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SCHOTT ZERODUR® Glass-Ceramic

A Closer Look at ZERODUR®: Bending Strength and Lifetime Calculations

Introduction

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When optics are used in space they must be reliable and long-lasting so that they can operate at high performance levels for many years. This requires materials with high thermal stability to withstand the drastic temperature changes experienced in space and high mechanical stability to survive the rocket launch. SCHOTT's ZERODUR® glass-ceramic has been meeting these rigorous requirements for more than 50 years.

ZERODUR's® unique properties include a near-zero coefficient of thermal expansion over a wide temperature range with excellent homogeneity over the whole volume. It is available in five expansion classes with different thermal behaviors and can also be tailored to specific application temperature profiles. The material can be used to make a variety of geometrical shapes that measure up to 4.5 meters in diameter.

1. How is bending strength experimentally evaluated?

The bending strength of a material plays a key role in its mechanical stability. For ZERODUR® bending strength is strongly dependent on the subsurface damage that occurs during surface processing with diamond grain tools (e.g. D151 to D25 with grain sizes between 150 to 20 µm). To test the bending strength, the first approach is to use a statistical evaluation approach. This involves performing a ring-on-ring test where 50 to 150 samples measuring 100 x 100 millimeters are produced with the grinding methods being studied. These samples are placed on a load ring that ramps up the stress on the sample at a rate of ~2 MPa per second. At this rate, it only takes seconds to minutes to reach the range where breakage occurs (Figure 1).

The tensile stress at which each sample breaks is then recorded, and a Weibull evaluation is carried out. The Weibull distribution plots the failure probability in percent versus the breakage stress. The three-parameter Weibull distribution fits the data of ground surfaces best and provides a threshold stress limit. Using this analysis, a ZERODUR® sample ground with a D151 tool exhibits a threshold stress limit of 47.3 MPa.

The threshold stress limit can be increased by using finer grounding grains, which reduces the depth of subsurface damage. Acid etching offers a way to add even more strength by rounding the crack tip and thus removing subsurface damage. For example, applying acid etching to the D151 samples will move the threshold from just over 47 MPa to above 100 MPa.

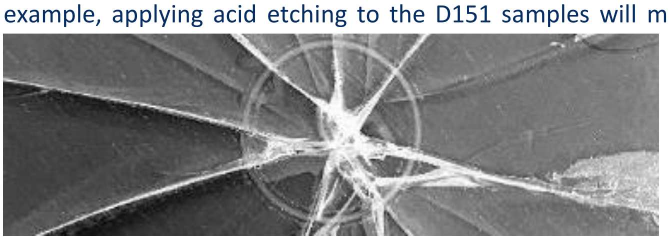

Figure 1: Close up picture of cracks in a ZERODUR® plate used to determine the bending strength experimentally.

2. What approach is used for lifetime calculations?

For lifetime calculations, it is important to keep in mind that with enough time, a crack can grow even below a critical stress range. A deterministic approach is necessary to figure out how long it would take to break a ZERODUR® piece with a given crack length if a certain stress is applied.

The most common crack-opening mode is the one where the crack is pulled open (Figure 2). The deterministic strength of this type of crack depends on the stress-intensity factor and fracture toughness. While the critical stress-intensity factor – leading to breakage – of ZERODUR® can be evaluated with different methods, a value of 0.9 MPa $m^{1/2}$ is commonly used for calculations. The geometry factor, which is determined by the geometry and position of the crack in relation to the length and width of the part, must also be considered. For example, for a ZERODUR® sample ground with a D151 tool an edge crack of length 180 µm with a geometrical factor of 1.1 can be assumed to produce a critical nominal stress of 60 MPa.

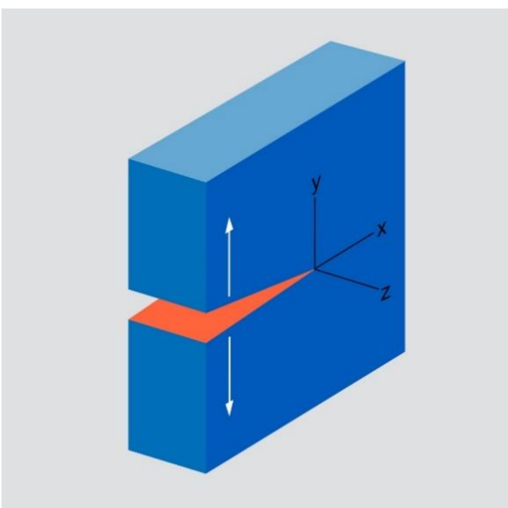

Figure 2: The crack opening mode is the dominant mode for occurring during breakage of ZERODUR®.

Taking the lifetime calculation even further requires considering the influence of humidity and the fact that tensile stress is enhanced by orders of magnitude at the crack tip. This stress enhancement provides enough energy for a reaction between water and silicone oxide bonds that will open a crack further.

Observations of a crack opening can be used to generate a crack growth curve that represents the logarithm of the crack velocity as a function of the logarithmic stress intensity factor. The stress corrosion area is the linear part of the curve with a given slope, which is the stress corrosion constant. This constant indicates that as the tensile stress or stress-intensity factor increase, so will the velocity of the crack opening.

A very steep curve in this region, i.e. a low stress corrosion constant indicates that the initial crack velocity is much lower. This means that it will take longer for the part to break, and, thus, the part will have a much longer lifetime (Figure 3).

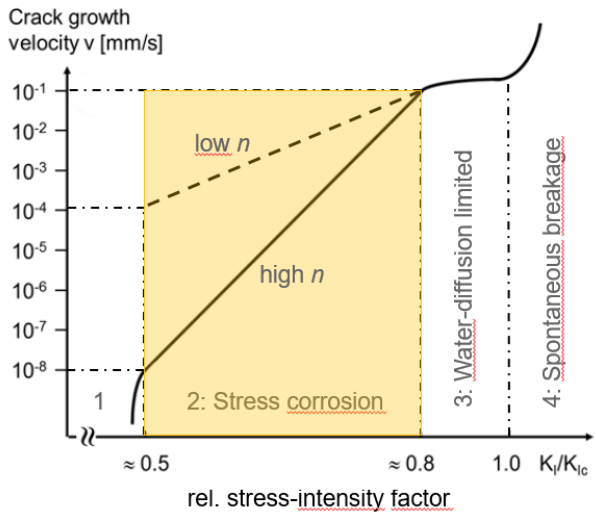

Figure 3: Different humidity conditions strongly influence the stress corrosion constant, resulting in different lifetimes.

The stress corrosion constant for ZERODUR® can be determined by using a ring-on-ring test setup with different stress increase rates and then measuring the median breakage stress for a set of samples. Dry nitrogen or normal humid atmosphere is applied so that the atmospheric influence is known. Graphing the breakage stress median versus the stress increase rate in a double plot provides the stress-intensity factor as the linear fit of the data within the stress-corrosion regime. The latest results for ZERODUR® using the ring-on-ring load variation method show a stress corrosion constant of 79.1 for a dry atmosphere and 31.1 for a normal atmosphere.

The stress corrosion constant and the threshold bending strength from Weibull distributions of sample sets with given surface condition can be used to calculate the lifetime of a surface treatment at a given constant load stress (Figure 4).

We worked with the Fraunhofer Institute for Mechanics of Materials to verify our lifetime calculations. They performed an experiment where 20 samples were loaded with 30 MPa, 24 samples were loaded with 34 MPa, and 26 samples were loaded with 38 MPa. All the samples except one were above the lifetime prediction curve, which shows that the calculated lifetime predictions match well with realistic values for ZERODUR®.

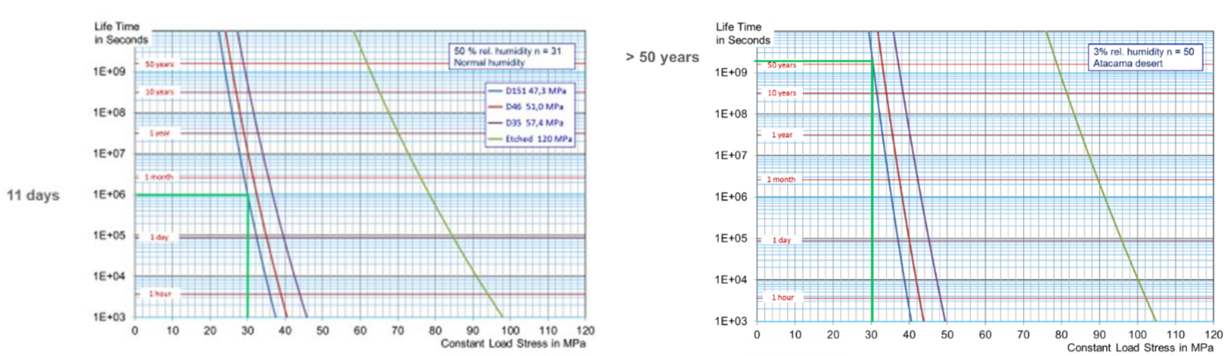

Figure 4: These plots show lifetime versus constant applied load stress for a given ZERODUR® surface treatment in humid and dry conditions. In a humid environment, under a constant load of 30 MPa, a D151 surface will break after 11 days. In a dry environment, the same surface under the same load will last more than 50 years

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.

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