How Edge Finish Affects the Strength of Sapphire

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ABSTRACT

Exotic Electro-Optics (EEO) has completed a study of how the edge finish of an A-plane sapphire sample affects its flexural strength when tested using the 4-point bend test method. Flexural bar samples were fabricated out of a sapphire panel that was polished to production quality using EEO's standard production methods. All samples were configured to meet the requirements for a C-size sample as defined by ASTM C-1161. The only difference between the three sample groups was the edge finish applied to the sample - conventionally ground, fine ground or a commercial polish edge finish. The edge finish on each sample was quantitatively characterized prior to strength testing. All samples were visually inspected prior to testing to identify any potential fracture initiation points. The samples were then tested using an Instron Universal tester per ASTM C-1161 in the UDRI Ceramics and Glasses Laboratory. After testing, a visual inspection was performed to identify the fracture initiation surface and location. Observations confirmed that all sample data was valid (all fractures initiated inside the two inner load dowels), no fractures were initiated on the edges, and no fractures initiated at any of the suspect sites noted in the pre-test visual inspection. The data was post processed using standard statistical and Weibull analysis methodologies. The results showed no significant difference when comparing the flexural strength of the three edge finish groups. The data suggest that the surface quality of the planar surfaces and the bevels is more critical than the finish of the full edge.

Keywords: sapphire, flexural, strength, finish,

1 INTRODUCTION

As a supplier of optics to the Defense, Aerospace, and Homeland Security industries, EEO is routinely requested to fabricate parts with a polished or extra fine ground finish on the edges of optical ceramic components. This requirement has a significant impact on the manufacturing time and yield. In many cases the peculiar profile of the edge (chamfers, rounds, and flats) and the particular feature size make it very difficult to accurately create the shape and provide a fine surface finish. In general, the most important factor governing the mechanical strength of an optical ceramic is the quality of the surface finish (1). As such, EEO recognizes how critical the surface finish of all surfaces is to determining the strength of an optical ceramic component. However, it is vital to fully evaluate the trade-offs between performance and fabrication process complexity in order to improve cost and delivery. It was in that spirit that EEO recently initiated a test program to try and determine the effect of edge finish on the flexural strength of sapphire. A 4-pt. bend test was chosen for this effort because of the strong influence of edge flaws and roughness when using this test configuration.

2 SAMPLE PREPARATION

The samples were the "C-size" configuration as defined in ASTM C-1161 with the following dimensions: length 3.937 inches (100 mm), width 0.315 inches (8 mm), thickness 0.220 inches (5.6 mm), parallel within 0.001 inches (0.03 mm). The samples were made from A-plane sapphire material which was fabricated using production processes that yield $1/10\lambda$ transmitted wave front error at 0.6328 µm wavelength. There were a total of twenty-eight (28) samples: 10 pieces with ground edges, 9 pieces with fine grind edges, and 9 pieces with commercial polished edges. All edging was performed using a vertical CNC mill using the classic "step down" method of fabrication to minimize sub-surface

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damage. The edge finish of each sample type was characterized using a non-contact profilometer. Ground edges had a maximum profilometer reading of 275 μin (.0001” cut-off). Fine ground edges had a maximum profilometer reading of 200 μin (.0001” cut-off). Commercial polished edges had a maximum profilometer reading of 175 μin (.0001” cut-off). The surface quality on the polished planar faces was 80/50 with scratch widths measured in microns per MIL-PRF-13830. Each sample was labeled with a unique serial number for tracking purposes.

3 TEST PROCEDURE

The testing was completed as described in ASTM C1161, Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature.

3.1 Pretest Inspection

Prior to testing, all 28 specimens were visually inspected using a low power stereo microscope and a light source fitted with a blue filter. Latex gloves were worn while carrying out the pretest inspections. It was noted that all of the specimens had small chips at the surface-bevel transition and light surface scratches. A photograph of the surface-bevel transition of a typical specimen is presented in Figure 1. A few other specimens had slightly larger chips and deeper scratches. Larger defects that looked like potential fracture initiation sites were marked with a felt tip pen. When the pretest inspections were completed, the specimens were wrapped in their original lens tissue and returned to the sample container.

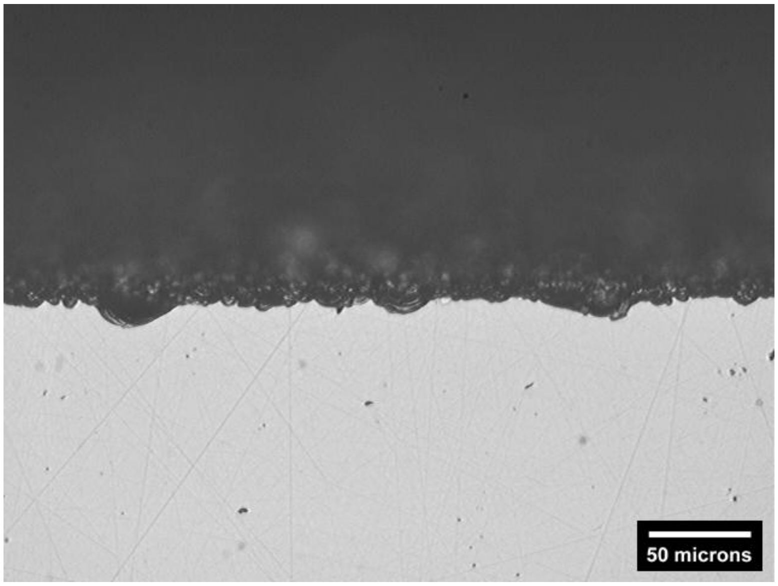

Figure 1: Photograph of the Surface/Bevel of Specimen 003-G
(Photograph courtesy of UDRI Advanced Ceramics Group)

3.2 Four-Point Flexural Strength Testing

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The 28 test specimens were tested using a standard four-point flexure fixture with an 80mm support span and a 40mm loading span. The fixture was fabricated from steel and uses hardened steel bearing cylinders. The bearing cylinders were free to rotate in their positioning slots. A rubber pad was positioned directly below the specimen in the fixture to help absorb the fracture energy and preserve the fracture surfaces. A diagram of the test fixture is presented in Figure 2 and a photograph is shown in figure 3. All the testing was completed using an Instron Universal Tester fitted with an Instron 1,000 pound load cell and Instron's Series IX software. Ambient laboratory environment during testing was 66 to 70°F with relative humidity ranging from 46 to 56%. The specimen dimensions were measured to the nearest 0.0001 inches using a digital micrometer. The lab technician wore latex gloves while performing this testing.

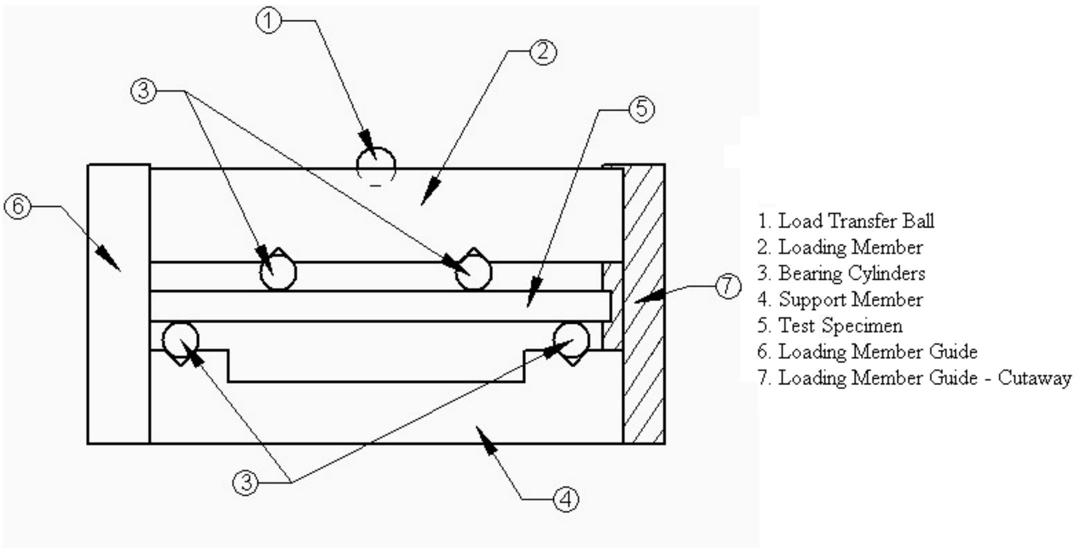

Figure 2: Diagram of "Size C" Four-Point Flexure Fixture

All testing was completed using the following procedure:

- Remove the specimen from the sample container.
- Carefully position the test specimen on the outer support bearings of the test fixture. Center the specimens under the applied load with an equal amount of overhang beyond the support bearings.
- Slide small pieces of cardboard between the ends of the specimen and the fixture loading member guides (this was added after the third test to cushion the impact between the loading member guides and the tested specimen).
- Install the upper half of the fixture taking care not to drop it on the specimen or change the specimen position in the fixture.
- Load the test fixture into the Instron Universal Tester, centering it in the load train.
- Install the safety shield around the fixture.
- Test the specimen to failure using a constant displacement rate of 0.04 in/min.
- Remove the fixture from the Instron Universal Tester.
- Measure the width and thickness of the specimen as close to the fracture initiation site as practical.
- Record the specimen serial number, width, thickness, failure load, time to failure, and relative humidity
- Collect the specimen remnants and return them to the sample container, making an effort to protect the fracture surfaces from damage.
- Inspect and clean the test fixture looking for specimen fragments and damage.

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- Repeat above steps for remaining specimens.

Figure 3: Four-Point Flexure Fixture loaded in the Instron Universal Tester
(Photograph courtesy of UDRI Advanced Ceramics Group)

3.3 Post Test Inspection

Once the four-point flexure testing was completed, all of the specimens were examined using the same low power microscopy equipment as in the pretest inspection to determine the fracture initiation site. This inspection gave a good indication of the fracture initiation sites but not specific flaws. A more thorough examination using higher magnification generally yields more conclusive results. It was noted that despite putting a rubber cushion under the specimen, there was still some secondary damage to the fracture surfaces. The fracture initiation sites were categorized as either a surface failure or a bevel failure. Surface failures occur on the surface of the specimen away from the bevel and edge. Bevel failures occur at the surface-bevel transition or in the bevel. If the overall edge finish was a dominant factor in initiating failures, one would expect the origin of the fractures to be located on those edges. Table 1 summarizes the fracture initiation sites by sample lot. The specimens were also checked during post-test inspection to ensure they failure was between the inner load points. It was noted that four specimens failed at or near one of the load points. All four of these specimens had higher flexural strengths than their group averages. None of the larger flaws identified in the pretest inspections appear to have been failure initiation sites.

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Table 1. Summary of Failure Initiation Locations

Sample Finish	Surface Failures	Bevel Failures
Ground	5	5
Fine Grind	3	6
Polished	4	5
Totals	12	16

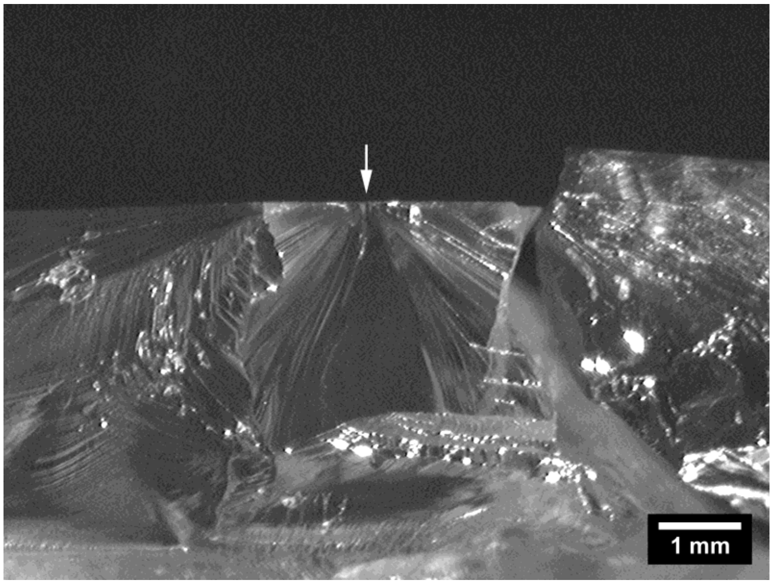

Figure 4: Typical Sample Fracture Initiation Site
(Photograph courtesy of UDRI Advanced Ceramics Group)

4 TEST RESULS

After all 28 specimens were tested; the flexural strength of each specimen was calculated. The following expression was used to calculate the flexural strength:

$$\sigma = \frac{3PL}{4bd^2}$$

where:

σ = flexural strength (psi),
P = break load (lbs),
b = specimen width (in),
d = specimen thickness (in).,
L = outer support span (in) = 3.15 in.

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The average flexural strength and standard deviation of the entire sample lot was calculated. These values were also calculated for each of the three different sample finishes. These calculations are summarized in Table 2.

Table 2: Average Flexural Strength and Standard Deviation Summary

Sample Lot	Average Flexural Strength (ksi)	Standard Deviation (ksi)
All Specimens	115.2	14.6
Ground Specimens	113.5	10.4
Fine Grind Specimens	119.2	16.1
Polished Specimens	113.1	17.6

The Weibull parameters for the entire data set were also calculated. Even though the three subsets of the entire sample lot are very similar, caution should be used when interpreting them as a single sample lot. The Weibull parameters are:

Weibull Modulus: 9.79

Intercept: -47.00

Characteristic Strength: 121.4 ksi

Mean Strength: 115.2 ksi

Median Strength: 116.9 ksi

The Weibull plots (3) are presented in Figure 4 and Figure 5.

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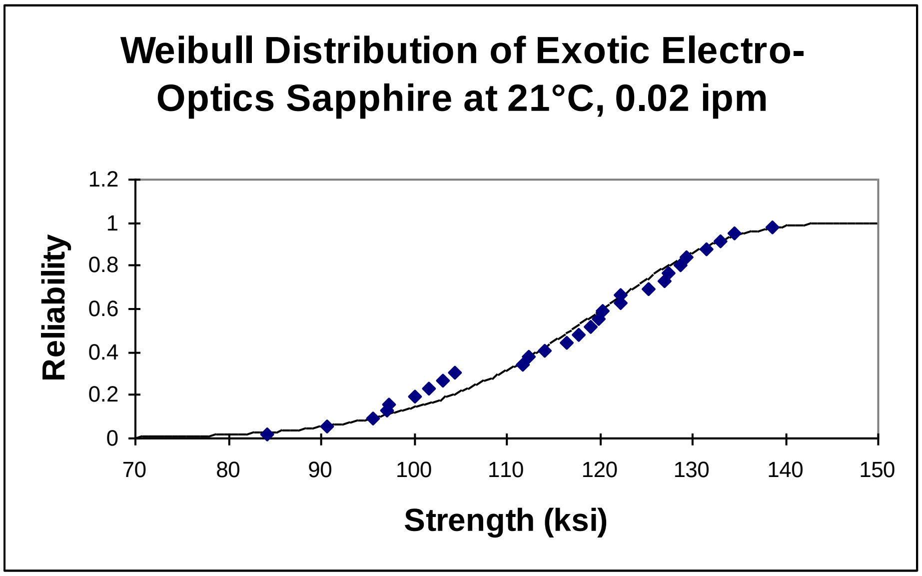

Figure 4: Plot of Probability of Failure vs. Strength.

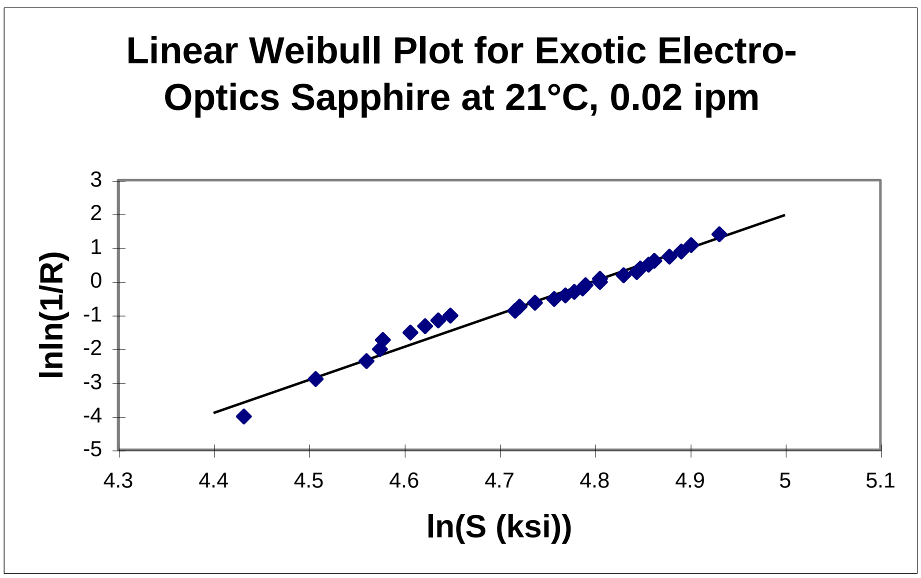

Figure 5: Linear Weibull Plot.

5 CONCLUSION

As noted in the introduction, the most important factor governing the mechanical strength of an optical ceramic is the quality of the surface finish (1). The test results presented herein do not refute this. However in addition, there is a perception that the surface finish of the edges of an optical component is also a comparably critical factor in determining

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its mechanical strength. The results of this testing on sapphire would suggest that this perception is not wholly supported for all optical ceramics. Comparing the mean flexural strengths between the three sample groups yields only a 5% difference. The highest mean flexural strength was seen for the sample group that had the fine ground edge. The lowest mean flexural strength and the largest standard deviation came from the sample group with the smoothest edge finish (commercially polished group). Both of these observations are contrary to the common wisdom. Although the limited number of samples precludes EEO from making the bold assertion that the mechanical strength of A-plane sapphire is less sensitive to its edge finish than other optical ceramics, these test results are strongly suggestive of just that. Further investigation is needed to fully answer the edge finish question.

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