Abstract

Since 1970, the glass ceramic Zerodur has demonstrated that it is a material of excellent choice for telescope mirror blanks, because of its near zero expansion, high homogeneity, besides other tailor-made properties for this application. In 1988, Schott Glaswerke received an order from ESO to deliver four Zerodur mirror blanks with 8.2 m in diameter, in the form of thin menisics. To produce such large monolithic pieces of glass ceramic, new melting, forming, ceramizing and machining processes had to be developed. Thanks to a new spin casting technology, the specification targets of ESO could be achieved. Today, production of all the blanks is completed. Three blanks are delivered to REOSC, where the finishing operation takes place. These three blanks have been accepted by ESO. The last blank will be delivered in summer this year. The results achieved were impressive: The mean value of the coefficient of thermal expansion was -0.043 x 10^{-6} K^{-1}, with an uniformity of 0.0009 x 10^{-6} K^{-1}.

I. THE PROGRESS OF TERRESTRIAL TELESCOPE TECHNOLOGY

A driving force for the development of new terrestrial astro-telescopes is increasing the light intensity of the rays from space by enlarging the area of the light-collecting primary mirror. To achieve light-collecting areas of up to 50 m², three approaches are being realized:

1. Light-weighted mirrors with honeycomb support structure made from boro-silicate glass, where enforced cooling is supplied. Several telescopes are on the construction.

2. The Keck-telescopes are composed of 10 m primary mirrors consisting of 36 mirror segments each. Each segment measures 1.8 m in diameter and 90 mm in thickness. The problem is that an off-axis polishing method has to be applied, which means spherical polishing under bending stress. After polishing and moving the stress, an aspherical surface of the mirror blank is the result. The Mirror material of these telescopes is Zerodur. The two Keck-telescopes are operated by the University of California and the California Institute of Technology at the Maunia Kea volcano in Hawaii. It is planned to combine these two telescopes to achieve the performance of a 14 m instrument. The European Southern Observatory operates with a concept of four operative single telescopes with monolithic primary mirrors. Four telescopes with an aperture of 8.2 m are under construction. It is expected that, due to interferometric combination of beams collected by these four telescopes, the highest resolution ever known can be achieved. To realize this concept, the main problem was to get a rigid and sufficiently stiff mirror substrate 8.2 m in diameter, not deforming under its own
weight. For monolithic mirror blanks used for telescopes up to 4 m in diameter, a thickness:diameter ratio of 1:6 is needed. So, for an 8.2 m blank a thickness of 1.4 m would be necessary, which means a weight per piece of about 150 t. Construction of telescopes with such high-weighted mirror substrates are not economically feasible. With concept of active optics, ESO overcome this problem.

Numerous actuators support thin Zerodur menisci which at the same time adjust the contour of the mirror as closely as possible to its ideal shape. This concept allows thicknesses of the 8.2 m mirror blanks of 177 mm only, which is equivalent to a weight reduction of more than 85 %. This concept has been realized in ESO's 3.5 m New Technology Telescope with excellent results. To produce such relatively thin Zerodur menisci by machining thick-cast plane plates is mechanically and economically not feasible. So, a spin casting technology had to be developed by Schott Glaswerke. Application of the spin casting technology allows a yield improvement of nearly 100 %, which reduces production costs accordingly.

II. MATERIALS REQUIREMENTS FOR TELESCOPE MIRROR BLANKS

A material suitable for telescope mirror blanks has to meet the following specifications:
- Low thermal expansion within the temperature range of application (-30 - +70°C), to avoid distortions due to temperature changes.
- Temperature dependence of the coefficient of thermal expansion within the temperature range of application must be extremely low.
- High natural stability and low specific weight must avoid mechanical deformations.
- Heat transfer coefficient should be high to avoid temperature gradients within the blanks.
- The material has to be ground and polished in order for optical surfaces with mean deviations of ±1.3 x 10^{-5} mm (NTT-Specification) to be achieved.
- Corrosion resistance and chemical durability must be high to apply aluminum coating to the mirror substrates. Aluminum coatings are the mirror material, to be removed from time to time to guarantee a high performance of the Aluminum mirror. The mirror substrate material has to withstand leaching, cleaning and drying processes, without development of any defects on its high-quality optical surfaces.
- Melting, casting, forming and ceramizing processes have to result in high-volume blanks of high homogeneity and an extremely low level of inclusions and striae. The homogeneity of the coefficient of thermal expansion within an 8.2 m blank has to be lower than 0.05 x 10^{-6} K^{-1}.
- Material must be a transparent one for the wavelengths of visible light, to allow economical quality control of the material. Comparison of the properties of the glass ceramic Zerodour with alternative materials shows that TiO_2-doped silica (ULE) nearly has similar properties. Silicon carbide, with its relatively low coefficient of thermal expansion, its low specific weight, and its higher heat transfer coefficient could be an alternative material to glass ceramics or ULE, but until now pieces with high volume and high homogeneity are technically not yet feasible. The following results of our material development are important for meeting the specification targets for large mirror blanks: The glass ceramic production process starts with melting, followed by forming, annealing, nucleation, and crystallization of the material. Controlled crystallization is possible if the Tamman-Curves of the nucleation rate and
the crystal growth rate do not overlap. Zerodur glass ceramic consists of 70 % crystal and 30 % glassy phase. To achieve transparency, mean crystal sizes of about 500 A should be derived. Therefore, at least $10^{13}$ nuclei per mm$^3$ must be developed, with a nucleation rate of $10^5$ nuclei per mm$^3$ per second - to ensure economical ceramizing times. Metastable, high-quartz-solid solutions containing Li$_2$O, ZnO, MgO, AlPO$_4$ and SiO$_2$ grow epitactically onto TiZrO$_4$ - nuclei. Transmission electron microscopy and X-ray analysis have shown evidence for this crystallization sequence. Nucleation temperatures are in the region of 600 - 620°C, and crystallization takes place from 680°C upwards. Within the crystallization process, the high-quartz-solid solution they show a zonary growth. The inner volume of the crystals is lower in SiO$_2$ content than the outer areas. So, the composition of the glassy matrix and the outer areas of the crystals are similar. This result is important for the application of Zerodur for mirror blanks. Due to these results, chemical durability and hardness of glassy and crystalline phases are similar. This avoids unwanted roughness of polished surfaces due to micro-hardness differences and destruction of the optical surface within the Al-removing process, due to selective etching. The coefficient of thermal expansion of the high-quartz-solid solution phase changes very sensitively with its chemical composition. For instance the substitution of LiAlO$_2$ for 10 Mol % of SiO$_2$ decreases the phase transition temperature from low quartz modification to high quartz modification from 573°C to about 200°C. The relative length change of glass ceramic consisting of high-quartz-solid solution crystals can be very sensitively adjusted by ZnO, Li$_2$O and MgO-content. Li$_2$O and ZnO decreases the values, and MgO increases the values of thermal expansion. The AlPO$_4$-content of the crystals controls the characteristic of the curves of the relative length change with temperature. Because high-quartz-solid solution crystals are metastable, they steadily change their chemical composition at temperatures above 800°C. At about 800°C, a transition to Keatite-solld solution phase occurs. Both effects can be used to adjust the coefficient of the thermal expansion of the mirror material by thermal treatments. To get material with thermal expansions as near as possible to zero, a chemical composition is used leading to slightly negative expansion coefficients after crystallization. With thermal treatment of 800°C within 100 - 200 hours, lowest expansion coefficients can be achieved. With these results, the most important fundamentals of crystal chemistry, structure and texture are described.

III. THE PRODUCTION PROCESS OF THE 8.2 m MIRROR BLANKS

As reported at the beginning, a spin casting technology had to be developed to achieve thin Zerodur menisci with 8.2 m in diameter, thicknesses of 177 mm, and a radius of 28.97 m. In 1984, the development started with a feasibility study. Pilot runs with 1.8 m and 4.1 m blanks were carried out successfully in 1987. ESO placed in September 1988, the order for four 8.2 m Zerodur mirror blanks. A new 2700 m² facility, with a 70 t discontinuous melting tank, casting, spinning, annealing, ceramizing facilities, storing sites, lifting and turning devices, an 8 m grinding machine, and quality inspection facilities were planned and erected within 21 months. The whole project started in September 1988, and it will be completed with the delivery of the fourth blank this year. To produce a blank with 8.6 m in diameter, 32 cm in thickness, and a curvature of 29 m, it takes 30 days for melting, 5 hours for casting and spinning, 3 months for rough-annealing, 2 months for rough machining, 8 months for ceramizing. Machining to specified dimensions and quality inspection take
another 5 months. This results in a total production time of about 2 years. Melting and homogenizing 70 t of Zerodur glass in a discontinuous tank was not a problem for Schott, because ever since 1970, 4 m blanks had been produced in massive form, which required about 45 t of glass. The raising to 70 t created no problems. To get an homogeneous blank it is important to control temperatures in the tank, the feeder, and the mold very carefully. To minimize inhomogeneities and uncontrolled crystallization, the pouring and spinning processes have to be carried out as fast as possible. Nevertheless, it takes 5 hours to cool down the melt from about 1300 °C to 900°C, where the glass maintains its shape. Within this period of time, the glass passes through the temperature region with maximum crystal growth velocity. Crystals grow on inclusions within the glass volume and at the reaction layer between the glass and the mold. It is impossible to avoid uncontrolled crystallization completely. The following measures lower the risk: Before pouring the melt into the mold, which is temperature-controlled, the tank feeder is heated up. Within the start-up phase of the powering process, the contaminated melt flows through an orifice in the bottom of the mold. When the melt is free from inclusions and striae, a stopper is pressed against the bottom of the mold, which now is filled with glass melt. Within the filled mold resting on a rotating support, the spinning process starts with typically 5 revolutions per minute to ensure that no surface glass is entrapped and transported into the interim volume. So the meniscus is formed. To accelerate the cooling process the mold cover is replaced by a cooling hood, which is cooled by sprinkling high amounts of water into its bottom steel plate. The forced cooling is stopped when the glass has reached a temperature of 900 °C. Further cooling to a safe temperature above the glass transition temperature proceeds by radiation. The mold, with the casting, is then transferred into an annealing lehr where a precise 3-month cooling program is applied. Stress formation during cooling-down to room temperature is particularly critical. The most dangerous stresses are caused by a crystalline reaction layer at the bottom side of the blank. It has a significantly lower CTE value than the glass, which is why this side will be put under tensile stresses. Taking the convex shape of the bottom side into account and applying the tools of fracture mechanics, FE-simulations indicated that tensile stresses on the bottom side should not exceed 2 MPa. With optimized production parameters, crystal layers < 0.5 mm thickness were obtained, which caused tensile stresses not more critical for the process. During the annealing process, the huge meniscus passes the glass transition region. Now, it behaves like a rigid body and does not adjust itself anymore to the mold, it did as viscous glass. To avoid breakage of the meniscus under its own weight, the latter has be supported actively by hydraulic elements. FE-simulations indicated that maximum tensile stresses introduced by the support system during cooling are 0.13 MPa. Because of the very slow annealing cycle, only small compressive stresses due to temperature gradients between surface and bulk volume elements, are expected. FE-simulation resulted in -4.8 MPa for the top surface and, -1.2 MPa for the bottom surface. When all measures derived from computer simulations and from test castings were applied to the production castings, no more failures of the glass blanks occurred anymore. After annealing, the crystal layer has to be removed from the blank to stop any subcritical growth of cracks which may take place. All of the handling and machining procedures with gigantic blanks are critical, too. Flexible support systems designed on the basis of FE simulation results were constructed and applied with success. The nucleation and crystallization processes takes 8 months. During this transformation, linear shrinkage of the body is about 1 %, which means the diameter reduces by about
8 cm. If the body stuck to the surface of the support system, breakage would be the result. To avoid this, the blank is put on a support plate with several thousands of small sand piles which allow the blank to move free from stress during the shrinking process. After ceramization, the blank is ready for machining to its final shape. Handling and supporting devices used for the glassy blank were used again for the glass ceramic blank. After drilling a central hole into the blank and achieving the specified dimensions, the blank was ready for inspection.

IV. PROPERTIES OF THE FOUR 8.2 m ZERODUR MIRROR BLANKS

As a result of quality inspection measurements on all four blanks, it can be reported that all specified values given by ESO were exceeded significantly. The inner quality of the blank material was specified by number and sizes of inclusions. The delivered blanks contained less than 20 % of the specified numbers. Stresses within the blank due to striae were not existent. Specified stresses were less than 25 nm. Stresses due to the annealing process were about 60 % of the given values (~6.2 - 7 nm/cm). Mean CTE was \(-0.043 \times 10^{-6} \times K^{-1}\). Specification values were \(0 \pm 0.15 \times 10^{-6} \times K^{-1}\) whereby the achieved CTE-homogeneity was \(0.009 \times 10^{-6} \times K^{-1}\). The specification value was < \(0.05 \times 10^{-6} \times K^{-1}\). All blanks were and will be delivered in time. For land and sea-transportation to REOSC, where the blanks receive their optical finishing, both companies, REOSC and SCHOTT, developed a transportation device. Again, all results of the material stability derived from FE-simulation were taken into account. The transportation procedures were carried out without failures.

During these days, the 8.2 m project at SCHOTT is coming to a successful end, thanks to the outstanding performance by Dr. Rudolf Müller, Dr. Hartmut Höness, and their project team.