Material Characteristics of CLEARCERAM®-Z HS

for Use in Large Diameter Mirror Blanks

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ABSTRACT

There is growing interest within the Astronomical community in the development and use of very large aperture telescopes which will incorporate the latest advancements in optical materials. Two of the most notable of these large size telescope projects, the Thirty Meter Telescope (TMT) and European Extremely Large Telescope (E-ELT), will use mirror segments in the actively controlled primary mirrors. In this paper we present the results of a material characteristics study on Ohara CLEARCERAM®-Z HS large diameter blanks which includes data on the CTE, CTE uniformity, residual stress and internal quality targeting potential use in the TMT Primary Mirror Segment Banks.

1. Introduction

The Thirty Meter Telescope (TMT) is one of several next-generation Extremely Large Telescopes currently under development. This 30 m diameter telescope is being jointly developed by the California Institute of Technology, the University of California, and the Association of Canadian Universities for Research in Astronomy (ACURA). The TMT project seeks to establish a new high-performance telescope technology called Giant Segmented Mirror Telescope (GSMT) by refining segmented mirror technologies used to build the Keck I and Keck II telescopes (with effective diameters of approx. 10 m) on the summit of Mauna Kea, Hawaii. Expectations for the TMT continue to rise, since this next generation of telescopes will be significantly larger than the telescopes currently installed at any ground-based astronomical observatory.

The initial candidate sites for the construction of the TMT were Mauna Kea (Hawaii) and Cerro Armazones (Chile). In July 2009, Mauna Kea was selected as the preferred site. According to the current TMT roadmap, construction is scheduled to start in October 2011, with late 2018 given as the target date for first light. The TMT's 30 m diameter aspherical primary mirror will consist of 492 1.44 m mirror segments (+ 82 auxiliary segments).

Ohara Inc. has manufactured CLEARCERAM®-Z ultra-low expansion glass-ceramics for many years, recently establishing a manufacturing process and capability for large diameter blanks. The M1 Primary Mirror Segment Blanks for the TMT require extreme precision in various parameters, including thermal expansion, homogeneity, residual stress, internal quality, and other properties. This paper presents results of a material characteristics study on Ohara CLEARCERAM®-Z HS large diameter blanks and indicates the material will meet the TMT Specifications for M1 Primary Mirror Segment Banks.

CLEARCERAM®-Z is a SiO_2-Al_2O_3-Li_2O glass-ceramic with ultra-low expansion characteristics near room temperature. To create this product we studied the relationship between the volumetric percentage and thermal expansion properties of the mother glass (with a positive coefficient of thermal expansion) and the β-quartz solid solution (with a negative coefficient of thermal expansion). Based on our calculations and findings, we are able to create crystals uniformly within the mother glass so that the glass-ceramic achieves ultra-low thermal expansion characteristics. This material is isotropic. In order to achieve the coexistence of positive and negative expansion materials within a 1.5 m diameter glass-ceramic blank it requires advanced melting/forming technologies, annealing/crystallization technologies, and blank fabrication techniques. The CLEARCERAM®-Z series consists of three products, Regular, HS, and EX, each offering different coefficients of thermal expansion (Fig. 1). Due to its favorable characteristics and large size production capability, CLEARCERAM®-Z HS is the material Ohara is proposing for use in the TMT Segment Blanks.

The coefficient of thermal expansion
(Temperature range: 0 to 50°C)

Clearceram®-Z Regular : 0.0±1.0 (x 10^{-7} / °C)
Clearceram®-Z HS : 0.0±0.2 (x 10^{-7} / °C)
Clearceram®-Z EX : 0.0±0.1 (x 10^{-7} / °C)

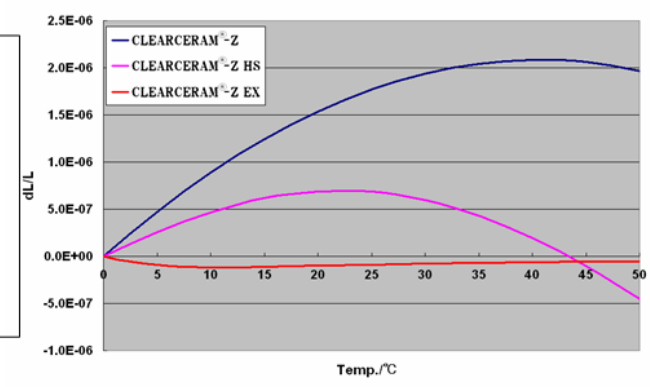


Fig. 1 Thermal expansion curves for CLEARCERAM®-Z

* Measured with Ohara's Fizeau-interferometer-type dilatometer

2. Manufacturing Processes

CLEARCERAM®-Z is manufactured by the following processes.

a) Material preparation/blending

Raw materials of precisely adjusted grain size and impurities are prepared and blended according to the composition specified for CLEARCERAM®-Z.

b) Melting

The raw material mixture obtained in step a) is melted in a melting furnace at temperatures of 1,300°C to 1,700°C. The glass material in this process contains formed glass, crystal nuclei, crystal components, refining components, and other substances in a mixed state. Conditions such as material feed, melting temperature/time, and refining conditions must be carefully controlled in order to produce a uniformly consistent product. Striae are indications of abrupt varying density within the glass and can be caused by phases or areas of slightly different composition. Striae occurs in sections or phases where the raw material components have poor uniformity or are not completely melted and results in a lack of homogeneity of the refractive indices. If the glass material features such a phase, the coefficient of thermal expansion after crystallization becomes uneven due to variations in glass composition and crystal solid solubility rates. The presence of such a phase can also result in defects (such as crystallization damage) that present themselves during manufacturing, due to differences in thermal expansion at the interfaces.

c) Forming/annealing

The molten material is poured into a mold and rapidly cooled producing a large size molded blank. During the pouring of the material, pouring speed and differences in heat dissipation temperatures within the molded blank can create layers or planes of striae. It is important to control the forming conditions precisely and minimize striae formation during this process to obtain homogeneity of the refractive indices, as was mentioned in step b). The formed glass is slowly cooled to room temperature to relieve stress and prevent internal distortions.

d) Machining

Given the low thermal conductivity of glass, heterogeneous layers generally form in a few sections of the glass surface or on the outer edge where the glass in contact with the mold, due to the significant difference in cooling rates between the surface and the interior portion of the glass. Since heterogeneous layers affect crystallization adversely, the surface and peripheral areas are removed via grinding operations utilizing diamond tooling, and these are referred to as “mother blanks”.

e) Crystallization

Crystallization is achieved by raising the temperature of the glass to the crystal forming temperature then maintaining the glass at temperature for a specific duration to achieve ultra-low expansion properties. This crystallization process must occur in a state in which heat is applied uniformly to the glass blank. Uneven heat distribution will generate distortions or cause variation in crystal grain size, resulting in uneven thermal expansion distribution.

f) Machining for glass ceramics

The surface and periphery are ground into the final cut disk shape utilizing diamond tooling to meet the specified dimensions.

g) CTE Measurements

All of the CTE measurements in this study were performed using Ohara’s Fizeau interferometer type dilatometer under the same conditions. The CTE of a specific test sample has been measured monthly using this dilatometer for several years, over the temperature range of 0 to 50 °C, and the repeatability (sigma) value is better than 0.02 x 10-7/°C.

3. TMT Specification for Primary Mirror Segment Blanks and properties of large-scale CLEARCERAM®-Z

Shown below is a comparison of the properties of the CLEARCERAM®-Z product with a diameter of 1,700 mm produced by the processes described in Section 2 and the TMT Specification for Primary Mirror Segment Blanks (TMT.OPT.SPE.07.001.CCR06).[1] It should be noted there have been subsequent revisions to the TMT specifications since we completed this study and we are now verifying our ability to comply with the latest revision.

3-1 Coefficient of thermal expansion

The TMT Primary Mirror Segment Blanks must meet the following requirements for thermal expansion. (TMT.OPT.SPE.07.001)

3.1.4 Coefficient of Thermal Expansion (CTE) Please note we have paraphrased the text from the TMT Specification	
SPE-M1.SEG.BLK-1400 SPE-M1.SEG.BLK-1410	The mean CTE for all blanks delivered: 0.0±0.4 x 10^{-7}/°C (-13 to +27°C) Standard deviation of average CTEs for all blanks about the mean CTE: ≤ 0.25 x 10^{-7}/°C (-13 to +27°C)
SPE-M1.SEG.BLK-1430	The lateral spatial variation of the CTE at any point within each blank of the Average CTE of the blank: ±0.1 x 10^{-7}/°C (-13 to +27°C)
3.1.5 Gradient of Coefficient of Thermal Expansion	
SPE-M1.SEG.BLK-1500 SPE-M1.SEG.BLK-1510	The mean CTE axial gradient: ≤ 0.45 x 10^{-7}/°C · m (-13 to +27°C) Standard deviation of the CTE axial gradient of all blanks about the mean CTE axial gradient: ≤ 0.45 x 10^{-7}/°C · m (-13 to +27°C)

We compared the above CTE specifications with the actual specifications for the 1,700 mm diameter CLEARCERAM®-Z produced by the manufacturing processes discussed in Section 2. The method and results of the evaluation are described below.

The glass material melted by the process described in Section 2 was molded into shapes measuring approximately 1,700 mm in diameter and 400 mm in thickness. The molded blanks were then machined and crystallized to produce eight mother blanks of three sizes: 1,650 diameter (dia.) x 350 mm thick (t), 1,650 dia. x 285 mm t, and 1,650 dia. x 274 mm t. The 1,650 dia. x 350 mm t mother blank we cut into 4 disks size 1,650 dia. x 87.5 mm t as shown in Fig. 2. The 1,650 dia. x 285 mm t and 1,650 dia. x 274 mm t mother blanks were cut into 3 disks each size 1,650 dia. x 87.5 mm t. Test pieces were obtained from 6 or 7 points distributed hexagonally on each piece, and the thermal expansion at each point was then measured (Fig. 3).

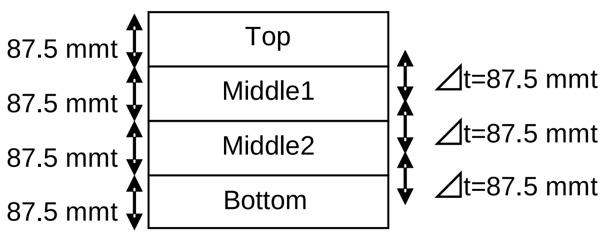


Fig. 2 Cutting locations and dimensions

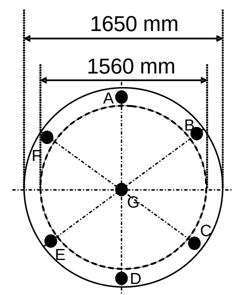


Fig. 3 Positions of test samples for thermal expansion measurements from each cut disk

In total, we produced 8 mother blanks and yielded 22 cut disks. From each cut disk, 6 or 7 test samples were removed and thermal expansion measurements performed. We measured the thermal expansion coefficient at a total of 141 locations. Table 1 provides detailed information on the test samples used for the thermal expansion measurements.

Lot	Mother Blank Size	# of Cut Disks Measured (Size ϕ1650 x 87.5 mm)*	CTE Samples /Disk **	# of CTE Samples Measured
A-1	ϕ1650 x 350 mm t	4	7	28
A-2	ϕ1650 x 285 mm t	3	7	21
A-3	ϕ1650 x 274 mm t	2	7	14
A-4	ϕ1650 x 350 mm t	3	6	18
A-5	ϕ1650 x 350 mm t	4	6	24
A-6	ϕ1650 x 350 mm t	2	6	12
A-7	ϕ1650 x 350 mm t	2	6	12
A-8	ϕ1650 x 350 mm t	2	6	12
Totals	8	22	51	141

Table 1 Details of test samples used for thermal expansion measurements

* 2 to 4 disks were cut from each mother blank.

** From A-1 through A-3, test samples at center point G were also obtained for a total of 7 samples / disk.

Table 2 lists the detailed results of measurements for Lot A-5 in accordance with Fig. 2 and 3.

Coefficient of Thermal Expansion [x 10^{-7}/°C]											
Position	A	B	C	D	E	F	Mean	Max	Min	Standard Deviation	Lateral Spatial Variation
Top	0.26	0.26	0.24	0.28	0.24	0.24	0.25	0.28	0.24	0.02	-0.03
Middle1	0.25	0.25	0.26	0.28	0.27	0.27	0.27	0.28	0.25	0.01	+0.02
Middle2	0.25	0.22	0.23	0.28	0.23	0.24	0.24	0.28	0.22	0.02	-0.04
Bottom	0.22	0.22	0.26	0.25	0.24	0.23	0.24	0.26	0.22	0.02	±0.02
Total							0.25	0.28	0.24	0.02	-0.03
Specification	0.0±0.4									≤ 0.25	< ±0.1
Judgment	OK									OK	OK

Table 2　Results of measurements of the coefficient of thermal expansion for Lot A-5

The gradient of the coefficient of thermal expansion is defined as the value obtained by dividing the difference of the mean CTE values of the blanks obtained (as shown in Fig. 1) by the distance between the cut disks. Table 3 gives the CTE gradient values for 4 cut disks coming from 1 mother blank (Lot A-5).

Position	Distance [m]	|⊿CTE|	CTE Gradient [|x 10^{-7}/°C · m|]	Judgment (Specification:≤ 0.45 x 10^{-7}/°C · m)
Top-Middle1	0.088	0.012	0.13	OK
Middle1-Middle2	0.088	0.023	0.27	OK
Middle2-Bottom	0.088	0.005	0.06	OK
Top-Middle2	0.175	0.012	0.07	OK
Middle1-Bottom	0.175	0.028	0.16	OK
Top-Bottom	0.263	0.017	0.06	OK

Table 3　The result of gradient of coefficient of thermal expansion for Lot A-5

Table 4 summarizes the verification results for all Lots A-1 through A-8 and demonstrates reproducibility among the lots.

Lot	Mean CTE [x 10^{-7}/°C]	Lateral Spatial Variation [x 10^{-7}/°C]	CTE Gradient [|x 10^{-7}/°C · m|]	Judgment
Specification	0.0±0.4	< ±0.1	≤ 0.45	OK
A-1	0.22 to 0.25	0.02 to 0.08	≤ 0.30	OK
A-2	0.28 to 0.30	0.03 to 0.05	≤ 0.15	OK
A-3	0.26 to 0.28	0.02 to 0.06	≤ 0.10	OK
A-4	0.25 to 0.26	0.02 to 0.06	≤ 0.05	OK
A-5	0.24 to 0.27	0.01 to 0.04	≤ 0.12	OK
A-6	0.20 to 0.21	0.02 to 0.05	≤0.02	OK
A-7	0.19 to 0.21	0.03 to 0.04	≤ 0.08	OK
A-8	0.27	0.02 to 0.06	≤ 0.01	OK

Table 4　Results of evaluations of the coefficient of thermal expansion for all blanks

Summarized below are the evaluation results for each of the thermal expansion parameters specified in TMT.OPT.SPE.07.001.

< SPE-M1.SEG.BLK-1400 >

According to the specification, the mean coefficient of thermal expansion of all samples must be 0.0±0.4 x 10^{-7}/°C in the temperature range of -13 to +27°C. Using 8 mother blanks, which produced 22 cut disks, we measured the coefficient of thermal expansion at 141 points. The results of measuring 141 samples indicated a mean value of 0.25 x 10^{-7}/°C, a maximum value of 0.34 x 10^{-7}/°C and a minimum value of 0.15 x 10^{-7}/°C. These results indicate the 141 samples meet the mean CTE requirements.

< SPE-M1.SEG.BLK-1410 >

According to the specifications, the standard deviation of average CTEs for all blanks about the mean CTE must be ≤ 0.25 x 10^{-7}/°C in the temperature range of -13 to +27°C. After measuring 141 samples the standard deviation was 0.039 x 10^{-7}/°C and this meets the specification.

< SPE-M1.SEG.BLK-1430 >

The requirement specifies the lateral spatial variation of the CTE at any point within each blank be within ±0.1 x 10^{-7}/°C (-13 to +27°C) of the Average CTE of the blank. Actual deviations were ≤ ±0.08 at the 141 points, meeting the requirement.

< SPE-M1.SEG.BLK-1500 >

According the specification, the gradient of thermal expansion must be ≤ 0.45 x 10^{-7}/°C · m. The gradient of thermal expansion for 22 points based on the number of samples shown in Table 1 was ≤ 0.30 and met the requirement.

According to the results described above, CLEARCERAM®-Z produced by the manufacturing method described earlier meets the TMT CTE (3.1.4) and CTE gradient (3.1.5) specifications. Producing glass that meets such rigorous specifications requires painstaking attention to detail during the manufacturing processes. Some of the key areas include: conditions for the preparation of raw materials (mixing/blending accuracy, duration and humidity control), melting conditions (temperatures, balance and stirring), forming conditions (temperatures, balance and cooling speed), annealing and crystallizing conditions (temperatures and rate of temperature increase/decrease), and machining conditions (coolant, coolant temperature, tools and rates). Since the combination of these factors affect the uniformity of the material, precise control is essential to produce crystallized glass with high refractive indices homogeneity, which inevitably results in excellent thermal expansion coefficient distribution in the crystallized glass.

To assess the uniformity of blanks produced by the manufacturing methods described in Section 2, we measured the homogeneity of disks cut from a CLEARCERAM®-Z mother blank size 1,650 dia. x 290 mm t. We sliced the mother blank into 2 blanks and from each of these blanks, we obtained 7 samples (14 samples in total) size 380 dia. x 80 mm t from the positions shown in Fig. 4. We ground the surfaces of these 14 samples with # 80 grit and the edge chamfer with #230 grit. We measured the homogeneity of these 14 samples with a Zygo Mark IV interferometer. Table 5 shows the measurement results.

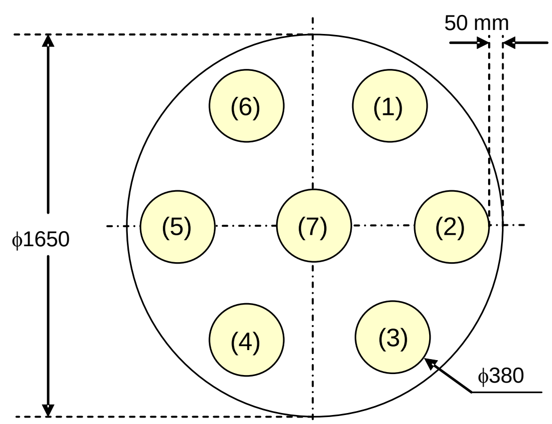


Fig. 4 Positions of the homogeneity measurement samples cut from the CLEARCERAM®-Z blanks

PV value (ppm)										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	Average	Max	Min
Top	2.54	1.19	1.62	1.64	0.99	1.98	1.53	1.64	2.54	0.99
Bottom	1.48	2.59	1.15	1.76	1.05	1.41	0.67	1.44	2.59	0.67

Table 5 Homogeneity measurement results of CLEARCERAM®-Z disks size 380 diameter x 80 mm thick

Fig. 5 shows an interferogram of sample TOP (4) PV = 1.64 ppm.

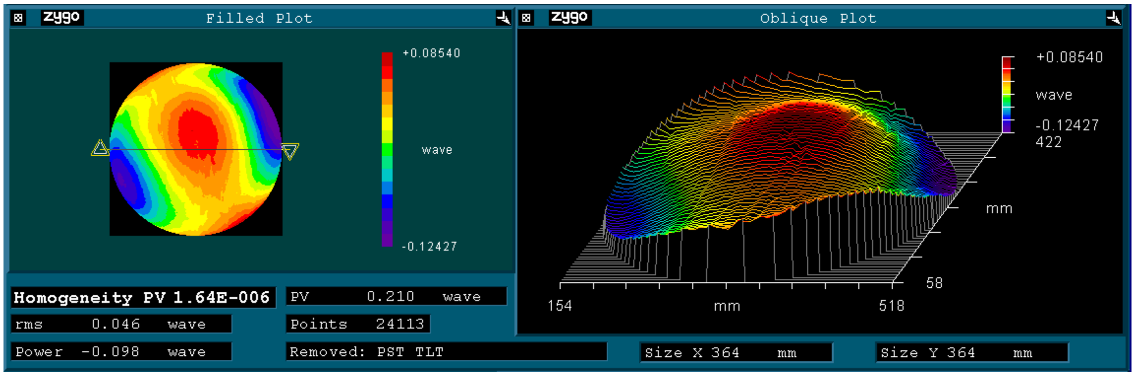


Fig. 5 Homogeneity map of sample TOP (4) size 380 diameter x 80 mm thick

In order to achieve such high levels of homogeneity we must avoid generating striae during the melting and forming operations and creating flaws or defects in the crystallized glass during the manufacturing process that might affect the physical properties. The results of the homogeneity measurements described above confirm the excellent quality of this glass-ceramic. The high degree of homogeneity results in uniform thermal expansion distribution, as well as other important internal quality distribution characteristics (discussed further below).

3-2 Residual stress characteristics

The following specifications apply to the residual stress characteristics for the TMT Primary Mirror Segment Blanks:

3.2 Residual Stress	
SPE-M1.SEG.BLK-2000	≤ 0.2 Mpa anywhere in the blank. Verified by measuring at 13 locations: 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, 330° at radius of 672+/-10mm and at Center.

Residual stress is generally expressed as follows:

Residual Stress (Pa) = Stress Birefringence (nm/cm) / Photoelastic Constant (nm/cm/Pa)

Since the photoelastic constant of CLEARCERAM®-Z is 3.0 x 10^{-5} nm/cm/Pa, the stress birefringence characteristic must be ≤ 6 nm/cm to achieve the required residual stress of ≤ 0.2 MPa. As part of our verification, we performed strain measurements using sample A-3 (Table 1). The sample measured 1,545 dia. x 58 mm t and its surface and periphery were machined with #80 grit and #100 grit, respectively. Table 6 shows the measurement results.

Location	Stress Birefringence [nm/cm]	Calculated Stress [MPa]	Location	Stress Birefringence [nm/cm]	Calculated Stress [MPa]
0°	3.4	0.11	270°	1.9	0.06
30°	2.1	0.07	300°	1.1	0.04
90°	4.1	0.14	330°	1.5	0.05
120°	1.5	0.05	360°	2.1	0.07
150°	0.3	0.01	Center	2.1	0.07
180°	0.9	0.03	Average	1.8	0.06
210°	1.0	0.03	Max	4.1	0.14
240°	1.2	0.04	Min	0.3	0.01

Table 6 Stress birefringence measurement results and calculated stress values for sample A-3

Production conditions, such as temperature distribution during glass formation, annealing conditions, temperature distributions during annealing, and crystallization conditions, must be closely examined to minimize stress birefringence in glass or crystallized glass. For the manufacturing method described in this paper, those conditions were determined based on the results of thermal simulations performed for each process, with the goal of minimizing distortions in the area of the product used for the TMT Primary Mirror Segment Blanks. In general, the manufacturing processes described in the paper result in larger distortions at locations close to the periphery due to the low heat conductivity of the glass (including glass in the liquid state), the heat capacity of the bulk glass, and the greater amount of heat diffused to the mold and toward the surface. Thus, residual stress located at points towards the center of the glass is expected to be equal to or lower than the measurements obtained in our experiment. The samples we measured using this manufacturing method met the TMT residual stress specifications (as shown in Table 6).

3-3 Internal quality characteristics

Shown below are the internal quality characteristics required for the segmented blanks for the TMT Primary Mirror Segment Banks:

3.5 Bubbles and Inclusions Please note we have paraphrased the text from the TMT Specification		
	Inside Critical Zone*	Outside Critical Zone**
SPE-M1.SEG.BLK-5010 Maximum mean diameter of any inclusion	1 mm	3 mm
SPE-M1.SEG.BLK-5020 Mean number of inclusions per blank	6	100
SPE-M1.SEG.BLK-5030 Maximum number of inclusions per any contiguous $100cm^3$ volume	N/A	10

* The Critical Zone is defines as the volume of material that is within 2 mm of the concave surface of the blank and the central 145 cm diameter.

**The minimum mean diameter of inclusions to be considered (detection limit) is 0.3 mm Inside the Critical Zone and 0.5 mm Outside the Critical Zone.

Sample A-3 shown in Table 2 was processed into a cut disk size 1,545 mm dia. x 58 mm t and its internal quality was visually checked by an inspector. The visual inspection provided accuracy at the 0.1 mm level, based on numerical measurements with a microscope. Table 7 gives the results.

	Result	Judgment
SPE-M1.SEG.BLK-5010	Largest inclusion was 0.8 mm	OK
SPE-M1.SEG.BLK-5020	18 inclusions in the sample blank, all located outside the Critical Zone	OK
SPE-M1.SEG.BLK-5030	No inclusions were found in the 15 pieces of 100 cm^3 random samples we selected	OK

Table 7 Results of internal quality inspections on Sample A-3

The following is a summary of the evaluation results of for each item related to TMT.OPT.SPE.07.001 distortion characteristics.

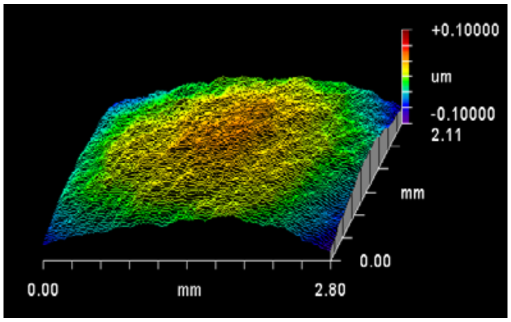
< SPE-M1.SEG.BLK-5010 >

We visually inspected the interior portion of a cut disk size 1,545 mm dia. x 58 mm t using focused light. The results showed that the diameters of the largest bubbles and inclusions were ≤ 0.8 mm in all zones, fully meeting the specifications for the inside critical zone.

< SPE-M1.SEG.BLK-5020 >

Bubbles and inclusions measuring 0.3 mm or more were counted and their locations recorded. A total of 18 such objects were found, all located outside the critical zone. We carefully analyzed the defects and found that all of them were inclusions, not bubbles. The result of our analysis showed the inclusions to be SiO_2-Al_2O_3-Li_2O negative expansion crystals, the same as the internally formed crystals in CLEARCERAM®-Z. We believe infinitesimal amounts of metals mixed in during processing in the melting furnace or another process acted as crystal nuclei, causing the formation of crystals identical to internally formed crystals. These objects do not in themselves affect physical properties, but their potential to damage the glass in ways that may affect optical/physical properties must be elucidated. To do so, we processed and polished a separate sample of CLEARCERAM®-Z, containing bubbles of about 0.5 mm in size, and the above-mentioned crystallized glass Sample A-3, with inclusions of about 0.5 mm in diameter, so that the bubbles and inclusions appeared at the surfaces. We then measured their surface shapes. As shown in Fig. 6, air cavities of bubbles resulted in pits, but the inclusions had no effects on the polished surfaces. We also repeated the process of machining and observation several times until the inclusions were exposed at the surface. However, the inclusions failed to come loose from the surface. We suspect a minor binding reaction occurred between the polished inclusions and the glass in contact with the inclusions. It is our considered opinion that such inclusions will have no effect on the polished surface.

< Inclusion (crystal) >



< Bubble >

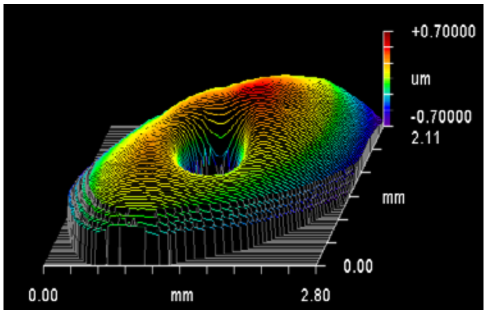


Fig. 6 Detailed images of a bubble and inclusion on the polished surfaces

< SPE-M1.SEG.BLK-5030 >

We arbitrarily selected 15 points from a three-dimensional space in Sample A-3 to check the number of inclusions measuring 100 cm^3 (50 x 50 x 40 mm). As indicated by the SPE-M1.SEG.BLK-5020 inspection results, the total number of inclusions found outside the critical zone in this sample was 18. However, since the 18 objects were uniformly distributed, we were unable to detect any at the randomly selected 15 locations.

4. Conclusion

The results of our verification indicated a mean CTE value (-13 to +27°C) of 0.19 to 0.30 (x 10^{-7}/°C). The results of CTE measurements at all 141 points ranged from 0.15 to 0.34 (x 10^{-7}/°C). The CTE lateral spatial variation was ≤ 0.08(x 10^{-7}/°C). The CTE gradient was < 0.30(x 10^{-7}/°C · m). The residual stress was ≤ 0.14 MPa. The maximum diameter of any bubble or inclusion was 0.8 mm. The number of internal inclusions found was 18 in a blank, all of them located outside the critical zone. The number of inclusions per any contiguous 100cm^3 volume density of internal inclusions was ≤ 1 piece. All these parameters tested meet the TMT Specification for Primary Mirror Segment Blanks (TMT.OPT.SPE.07.001.CCR06). We have demonstrated and verified on full size blanks that Ohara CLEARCERAM®-Z is a suitable material for use in the TMT Primary Mirror Segment Blanks. Additionally, the homogeneity of the crystallized glass was < 3 ppm on 14 sample disks size 380 diameter x 80 mm thick. The CLEARCERAM®-Z offers excellent internal quality and thermal characteristics.

Several candidate materials currently offer the properties (low expansion, strength, durability) and the dimensional requirements for use in the TMT primary mirror. Crystallized glass appears superior to the others for its ultra-low thermal expansion, a critical aspect for the application in question. Among several types of crystallized glass, CLEARCERAM®-Z provides the advantage of low viscosity at a given temperature, which not only makes it easier to eliminate bubbles during melting, but also helps to minimize striae formation. Furthermore, the compositional design of CLEARCERAM®-Z results in optimal conditions for crystallinity and processing characteristics (abrasion, hardness) for excellent workability.[2]

Due to its superb characteristics, CLEARCERAM®-Z is now being used for various applications, including stages and mirrors for semiconductor/LCD exposure equipment, large scales, and aerospace related materials, among others, in addition to use as a material for mirrors in large telescopes.

As telescopes continue to grow in size, it is our hope that CLEARCERAM®-Z ultra-low expansion material will become an enabling component, helping to advance the state of the art for extremely large telescopes, and other technologies as well.

5. References

1) SPECIFICATION FOR PRIMARY MIRROR SEGMENT BLANKS (TMT.OPT.SPE.07.001.CCR06)
2) Chris Ghio, Kousuke Nakajima and Jessica DeGroote, “Manufacturability study of CLEARCERAM®-Z(T008) compared to other low CTE materials,” Optical Society of America, 2008

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