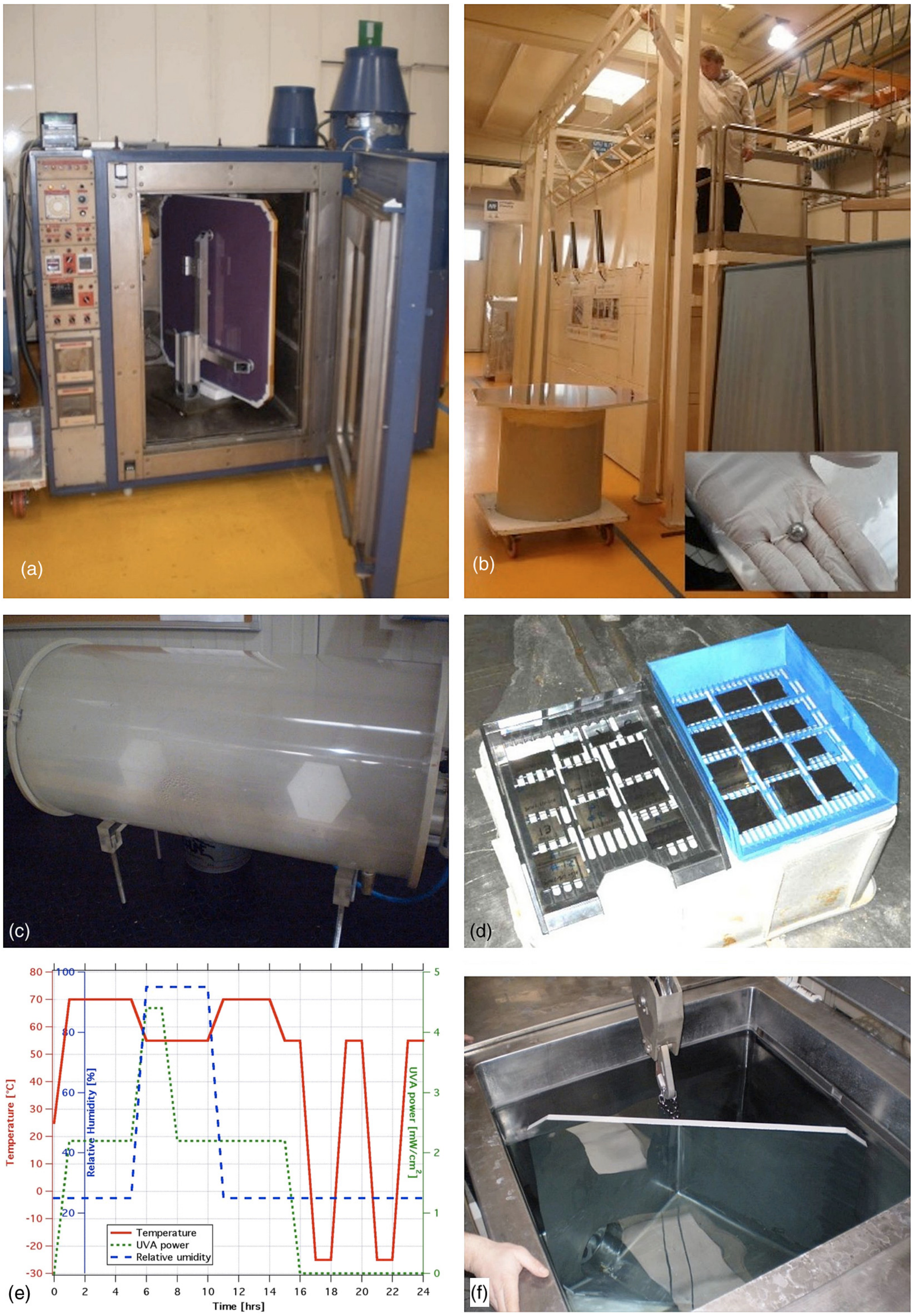

Fig. 9 (a) Temperature cycling test; (b) mechanical impact test; (c) salt-fog test; (d) damp heat test; (e) temperature, humidity, and UVA power cycles for weathering tests; and (f) soak test.

(3) The resin is made to polymerize with the proper curing cycle. Temperatures and timing play a role in the resulting radius of curvature and shape of the mirror, as well as the amount of glue [see Fig. 8(d)].
(4) Once the polymerization has taken place, the vacuum suction is stopped and the sandwich is carefully released from the mold [see Fig. 8(e)].
(5) After a deep cleaning of the front glass, the reflective coating is deposited. Methods and layers are chosen in accordance with the final application of the mirror. For example, in case of outdoor applications such as for the Cherenkov, a protective coating (e.g., Quartz) has been applied to enhance the surface strength and peak reflectivity. It is also worth mentioning that because the sandwich is kept together by the glue, attention must be paid to the heating caused by the coating process [Fig. 8(f)].
(6) Finally the interfaces with the telescope supporting structure are fixed, and the edges of the mirror can be sealed. This solution also ensures higher rigidity and mechanical protection of the mirror edges/corners [see Fig. 8(g) to 8(h)].

A few remarks are here reported. Both the glass foils and the honeycomb sheets can be either off-the-shelf commercially available products or customized ones depending on the target cost and requirements of the mirrors under manufacturing. For example, considering the relaxed optical requirements for the Cherenkov telescopes application the market provides a wide variety of technical glass having the required thickness and surface microroughness. Avoiding use of optical glass is possible to keep costs very low.

Concerning the CS process, it is clear that as the glass foils and honeycomb are pressed against the mold an elastic deformation occurs, and so, at mold removal, some sort of spring back is expected. The spring back phenomenon, whose amplitude can be preventively estimated by proper analyses, should be taken into account in the mold machining in order to reduce the shape error of the panel. Nevertheless, the CS turns to be very flexible in terms of radius of curvature of the mirrors. In fact, if from a single replication mold it could be thought that only one radius of curvature should be obtained, by a careful control of the spring back effect during the gluing process, it is possible to obtain a controlled spread in the radius of curvature of the mirrors. As an example, the case of the MAGIC II project[7] is shown in Sec. 4.3.

4.2 *Validation Tests*

Because of the peculiarity of IACT as briefly described in the introduction, the mirrors have been intensively tested for their robustness. The most significant results are discussed in this section.

One test performed was to investigate to what extent the performances of the mirror are affected by climatic stress (temperature cycling). The environmental durability of the

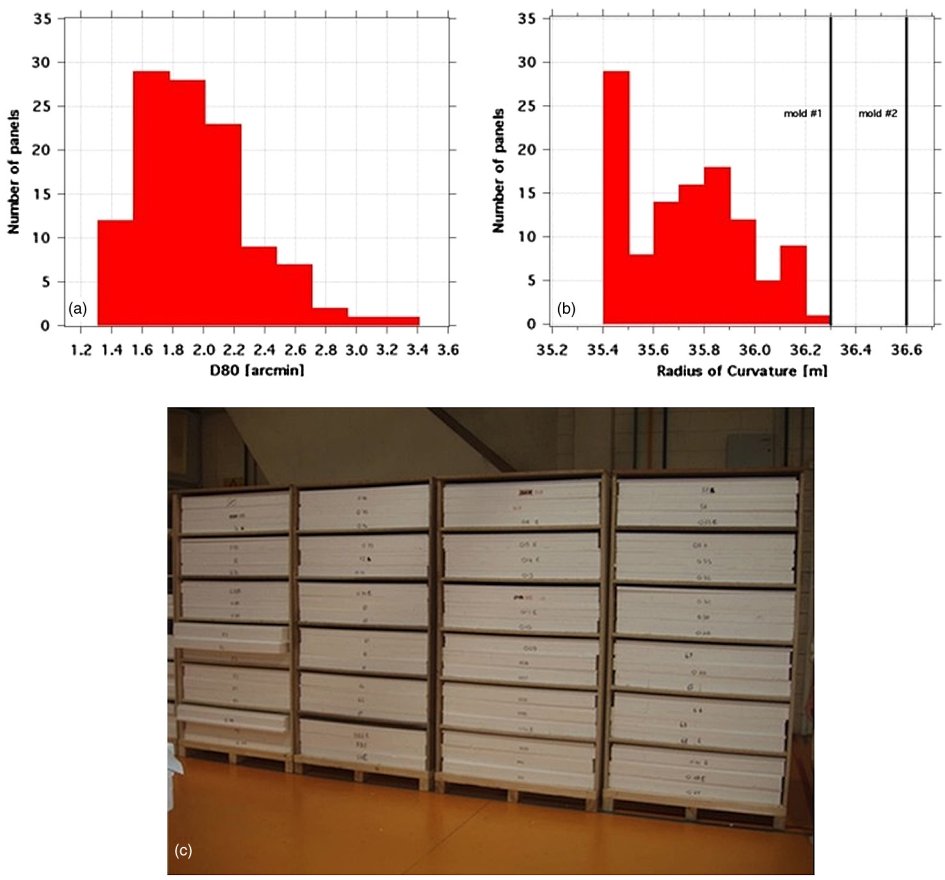

Fig. 10 The distributions of the D80 (a) and the radii of curvature (b) for the 112 mirrors produced for the MAGIC II telescope. The full production into their shipping boxes (c).

coating reflective layer and of its adhesion to the glass substrate have been tested on specimens. Such performances were also assessed on full size mirrors, and the optical performance stability was evaluated. Thermal cycles ranged from −10°C to 60°C. A degradation on the order of the 3% on the focal spot dimension was measured, while no coating removal was observed on the optical surface. Figure 9(a) shows a mirror fitted into the climatic chamber.

The mirrors may occasionally be subject to mechanical impact, such as birds flying or picking on the mirrors, or possibly, hail fall. The mirrors were also tested in terms of resistance to the mechanical impact stress. A steel ball was dropped over the optical surface of the mirror in accordance with BS 7527-2.2:1991; degree of severity was 1 [see Fig. 9(b)]. No evidence of damage was observed after the test. No cracks, bumps, or defects on the optical surface were highlighted from the visual inspection performed after the impact.

Weathering tests, such as salt-fog, damp heat, salt-mist, humidity, and UV-A irradiation were also performed on specimens. The tests lasted for 42 days with cyclical changes in temperature, relative humidity, and UV-A irradiation power profiles, as plotted in Fig. 9(e). No measurable change in the reflectivity was detected. As an additional test, the mirrors were completely dipped into water for the duration of 24 h. The weight of the mirrors before and after the test was checked; no penetration of water inside the sandwich structure occurred.

4.3 *Mirrors Production*

The possibility to exploit technologies capable of mass producing the mirrors is also a key feature for the success of the next generation of telescopes. The CS process demonstrated this potential. We report two examples of its application, both concerning the case of Cherenkov telescopes, conducted by Media Lario Technologies and INAF-OAB.

The MAGIC II telescope[8,9] (see Fig. 1) is the largest Cherenkov telescope in operation today, as well as the largest optical light collector with imaging capabilities. It is located at La Palma island (Canary Island), 2200 m asl, at Observatorio del Roque de los Muchacho. MAGIC II has a segmented surface of nearly 240 m^2 composed by square tiles. The telescope has a parabolic nominal profile; it is approximated by spherical mirror segments with appropriate radius of curvature. More than 100 of those have been realized with the CS process. Each mirror has 1 m^2 in area and less than 10 kg in weight, achieving an extremely aggressive areal density profile. The mirrors show a typical residual error of about 15-μm rms, with respect to the best fitting sphere; a factor three times greater than replication molds. The light

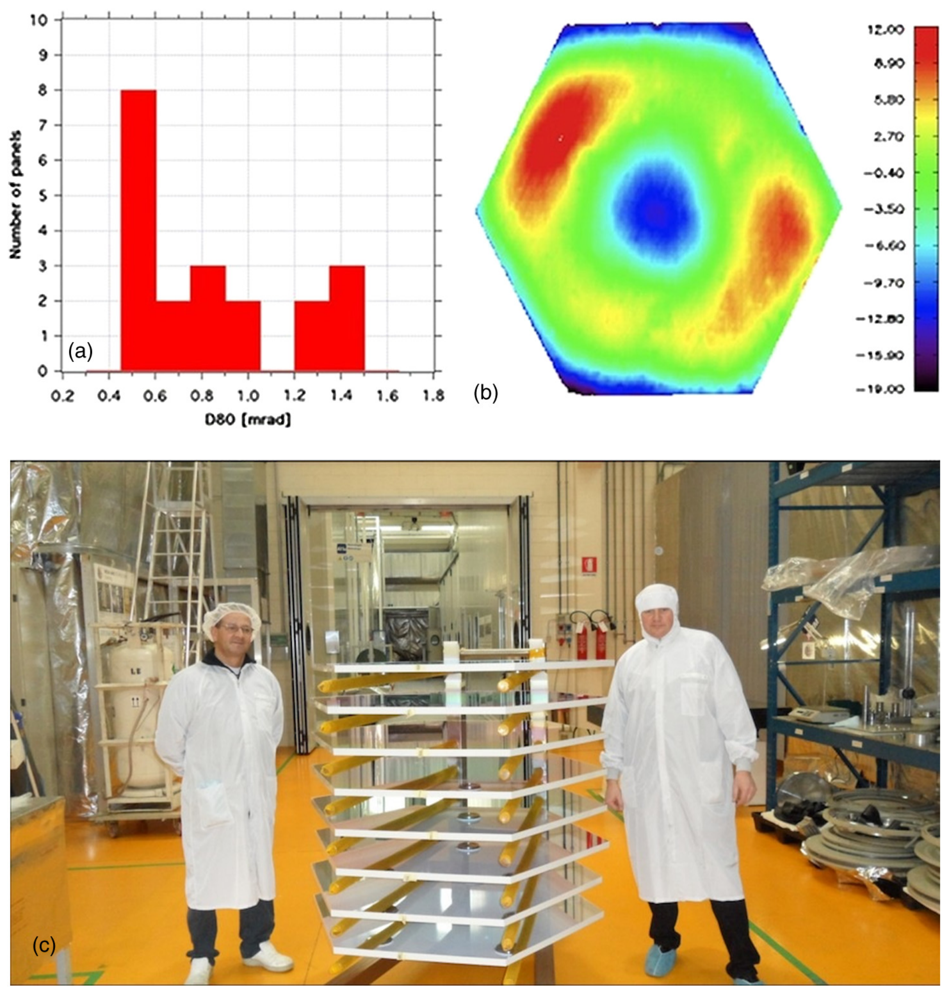

Fig. 11 The distributions of the D80 at the nominal radius of curvature (a) and the typical residual errors map (b). Part of the mirrors ready to be packed and shipped (c).

concentration, defined as the circle containing the 80% of the focused light (D80), turns around 2 arcmin, as shown in Fig. 10(a).

The full production has taken less than three months and two replication molds. The plot in Fig. 10(b) shows the distribution of radii of curvature of the mirrors in comparison with the molds. The spring back effect after the vacuum suction release is well observed; however, by careful control of the process, it has been possible to produce mirrors with a dozen different radii of curvature. The (different) radii of curvature produced were deliberately matched to the telescope requirements. This fact has minimized the number of replication molds, and maximized their depreciation over the cost of each mirror. Finally, a production yield as high as the 97.4% was successfully achieved.

Vice-versa, for the CTA-MST project[10] it was required to demonstrate the repeatability of the CS process by delivering a set of mirrors within the specification: D80 better than 1.5 mrad at the nominal radius of curvature, with a goal of 1 mrad (i.e., at the same radius of curvature for all the mirrors). A second production was performed on a small number of prototypes. The mirrors were hexagonal in shape (1.12 m, flat-to-flat) with an enlarged dimension, with respect to the MAGIC II production. As shown in Fig. 11(a), all mirrors were compliant with the specification, with 15 out of 20 reaching the goal. The residual errors map of the mirror surface (with respect to the best sphere) is typically better than 6-μm rms; an example is reported in Fig. 11(b).

Finally, the mass of the mirrors was measured to be 11.75 kg, and the cost of some thousands of euro.

5 Conclusions

The paper presents a novel method for the realization of segmented mirror surfaces. Two thin glass foils were bent at room temperature over a replication mold, and a honeycomb sheet was interposed between the two glass foils. A structural adhesive keeps the parts together, forming a stiff and lightweight sandwich structure. This process is called cold shaping.

The implementation was described and a number of validation tests were discussed. The authors also showed examples demonstrating the scalability of the process to industrial level, with the production of several tens of pieces.

In parallel, the process was also studied by means of finite element analyses in order to probe the wide space of the parameters. The analyses addressed the bending limits in relation to the shape, dimension, and thickness of the glass; moreover, the effects of a variety of loads (wind, temperature, gravity) were commented.

Throughout the validation tests and the application on a real case (i.e., the MAGIC II telescope), the validity of the CS process was demonstrated in delivering lightweight but very robust mirrors for aggressive environments. In fact, the process was developed for the realization of mirrors for Cherenkov telescopes, for which the mechanical properties prevail on optical ones. However, different choices on the materials, the implementation, and tailored designs could, in principle, lead the realization of mirrors with more demanding optical requirements.

Acknowledgments

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