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Development and Validation of a Miniaturized Ball-on-Three-Ball Test for Biaxial Flexure Strength of Technical Ceramics

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Abstract

Miniaturized (~3 mm diameter) advanced technology nuclear fuels are of interest for their ability to simulate mechanical properties of their larger counterparts in a fraction of the time (2 years compared to 25 years). However, understanding the mechanical properties of these miniaturized samples is an important aspect of their development and qualification. In this study, a miniaturized ball-on-3-ball (B3B) fixture was designed to determine the traverse rupture strength (TRS) of right-cylindrical ceramics. Fixture revisions led to an optimal final design. Three technical ceramics were tested to validate the miniaturized B3B fixture, including high purity alumina (Al2O3), magnesia partially stabilized zirconia (MSZ), and yttria partially stabilized zirconia (YTPZ). Two different sample preparation methods and fixture geometries were to optimize testing conditions. Grain size and distribution analysis was also conducted via thermal etching and imaging to verify the grain structure of each material used in testing. The TRS and Weibull data for alumina and MSZ obtained in this study yielded comparable results to prior results to a B3B fixture for larger volume samples. A validated miniaturized B3B fixture will have the potential to become a primary method of obtaining mechanical properties of miniaturized advanced technology fuels.

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LAYING THE GROUNDWORK FOR A MECHANICAL TEST FRAME FOR MINIATURIZED MATERIALS

INTRODUCTION

- Determining the true strength of ceramics is difficult due to their brittle nature, which makes the force at which the material will fail stochastic
- The ball-on-three-ball (B3B) test is a biaxial strength test with several advantages[1]:
  - Ease of test piece preparation,
  - Higher accuracy due to the test accurately incorporating edge defects
  - Ease of miniaturization
- Goal: create a miniaturized B3B fixture capable of producing accurate results using three well known technical ceramics:
  - Alumina
  - Magnesia partially stabilized zirconia (MSZ)
  - Yttria partially stabilized zirconia (YSZ)
- Each materials microstructure must be verified through a grain size analysis for microstructural characterization.

FIXTURE DESIGN

- Two fixture revisions featured in this poster:
  - Fixture A
  - Fixture B
- Fixture B was created to minimize the centering issues present during fixture A testing.
  - Magnetic centering rings as opposed to a tapered aluminum sleeve
  - 'Steel pin alignment' in fixture B prevented lateral movement of the top ball pin present in fixture A
  - Fixture B features exclusively machined steel parts as opposed to the aluminum alignment sleeve used in fixture A

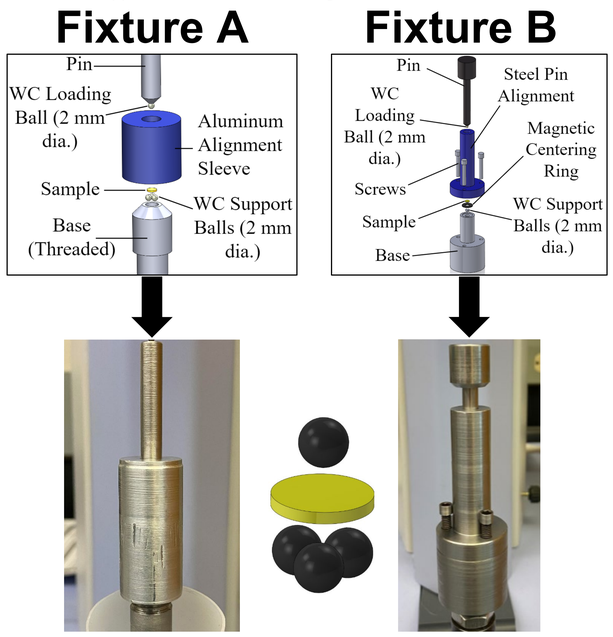


Figure 1. CAD drawings and images of Fixture A and Fixture B along with a ball-on-three-ball schematic

WEIBULL DISTRIBUTION PLOTS

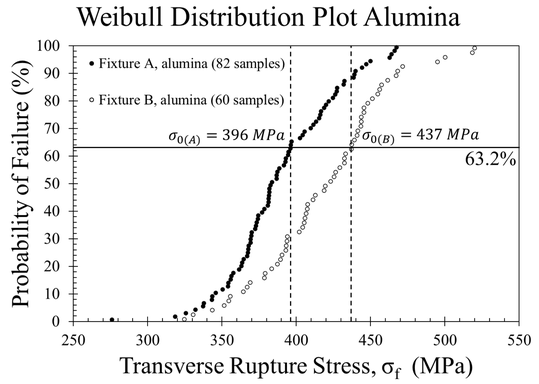
<u>Weibull distribution</u> - the best statistical model to describe the lifetime/failure frequency in brittle materials

- Volume dependant (larger volume, more defects)
- Maps the probability of failure at varying stresses
  - Minimum of 30 samples
- Characteristic strength of a Weibull distribution plot is the transverse rupture stress with a 63.2% probability failure
  - Example: figure 3 at 396 MPa and 437 MPa
- Weibull modulus (represented by the slope of the linearized plot) represents the distribution of flaws within a sample set
  - Higher weibull modulus represents a more consistent distribution of flaws
  - Lower weibull modulus represents a more stochastic distribution of flaws
- Characteristic strengths used for comparison to other studies (table 1)

Figure 2. Example alumina sample

Table 1. Results from biaxial testing using Fixture A and Fixture B compared with literature

RESULTS	Fixture A (stock sectioned)		Fixture B (stock sectioned)			Values from Literature[3,4]		
Material	**Alumina**	**MSZ**	**Alumina**	**MSZ**	**YSZ**	**Alumina**	**MSZ**	**YSZ**
No. of Pellets Tested	82	60	60	60	60	>30	>30	>30
Characteristic Strength (MPa)	396	1130	437	1168	1380	388	1026	1215
Weibull Modulus	13.00	9.94	12.02	12.36	7.00	14.3	13.8	11.6



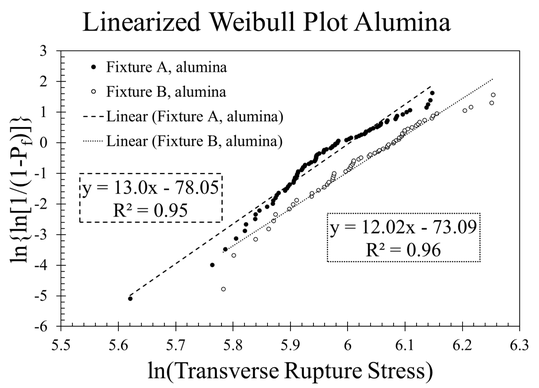


Figure 3. Example alumina Weibull distribution and linearized Weibull plot

GRAIN SIZE ANALYSIS

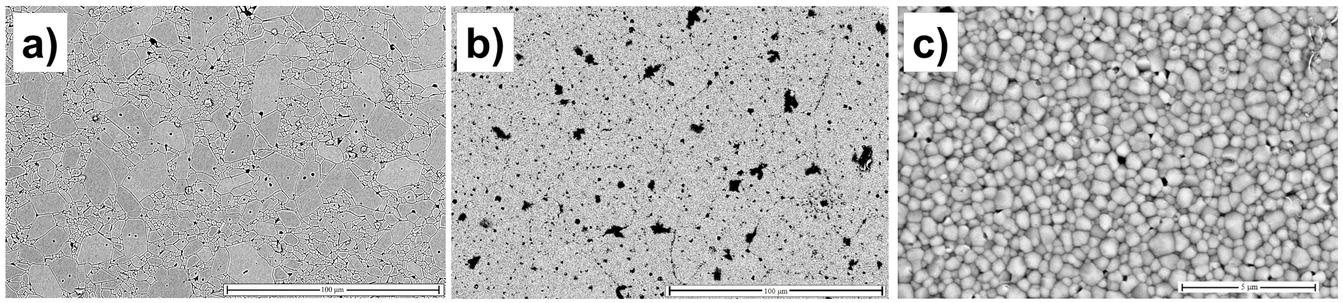


Figure 4. SEM images utilized in grain size analysis. a) alumina, b) MSZ, c) YSZ

- Thermally etched samples (approx. 90% of sintering temp for 40 minutes)
- Grain diameter in microns (μm), results in table 2
- Analyzed using ImageJ

Table 2. Results from grain size analysis using ImageJ in μm

RESULTS	a) Alumina	b) MSZ	c) YSZ
Grain Size (μm)	4.17	36.9	0.41
Literature[3,5](μm)	5.60	35.0	0.70

CONCLUSION

- Fixture B creates accurate and replicable data in accordance with previous studies and mitigates the issues present in Fixture A
  - Improved centering mechanic
  - Features only machined steel parts
- As expected, smaller volume specimens yielded a higher characteristic strength value compared to previous studies using larger samples
  - Larger volumes yield a larger probability of a critical flaw or defect within the specimen, subsequently a smaller sample will have a lower probability of said flaw
- For Fixture B, the Weibull modulus saw a slight increase between alumina and MSZ, with YSZ seeing a decrease compared to larger samples
  - An increase was to be expected due to a more even distribution of flaws in a smaller volume (YSZ displaying interesting results)
- The microstructure of the material tested aligned with other transverse rupture strength studies using the three technical ceramics in literature[3,5]
- The use of fixture B from this study has demonstrated the capability of being able to produce mechanical properties of miniaturized advanced technology nuclear fuels:
  - Fixture B can be used to obtain the mechanical properties of these fuels as well as predict when and how miniaturized fuels will fail

FUTURE PLANS

- Manuscript publication based on the miniaturization and verification of the B3B test for ceramic materials

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