Technical Synopsis of
"Properties of Zerodur Mirror Blanks for Extremely Large Telescopes"

Aron Traylor
Optical Sciences 521 Opto-mechanical Engineering
29 October 2010

Purpose for the Summary:

The desire to see deeper and deeper into space, drives the need to increase the collection area of telescopes. To accomplish this, we would simply increase the diameter of the telescope. The largest telescopes have single glass primary mirrors measuring 8.4 meters across, that's over 27 feet, but the designs today want to go larger. Due to the enormous size, massive weight and a host of other reasons, we are at a point where constructing larger mirrors out of a single piece of glass is not really feasible. The only real solution is to adopt a segmented mirror approach. Some telescope designs have already begun to adopt a segmented mirror design. See Figure 1 for an example of a segmented primary mirror. This paper discusses some of the details related to the manufacturing transition from single to segmented mirrors. Understanding the design constraints and how the segments will be manufactured will lead the optics designer to develop a cost effective system balancing customer and supplier needs.

Introduction:

Extremely large telescope projects can only be achieved through the use of segmented primary mirrors. Currently there are several extremely large telescope projects in the planning phase. The primary mirrors of these designs range from 25 m to 100 m (see Table 1). As seen in Table 1, the majority of these designs required around 1000 or more hexagonal mirror segments. With this many individual mirrors, telescope mirrors are no longer custom one off designs. There is a huge potential for savings when the optical designer and the mirror substrate supplier understand each others constraints.

Schott ZERODUR glass has successfully been used to create single glass primary mirrors for nearly 40 years. The same material properties that make it good for single glass mirrors also make in an excellent material choice for creating segmented mirrors. A limited number of mirror blanks have been manufactured to meet the needs of past segmented telescopes, but as demand for segmented mirror blanks increases, the process will need to become more efficient. The following discussion will cover several topics relating to the physical, optical and material design aspects of segmented mirror blanks that can lead to efficient manufacturing and cost savings.

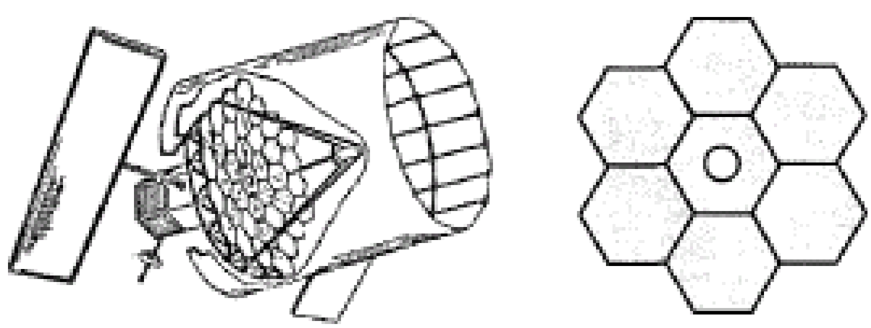

Figure 1: Segmented mirror concept

Project / Country	M1 Diameter	Number of segments	Segment dimensions
TMT / USA	30 m	861 hexagons	1.3 m (diagonal)
OWL / Europe	100 m	3048 hexagons	1.84 m (diagonal)
EURO50 / Europe	50 m	400 hexagons	2 m (diagonal)
CFGT / China	30 m	1122 segments	0.8 x 0.8 m
JELT / Japan	30 m	1080 hexagons	0.92 m (diagonal)
GMT / USA	25 m	7 discs	dia. 8.4 m

Table 1: Future planned telescopes designs with segmented mirrors

Segment Geometry:

Schott manufactures segmented mirror blanks which are typically based upon a hexagonal mirror pattern, but they do not have to be true hexagon shapes. Schott casts the mirror blank and then rough grinds it to the customer's dimensions. The blank is then polished by either Schott or another supplier to its optical prescription. See Figure 2 for some images of finished hexagonal mirror blanks. Originally Schott would cut round castings into hexagons. This old process required significantly more manufacturing time and produced significantly more waste because the hexagon shape was cut from a round blank. For additional cost savings, producing regular hexagons of various sizes is less expensive than producing irregular hexagon shapes. If the designer can constrain the design to regular hexagon mirror shapes, there will be cost savings.

Figure 2: Zerodur mirror blanks for LAMOST (left) and GTC (right)

Tolerance Considerations:

With hundreds or thousands of mirror blanks, tolerances are a significant concern. In production, the segment blanks will be sliced out of a thicker boule (Figure 3). In most cases a thickness tolerance of +/- 0.2 mm is normal and for the most part less critical. Tighter tolerances are not recommended. The larger tolerance range allows for cost savings in the event the surface needs to be improved by removing some additional fraction of the thickness during polishing. If tighter tolerances are required of the mirror blank, costs will increase. A trade off should be considered between the cost of the mirror blanks and the cost of the mount and/or actuator system could lead to savings.

Plano-concave blanks are easiest to produce, but meniscus shapes are doable as well. A profile tolerance of 0.2 mm for the optical surface is a readily achievable number. For the back surface, a 0.4 mm profile tolerance gives plenty of margin. Figure 4 contains a histogram of the profile tolerance of radial surfaces achieved during the GTC project. The front surface of the meniscus blank is concave while the back surface is convex. As shown in the figure, nearly all parts are well within specifications. These are ground blanks, they will require polishing to achieve the optical surface.

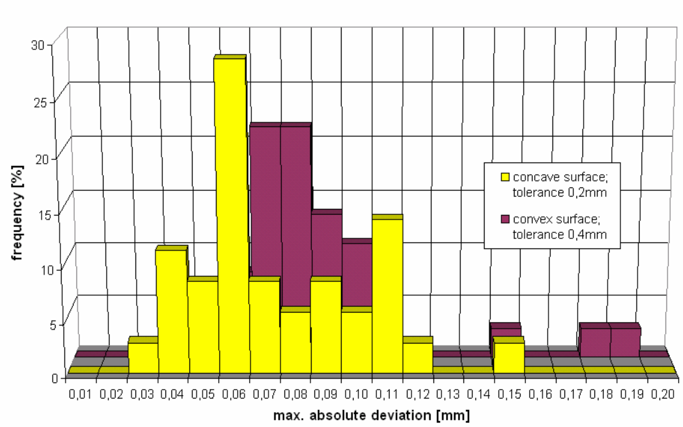

Figure 3: Raw Zerodur boule (left) Figure 4: Radial surface tolerances (right)

Chamfers:

An interesting topic regarding edge chamfers was brought up in this report. Almost all optical designs incorporate edge chamfers to prevent edge chips. However with segmented mirrors, sharp edges are preferred by the astronomers to avoid straylight and scattering. With approximately hundreds or thousands of mirror segments in the telescope during the various handling, installation and recoating steps the risk of edge chips becomes a serious issue. The specification of the chamfers can have a serious effect on image quality or cost. For the purpose of safety during handling Schott recommends a 3 – 4 mm / 45° chamfer around the optical surface. At this point, a detailed risk analysis is necessary to determine the best course of action between the straylight effects and the risk of end chips.

Blank Surface Roughness:

Diamond turning is used to finish the mirror blanks, but this is by no means an optical quality surface. It is also important to know that Zerodur has maximum crack depths equal to or smaller than the maximum grain size of the sieve fraction[2]. This creates roughly 60 micron cracks with typical diamond tooling. In other words, don't expect a smooth surface. The surface finish of Zerodur mirrors comes from the finishing process. Usually the optical finisher takes off a layer with additional lapping and polishing steps. This process typically removes the microcracks. With adequate polishing, surface roughnesses below 0.3 nm have been achieved with Zerodur. Simply don't require the mirror blank to have a smooth surface.

Bubbles, Inclusions and Striae:

Glass of this size is bound to have some imperfections. Fortunately, the glass is used with a reflective coating. Bubbles, inclusions, and striae have little to no effect as long as they are not on the optical surface. Schott manually checks each piece to ensure the surface and material near the surface is free from these imperfections. Schott can locate imperfections with a lateral position +/- 1 mm and a depth of +/- 2 mm. Current processes ensure the critical zone (4 mm of depth from the optical surface) is free from imperfections. This is obviously important for bubbles, but to be sure, the critical zone is also free of the other imperfections as well. It is important to note that significant defects rarely occur. Having optical properties too tight outside of the critical zone is counterproductive because this will decrease yield and increase testing costs.

Material Properties:

Schott designed Zerodur to have a thermal expansion coefficient of zero. This is why Zerodur is ideal for single glass mirrors. Some segmented telescopes have been created out of aluminum segments, but even with the ability to tilt compensate each individual segment to correct for thermal expansion, Zerodur would be my choice. Zerodur is currently supplied with a mean coefficient of linear thermal expansion (α) over the temperature range 0 °C to 50 °C in three expansion classes:

Expansion class 2: 0 +/- 0.10 · 10-6 / K
Expansion class 1: 0 +/- 0.05 · 10-6 / K
Expansion class 0: 0 +/- 0.02 · 10-6 / K

Every mirror blank can be measured to ensure this material property is met. The GTC telescope, consisting of 36 mirror blanks, was manufactured well within the specified range of expansion class 1. This test is costly. To save costs on future runs, Schott recommends sample testing blanks from the boule, with the boule acting like a lot. The CTE samples from one boule may be taken as a common reference for several blanks reducing costs.

Conclusion:

Products like Zerodur can overcome the technical issues presented by extremely large telescopes with a single mirror or with segmented mirrors. Extremely large segmented mirror telescopes have their own design considerations that need to be considered. Through careful engineering and planning taking into account the concerns presented, there is a significant potential for reducing costs. Understanding the supplier's constraints while designing the optical system will reduce costs, reduce the time to first light, and yield the best overall system.

References:

1. Thorsten Dohring, Peter Hartmann, Ralf Jedamzik, Armin Thomas, and Frank-Thomas Lentes, "Properties of Zerodur mirror blanks for extremely large telescopes", Proc. SPIE 6148, 61480G (2006), DOI:10.1117/12.674089
2. P. Hartmann: "Recommendations for the material adequate design of ZERODUR parts", Technical Information, SCHOTT, Mainz / Germany, June 1993