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SCHOTT ZERODUR® Glass-Ceramic

A Closer Look at ZERODUR®: CTE Homogeneity and Mechanical Properties

Introduction

SCHOTT Academy of Optics is a free, online seminar series designed to take your industry knowledge and expertise to new levels.

Throughout the series, you will learn from leading glass and material experts as they cover various topics pertaining to the optics industry.

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Advanced optics used in space applications must perform in extreme environments. During just one orbit, telescope mirrors aboard satellites cycle through hours of hot sunlight followed by the cold darkness of space.
These temperature swings are not only large but also occur outside the room temperature ranges in which the optics were assembled. Mechanical stability is also critical for ensuring that the optics survive the forces of up to five times Earth's gravity experienced during a rocket launch.

Figure 1: High-resolution optics in space need to be highly reliable, but face challenges that require a high thermal and mechanical stability as well as high-precision processing.

Thanks to its superior thermomechanical properties, SCHOTT's ZERODUR® glass-ceramic has risen to meet the challenges of space applications for more than 50 years. This unique material not only exhibits a near zero coefficient of thermal expansion (CTE) over a large temperature range but also features a highly homogeneous CTE throughout its entire volume. This means that the material does not expand or contract in response to temperature changes. In addition, excellent mechanical properties mean its optical properties remain unchanged even after a strenuous launch into space.

1. Precision CTE homogeneity measurements

A high CTE homogeneity throughout the volume of a blank is critical for preventing surface deformations that can form on a space mirror in response to changes in temperature. Although materials such as silicon carbide exhibit high diffusivity, they will still experience surface deformations in response to large changes in temperature. Thus, a high diffusivity cannot compensate for a high CTE as shown in Figure 2.

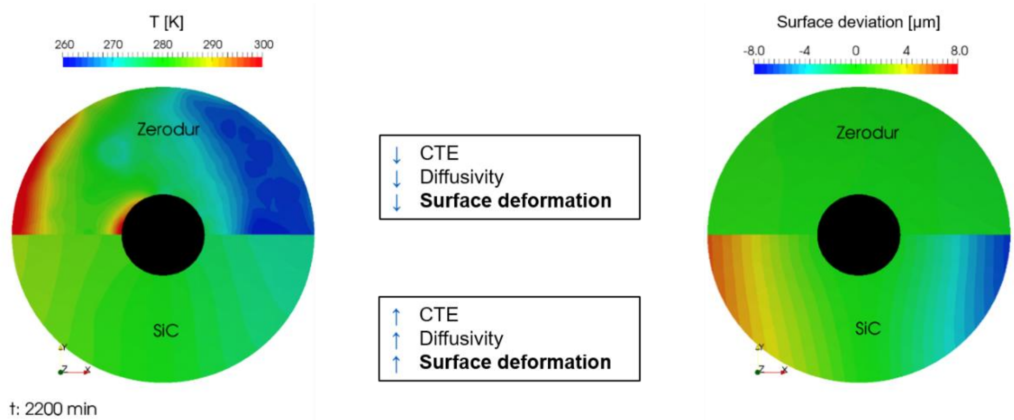

Figure 2: Comparison of a low CTE, low thermal diffusivity material (ZERODUR®, top) and a higher CTE, higher thermal diffusivity material (bottom): simulated temperature gradients induced by orbiting (left) and resulting surface deformation (right).

Evaluating the CTE homogeneity of a mirror blank involves measuring the CTE of samples from various locations of the component and then calculating the CTE difference between the highest and the lowest value measured.

ZERODUR® typically exhibits single digit ppb/K CTE homogeneity for parts up to 4 m in size. This translates into almost no short range CTE variation observed on the millimeter scale within ZERODUR® parts.

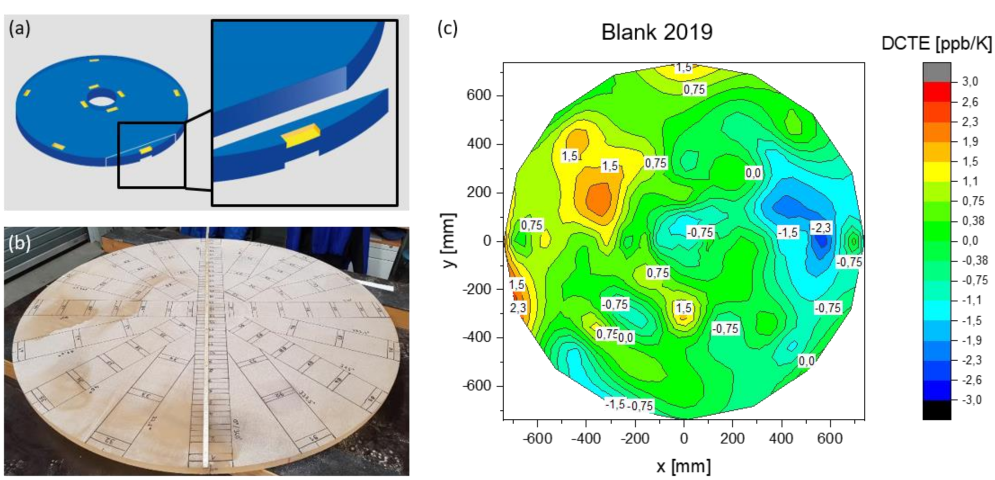

Figure 3: CTE homogeneity measurements: (a) schematics of the sample (yellow) extraction, (b) photography of the marked CTE sample positions to extract for the CTE mapping in (c) The blank measured in 2019 exhibits a CTE homogeneity of 5.3 ppb/K.

To measure CTE homogeneity, we use highly accurate push rod dilatometers that are built in house. Samples are cut from either the component's outer circumferential area or near a center hole as well as from the top and bottom.

Between four and 24 samples, each typically 100 X 6 X 6 mm, are used for the analysis.
For the standard measurement, the samples are subjected to a specific heat and cooling cycle between 0°C to 50°C. SCHOTT has been refining this analysis for years and with our latest dilatometer, can

achieve an accuracy of +/- 3 ppb/K and reproducibility of +/- 1 ppb/K. This equates to extremely accurate homogeneity evaluation.

The excellent CTE homogeneity achievable for single blanks is also available for serial production. SCHOTT is in the process of demonstrating this capability by producing the 949 1.5-m mirror blanks that will make up the main mirror for the for the European Southern Observatory's Extremely Large Telescope, which will be built in northern Chile.

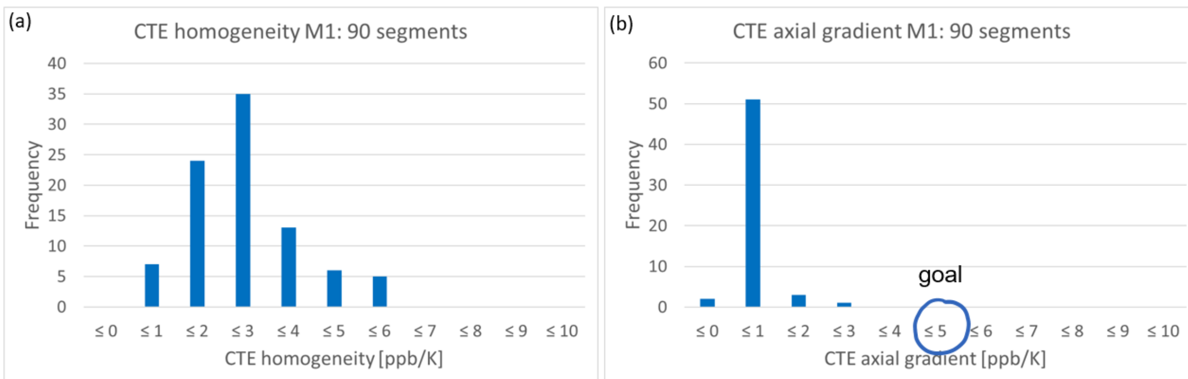

Figure 4: CTE homogeneity measured from 90 mirror blanks dedicated for the Extremely Large Telescope: the CTE results within the plane as well as along the axis exhibit single digit ppb/K.

2. Mechanical stability and surface deviation

In addition to being robust against the temperature changes, ZERODUR® also exhibits a high mechanical strength that makes it able to survive the vibrations and force experienced during a rocket launch. SCHOTT's fabrication expertise also ensures that the final components are made in a way that resist breakage.

The bending strength of a mirror blank depends on its surface conditions. These blanks are created using a diamond grinding process that inherently introduces micro cracks that can limit the strength of the part, depending on how deep they go.

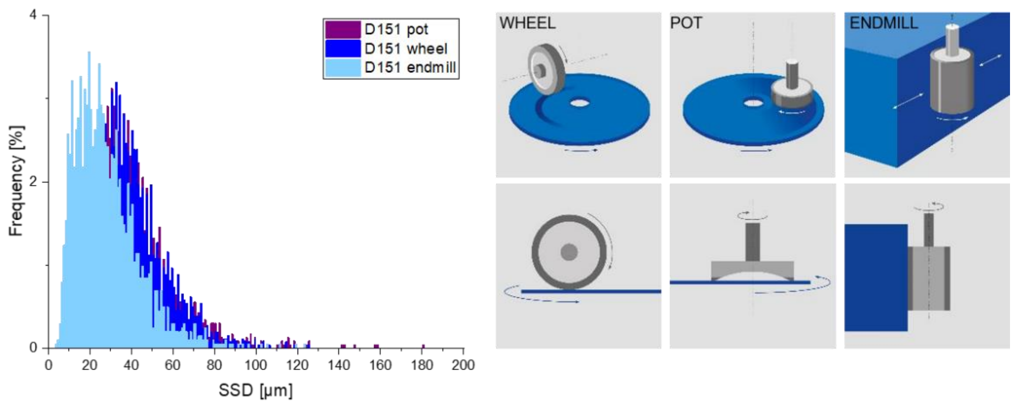

Figure 1: Sub-surface damage dependence on the tool and grinding geometry compared for wheel, pot and endmill geometry.

When stress is placed on a part, it can quickly increase the size of micro cracks, leading the glass-ceramic to break. The depth of this subsurface damage is determined by the grain size of the tools, tool geometry and other parameters related to the processing. By taking extreme care during the grinding process and using the smallest grain size possible, subsurface damage can be limited to just 10 to 15 microns.

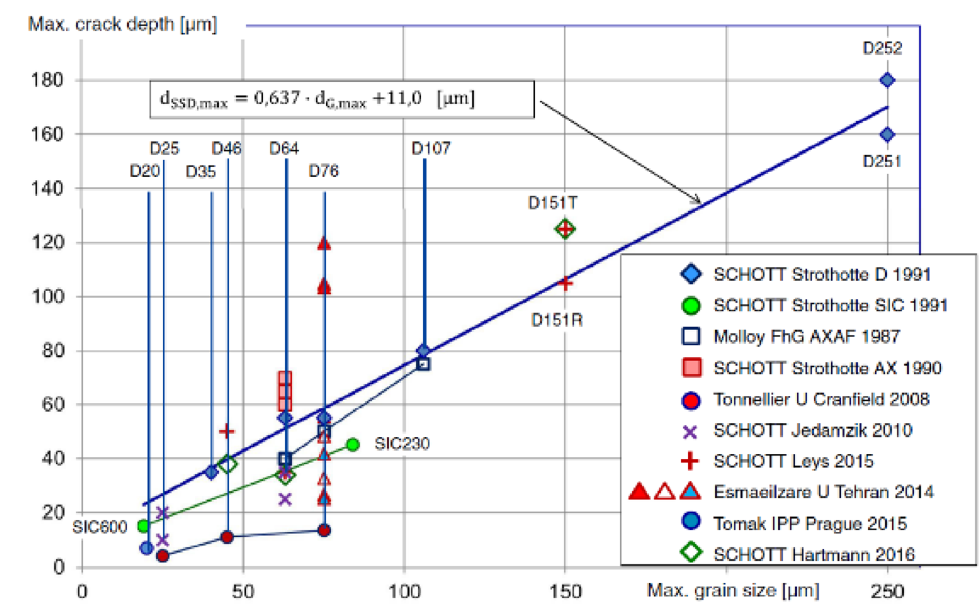

Figure 2: Correlation of sub-surface damage to the grain size of abrasive processing such as grinding and lapping. Smallest sub-surface damage of < 20 µm are possible.

SCHOTT has invested a great deal of effort in measuring and providing data on the bending strength of ZERODUR®, which is evaluated using the ring-on-ring strength test.

For this analysis, between 50 and 150 samples measuring 100 X 100 X 6 mm are cut from a large blank. Stress on each sample is typically increased at a rate of 2 MPa/s until it breaks, which takes about a minute.

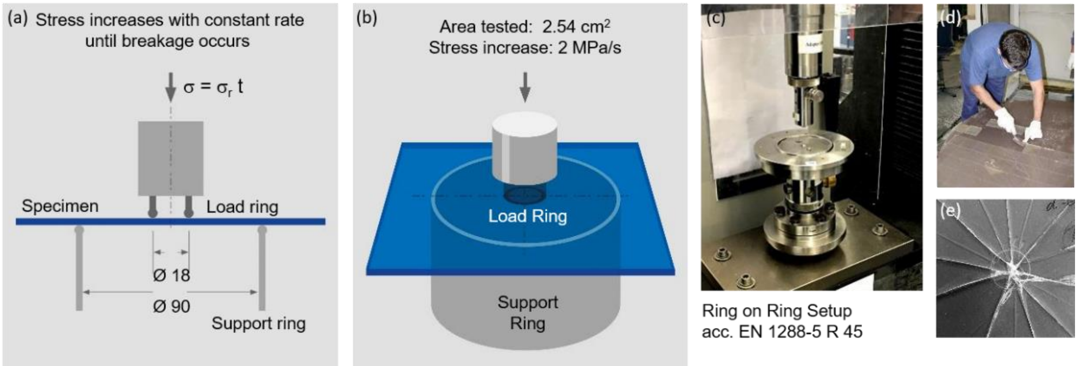

Figure 3: Setup and execution of breakage test for the evaluation of bending strength: (a,b) show the setup schematically, (c) is a photo of the ring on ring setup used, (d) shows the sample extraction from the blank and (e) is a microscopy top view impression of a typical crack.

Although the resulting stress values can be used to create a frequency distribution, this will not reveal rare events that lead to breakage. We have found that applying three-parameter Weibull statistics to the stress values are the best way to determine the bending strength threshold — the minimum strength below which breakage probability is zero. Three-parameter Weibull distributions are more realistic than the two-parameter version because they account for the fact that there is a limit to how big a crack could be.

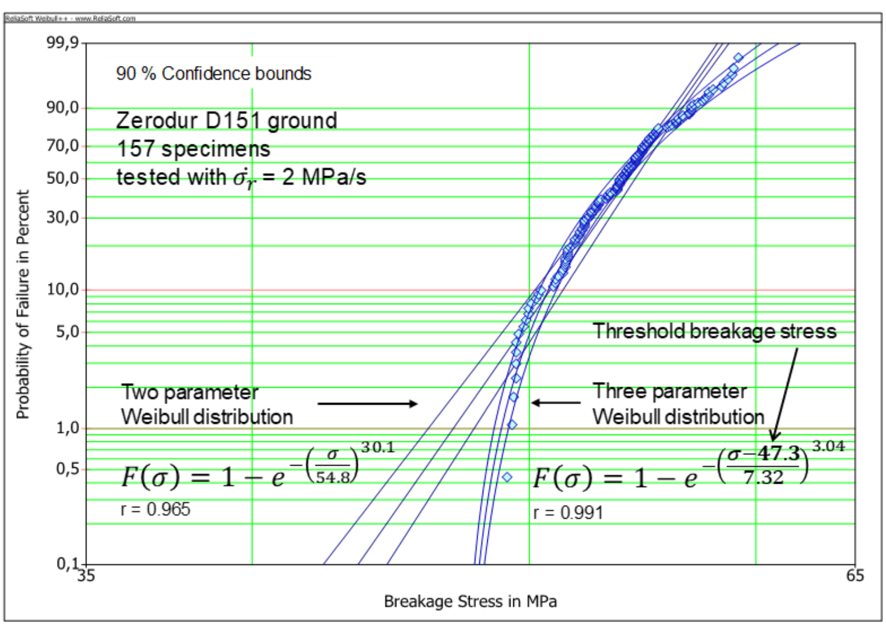

Figure 4: Probability of failure as a function of breakage stress: Fitting the three-parameter Weibull statistics enables the extrapolation towards a threshold breakage stress.

If you examine the Weibull distributions for surfaces ground with various grain sizes, you will see that strength increases with lower grinding tool grain sizes because they produce smaller micro cracks. Our data shows that ground surfaces can exhibit strength of better than 30 MPa. However, it is important to note that this data is only valid for stress that was ramped up over just one minute. In real-world applications, optics are usually exposed to much lower stress rates over longer periods of time. A lifetime calculation can be used to better understand these situations.

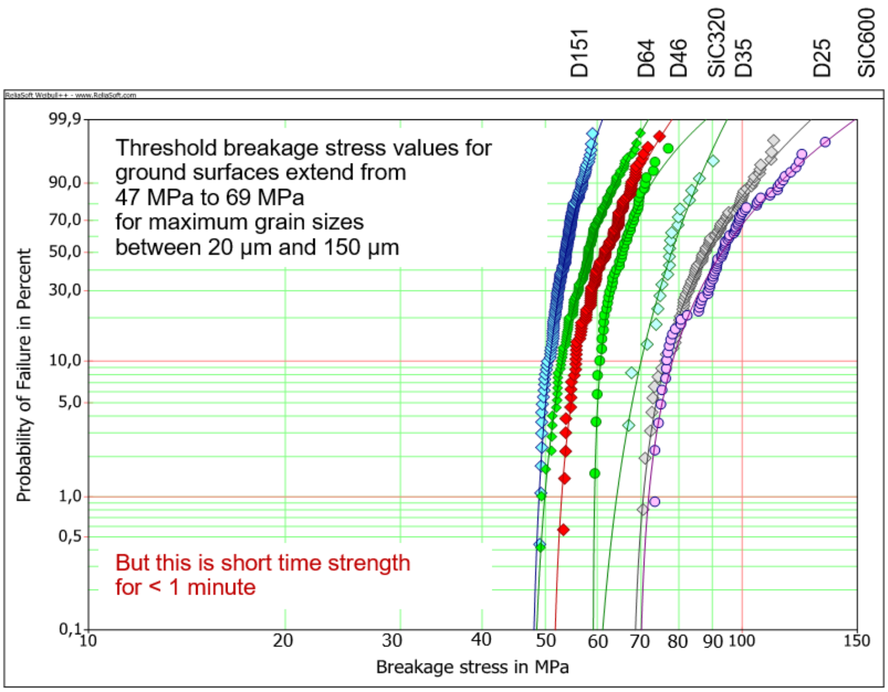

Figure 5: Comparison of bending strength for surfaces machined using different diamond grain sized between D151 and D25 as well as for surfaces machined with SiC grains: The breakage stress threshold increases with finer grain sizes.

Acid etching can be used to further decrease subsurface damage and improve strength to better than 90 MPa. The acid treatment rounds out crack tips, which are almost always the source of breakage. Through experienced subcontractors, SCHOTT offers acid etching for light-weight structures, monolithic blanks up to 4 m in diameter and serially produced blanks.

Want to learn more about ZERODUR®?

More information on ZERODUR's mechanical strength is available in the paper Minimum Lifetime of ZERODUR Structures Based on the Breakage Stress Threshold Model.

You can also visit our website for more information and resources: www.schott.com/products/zerodur.