Spatial Distribution of Flexural Strength in Y-Ba-Cu-O Bulk Superconductors

Kai Yuan Huang (Danny)

Supervisor: Prof. David Cardwell

Bulk Superconductivity Group, University of Cambridge, UK

E-mail: kyh30@cam.ac.uk

Overview

- Introduction
- Mechanical Properties of Bulk Superconductors
- Three Point Bend Test Results
- Indirect Tensile Test Results
- Conclusions

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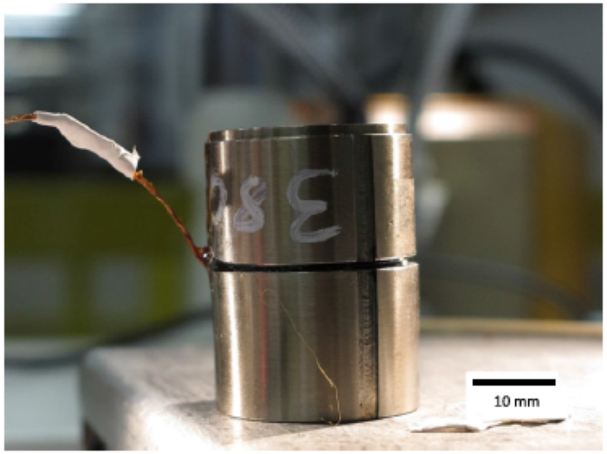
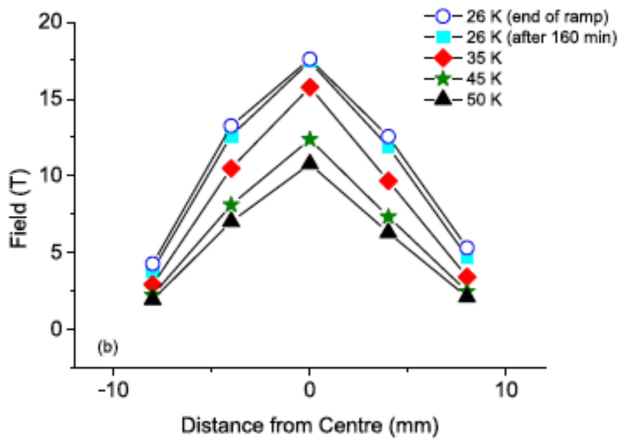
Introduction to Bulk Superconductors

- Large, single-grain (RE)BCO can be fabricated with high success rate (**up to ~ 60 mm in diameter**)
- A prominent application is as **high-trapped-field magnets**
- Maximum trapped field reported to date is **17.6 T** at 26 K between two 25 mm diameter GdBCO/Ag *(Durrell J H et al. 2014, Supercond. Sci. Technol. 27, 082001)*

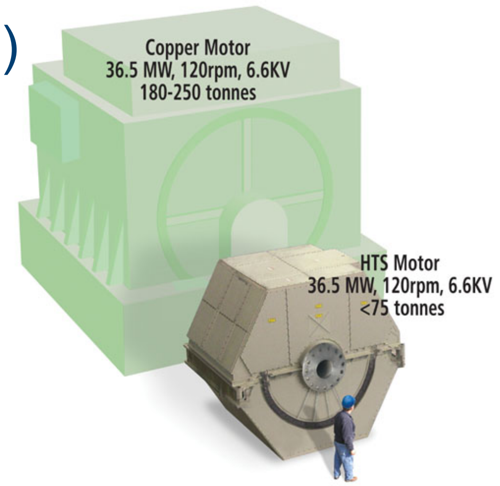




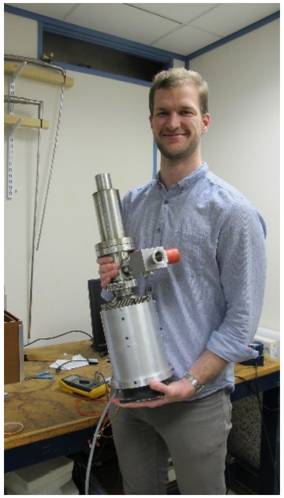
Introduction to Bulk Superconductors

Potential Applications

(a)



(b)



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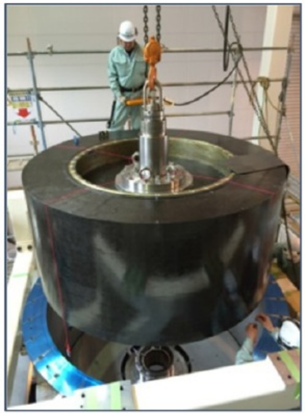

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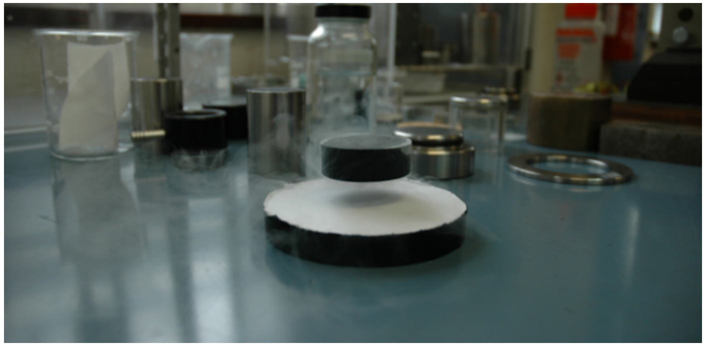

Ref: AMSC Northrop Grumman 21st Surface Navy Association National Symposium
Zhou D et al. 2017 Appl. Phys. Lett.110 no. 6 p. 062601
Ogata M et al. 2016 Supercond. Sci. Technol. 29 054002

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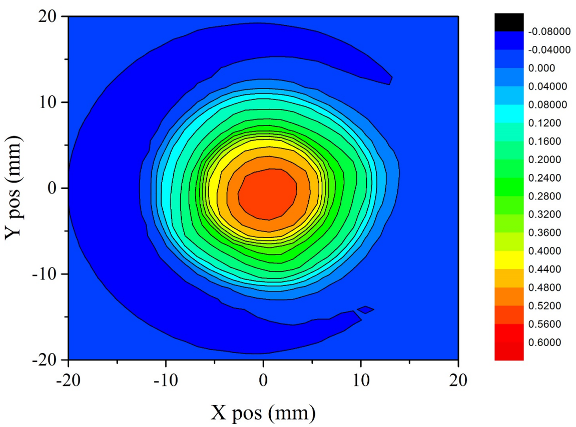
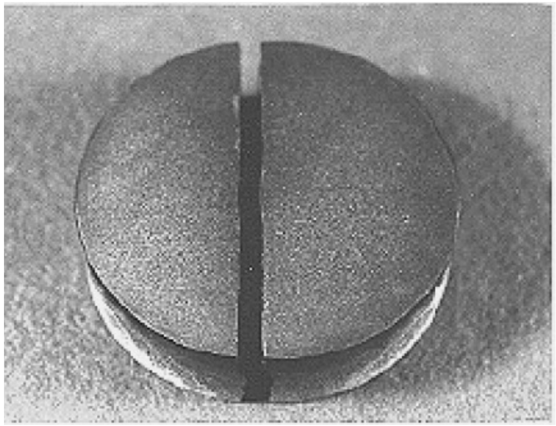
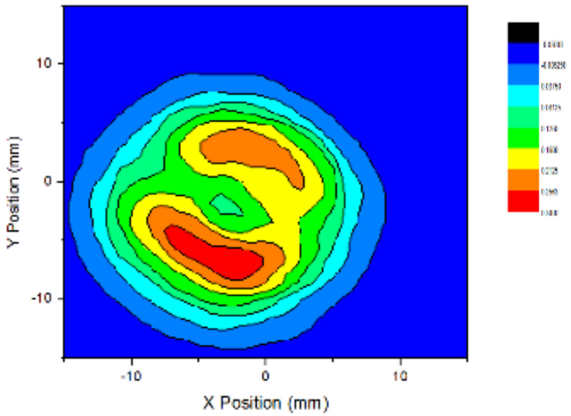
Mechanical Properties of Bulk Superconductors

- Significant tensile stresses due to **large Lorentz force**
- (RE)BCO inherently **brittle** due to multi-layered perovskite structure
- **Crack formation** has been observed during high-field magnetization (at an external field of ~ 8 T for non-reinforced YBCO bulks)



Ideal field profile





Field profile after cracking

Ref: Nariki S et al. 2005 Supercond. Sci. Technol. 18 S126

Mechanical Properties of Bulk Superconductors

Magnetic stress σ	$\sigma \propto \frac{2{B_0}^2}{\mu_0}$
Surface field B_0	$B_0 \propto \mu_0 J_c R$

The tensile strength places a limit on the maximum trapped field achievable

Ref: Ren Y et al 1995 Phys. C: Supercond. 251 15
Johansen T H 2000 Supercond. Sci. Technol. 13 830

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Three Point Bend Test - Method

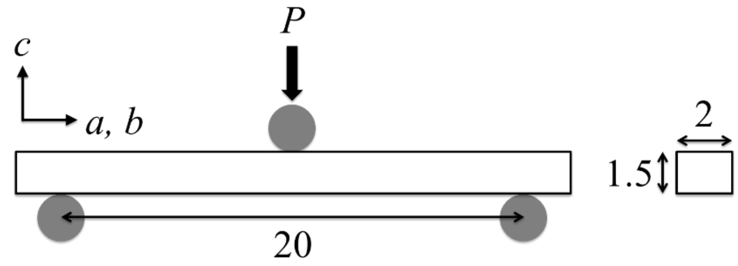
1. 25 mm diameter 10 mm thick YBCO single grains via TSMG and TSIG

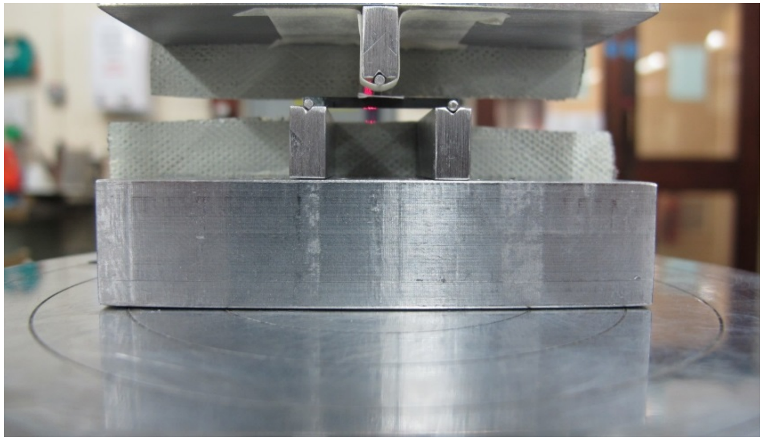
2. Cut into bar specimens, of dimensions 2 mm x 1.5 mm x 20 mm

3. Tensile stress applied along *ab* planes

4. **Flexural strength σ_f:**

$$\sigma_f = \frac{3PL}{2wt^2}$$





Spatial Distribution of Flexural Strength

- 60 measurements from 4 bulks*
- $\boldsymbol{\sigma_f}$ **= 49.3 ± 12.7 MPa**
- ***m*** **= 4.46**

Use m to quantify spread in σ_f

Where *m* is the Weibull modulus

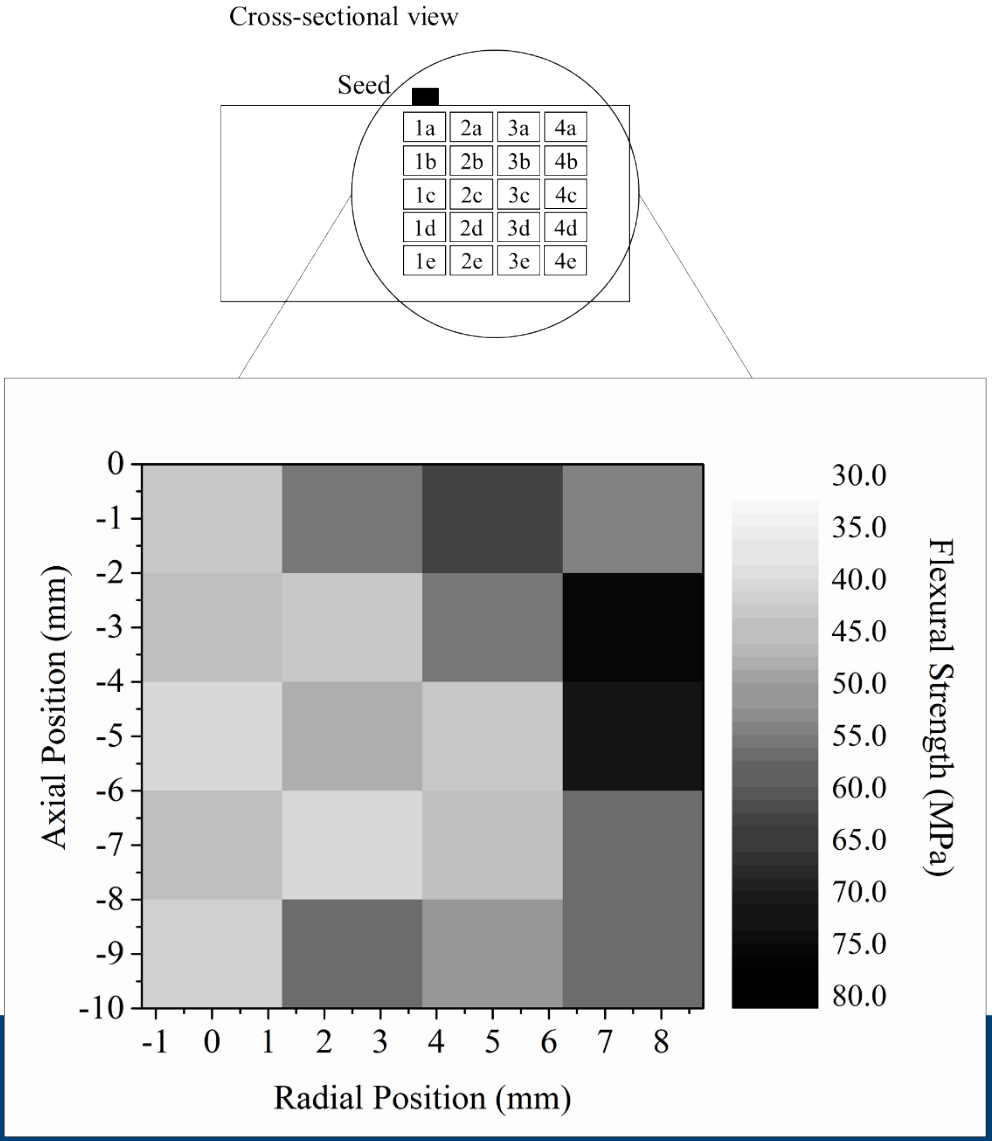
Weibull statistics common for ceramics

In general, high Weibull modulus ➔ less scatter ➔ more predictable and more reliable

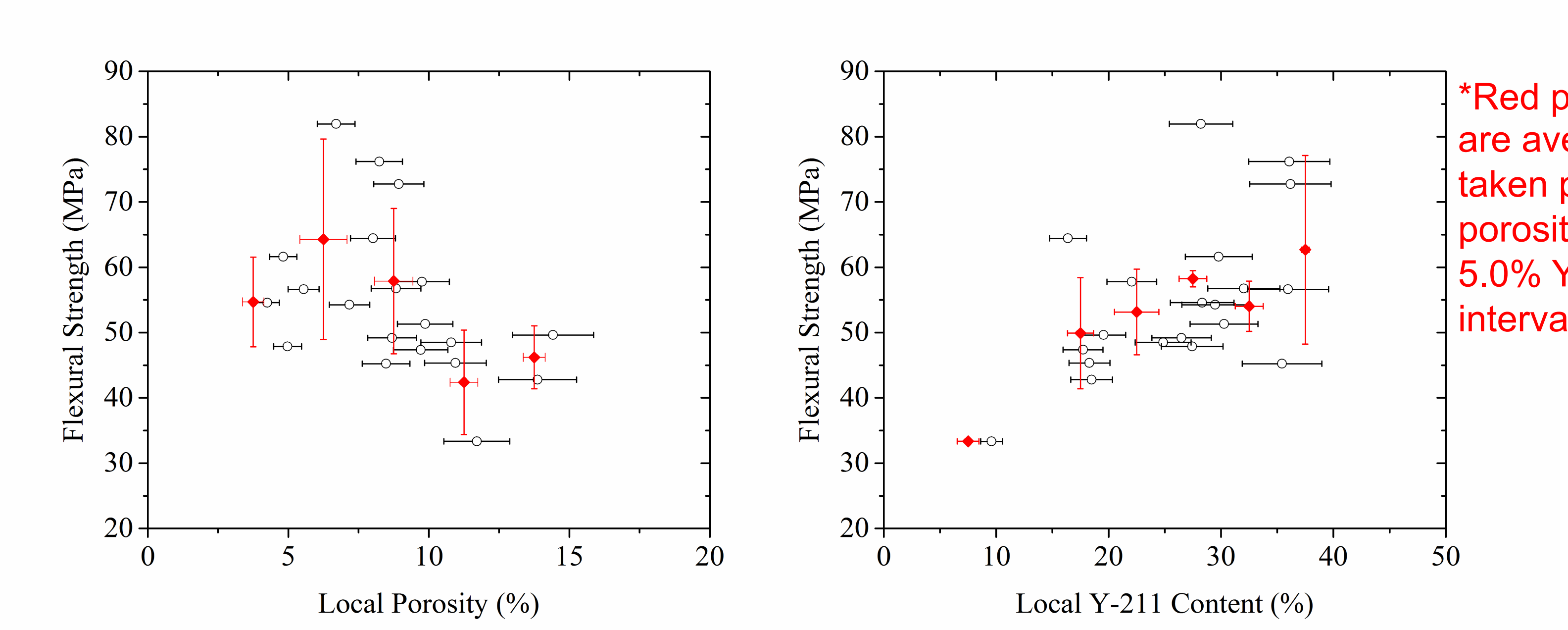
*one of which was a commercially available bulk from CAN SUPERCONDUCTORS

Spatial Distribution of Flexural Strength

- 60 measurements from 4 bulks
- **σ_f = 49.3 ± 12.7 MPa**
- ***m* = 4.46**
- But wide spread of σ_f is not entirely random
- Apparent low strength region in the centre
- Increasing strength with distance from seed



Spatial Distribution of Flexural Strength



*Red points are averages taken per 2.5% porosity or 5.0% Y-211 interval

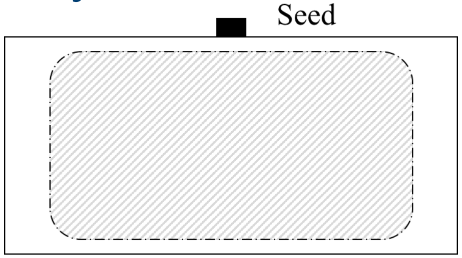
- Variation in σ_f due to variations in local porosity and Y-211 content
- The microstructural variation with position is fairly reproducible (next slide)

➔ So we believe $\boldsymbol{\sigma_f}$ **has a positional-dependence**

Spatial Distribution of Flexural Strength

Well established microstructural variations shown below:

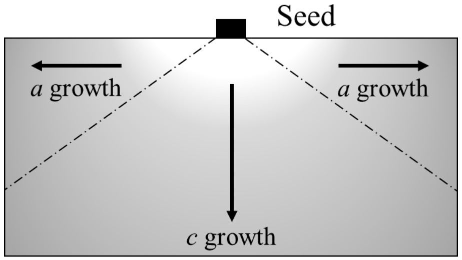
Porosity



*High porosity highlighted

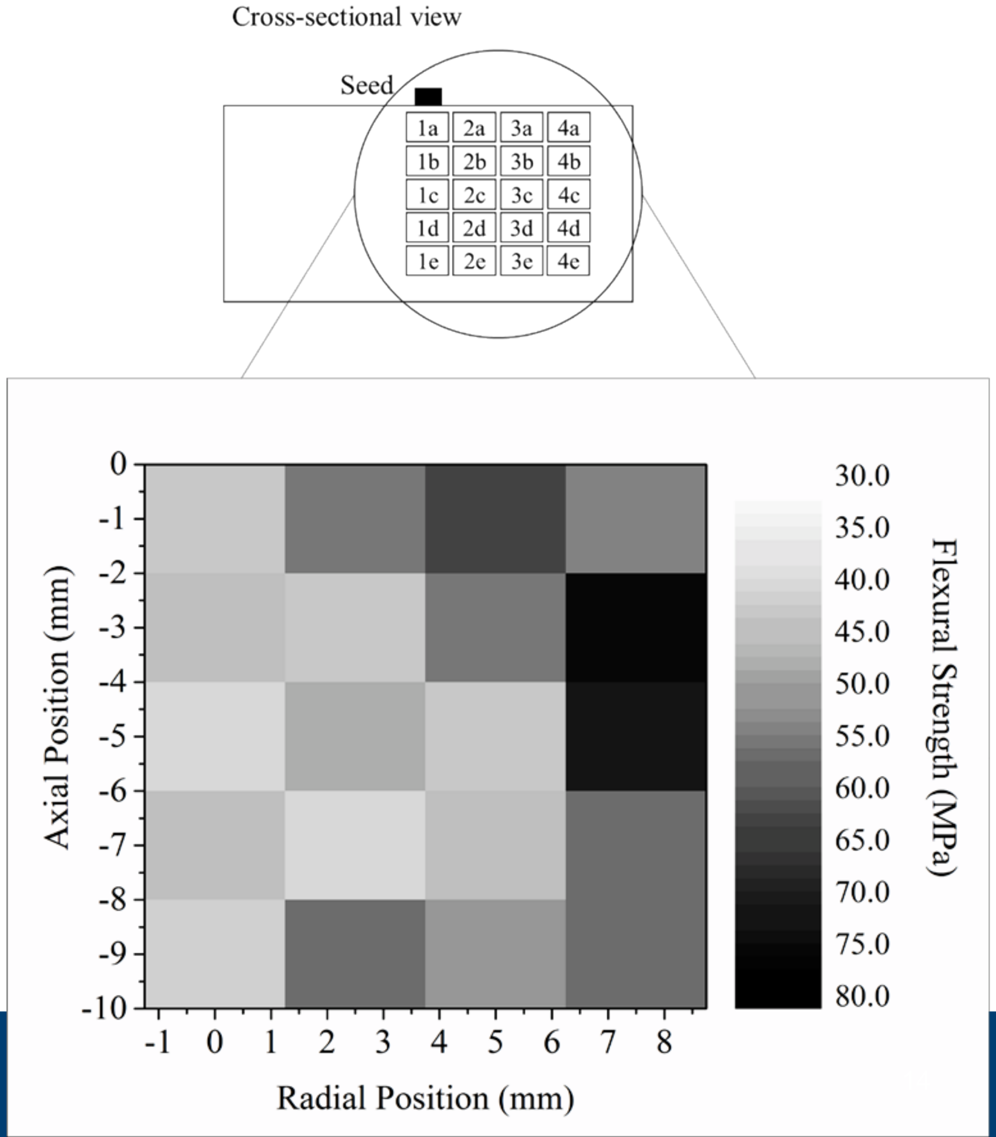
Cross-sectional view

Y-211 volume fraction



*Increasing 211 content

Cross-sectional view



Ref: Endo A et al. 1996, Journal of Materials Research, 11 (4) p. 795-803

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Indirect Tensile (Brazilian) Test - Method

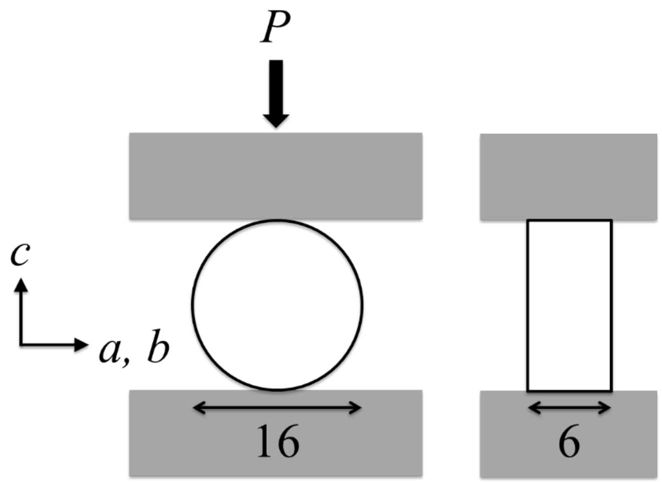
So what is the **bulk-to-bulk variation**?

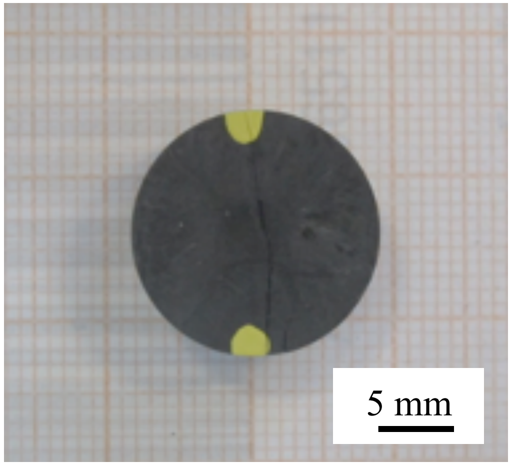
1. Compressed whole as-grown bulks

2. Compression induces perpendicular tensile stress across the centre

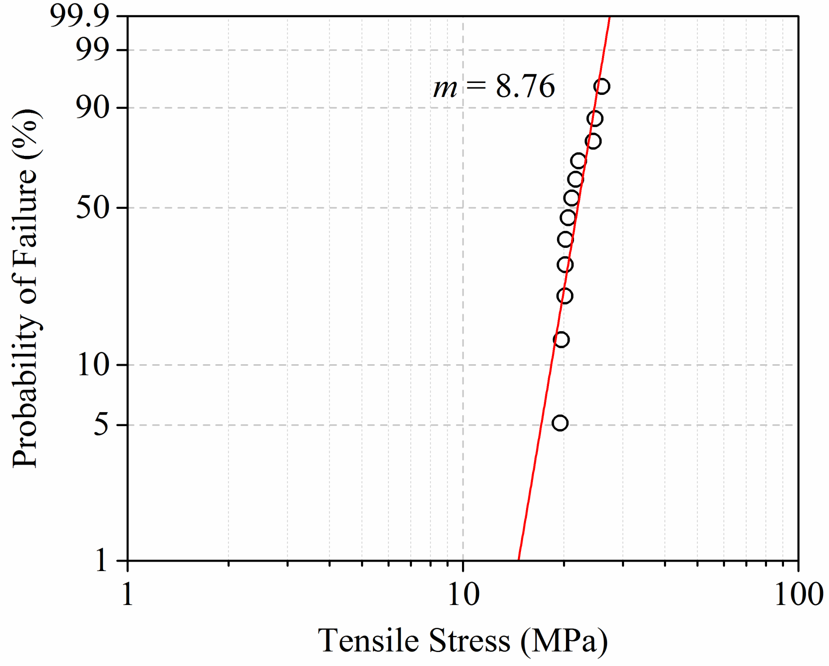
3. **Indirect tensile strength σ_{ids}**:

$$\sigma_{ids} = \frac{2P}{\pi D t}$$





Indirect Tensile (Brazilian) Test



- Twelve 16 mm diameter YBCO from 3 production batches
- ***m* = 8.76** (comparable to Al_2O_3 engineering ceramic) ➔ **high reliability and predictability**
- *m* = 4.46 from earlier flexural strength results
- $\sigma_0 \approx$ 22 MPa agrees well with σ = 25 MPa deduced by Fuchs et al.

Ref: Fuchs G et al. 1997, Appl. Phys. Lett. 70, 117

Conclusions

The variation of the tensile strength:

1. **Within a single bulk:**

Large spread in strength (*m* = 4.46), but is not entirely random, i.e. follows microstructural variations

➔ New ideas for mechanical reinforcements

2. **From bulk to bulk:**

Much narrower scatter (*m* = 8.76), batch processing produces consistent overall mechanical strengths, with highly predictable failure probabilities

➔ Sufficient mechanical reliability for application as trapped-field magnets

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