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Indentation Based Techniques to Measure Residual Stresses in Engineering Ceramics

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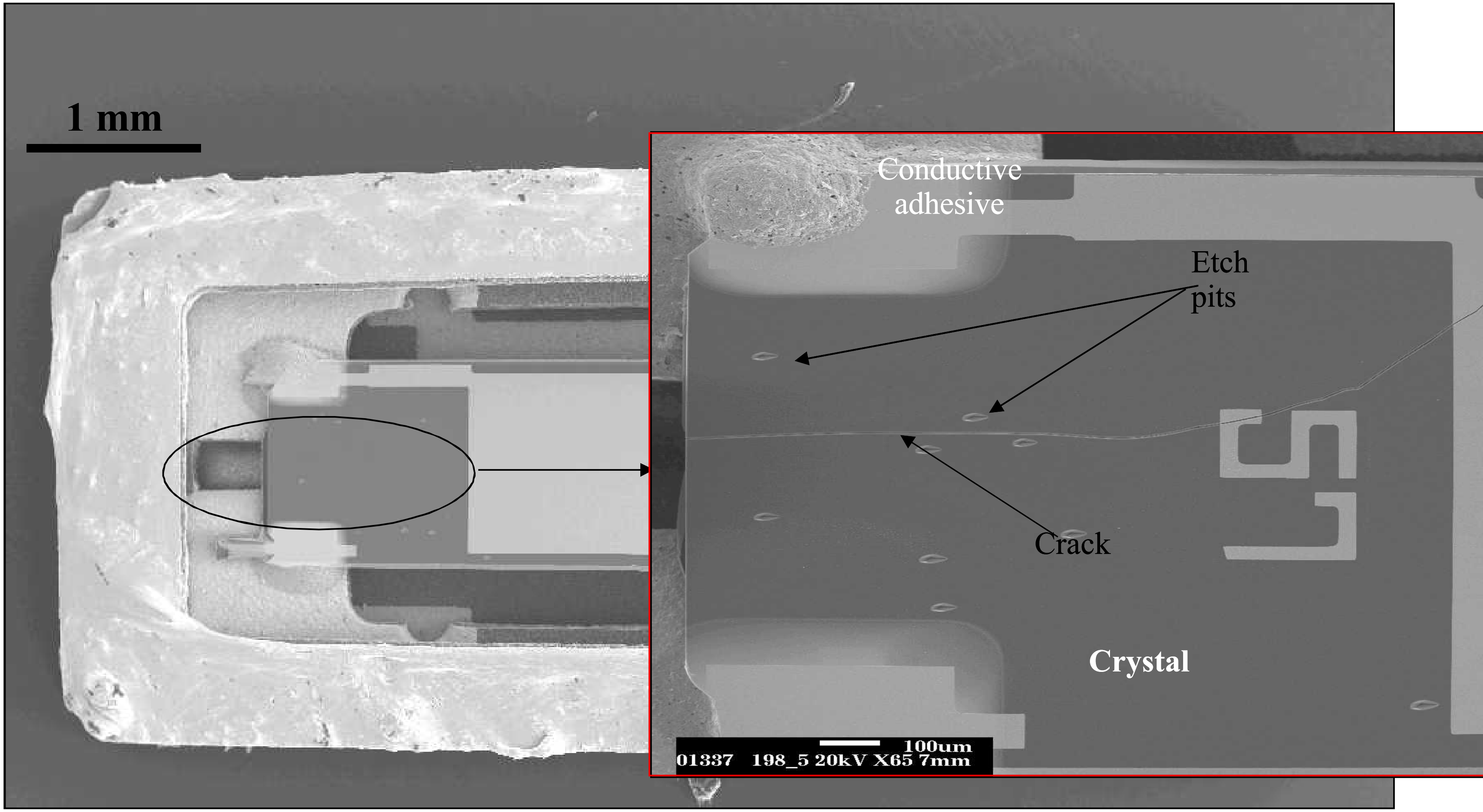
Outline

- **Localized (residual) stresses are important**
  - Examples of material failures from residual stresses
- **Why measure stresses?**
  - Use of Vickers indentation for residual stress measurements
- **Method to use Curved Cracks to Measure Stress**
  - Fracture mechanics analysis, and use in LTCC-gold via
- **Development of Cube-corner Indentation Method**
  - Experiments on stressed glasses (calibration)
  - “Quarter- penny” cracks; Fracture Mechanics Analysis
  - Volume Resolution of technique, Practical Use & Limitations

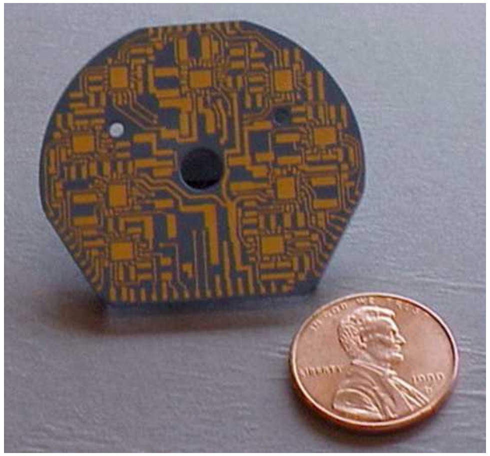
Quartz Resonator Cracking

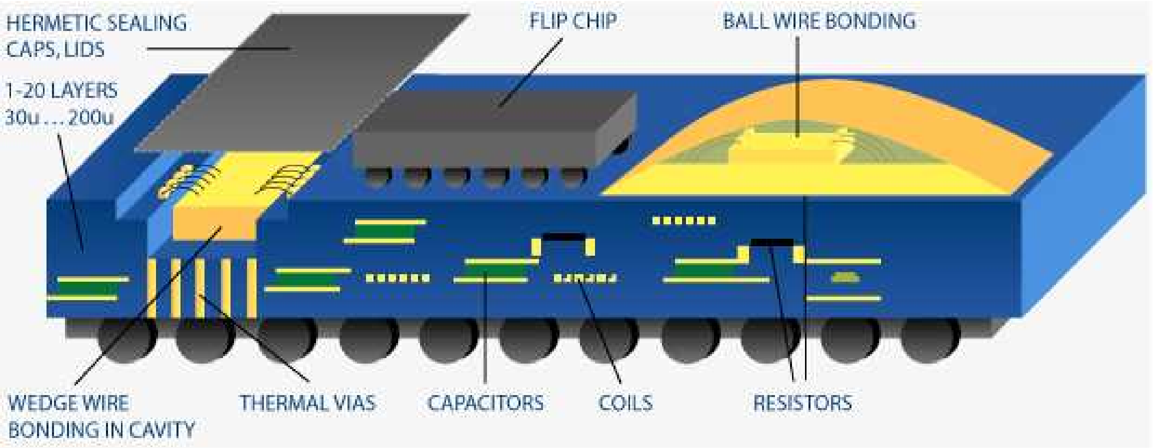


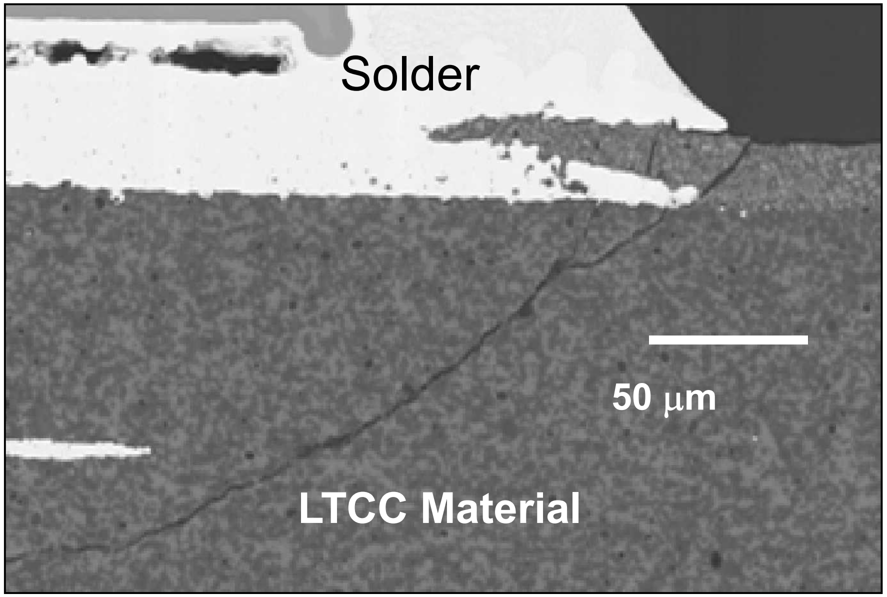
-Cracking fractures the electrical lines

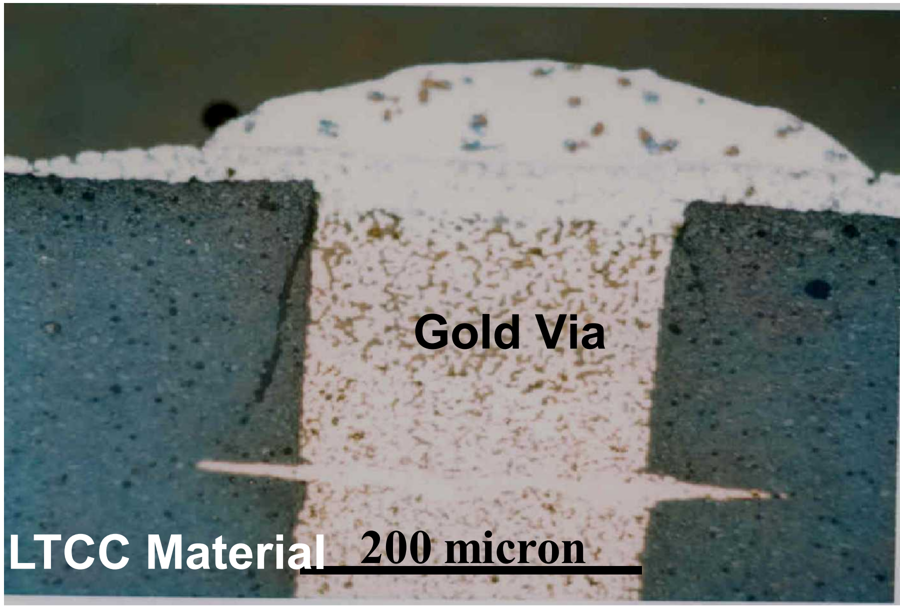
- Polymer adhesive causes stress

Cracks in Various Low-temp. cofired ceramic









- Metal-ceramic thermal expansion mismatch causes stress

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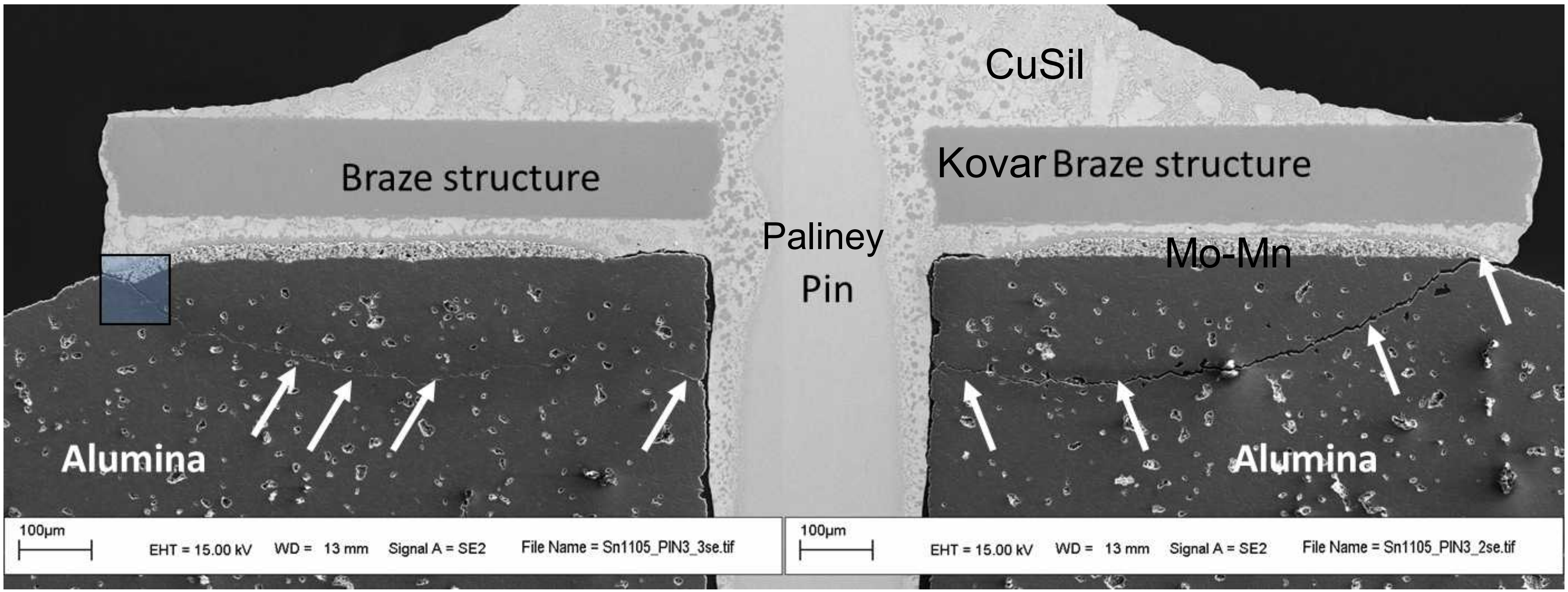
Why do we have to measure stresses?

Brazed alumina

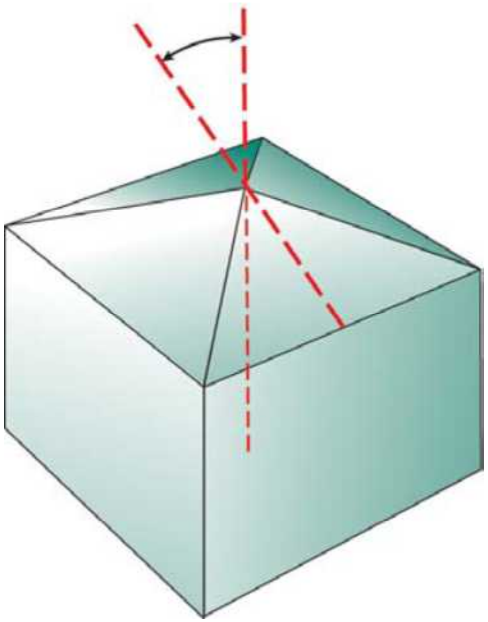


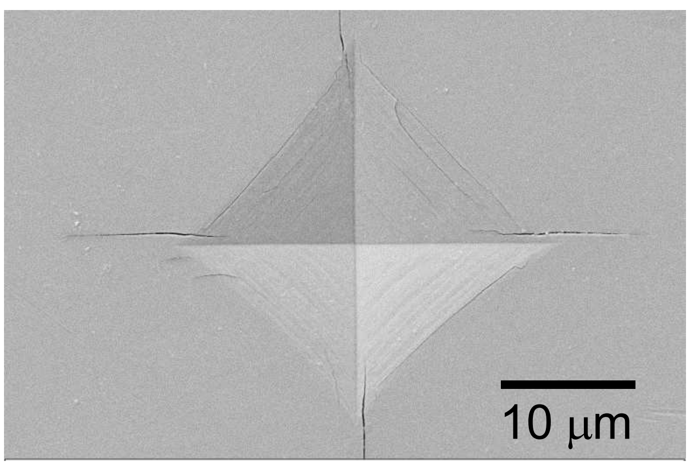
Many of the temp. dependent properties of materials involved are not known. Constitutive inputs for FEA have questionable validity

Chemical reactions between materials change these values

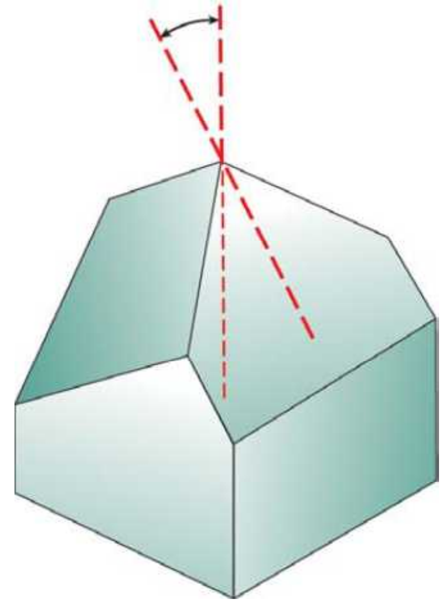
Indenter Shapes used

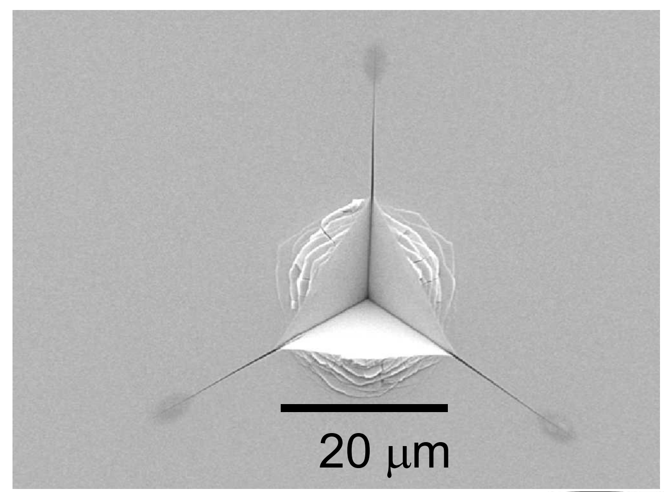
Vickers





Cube-Corner





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Crack Geometries around Vickers

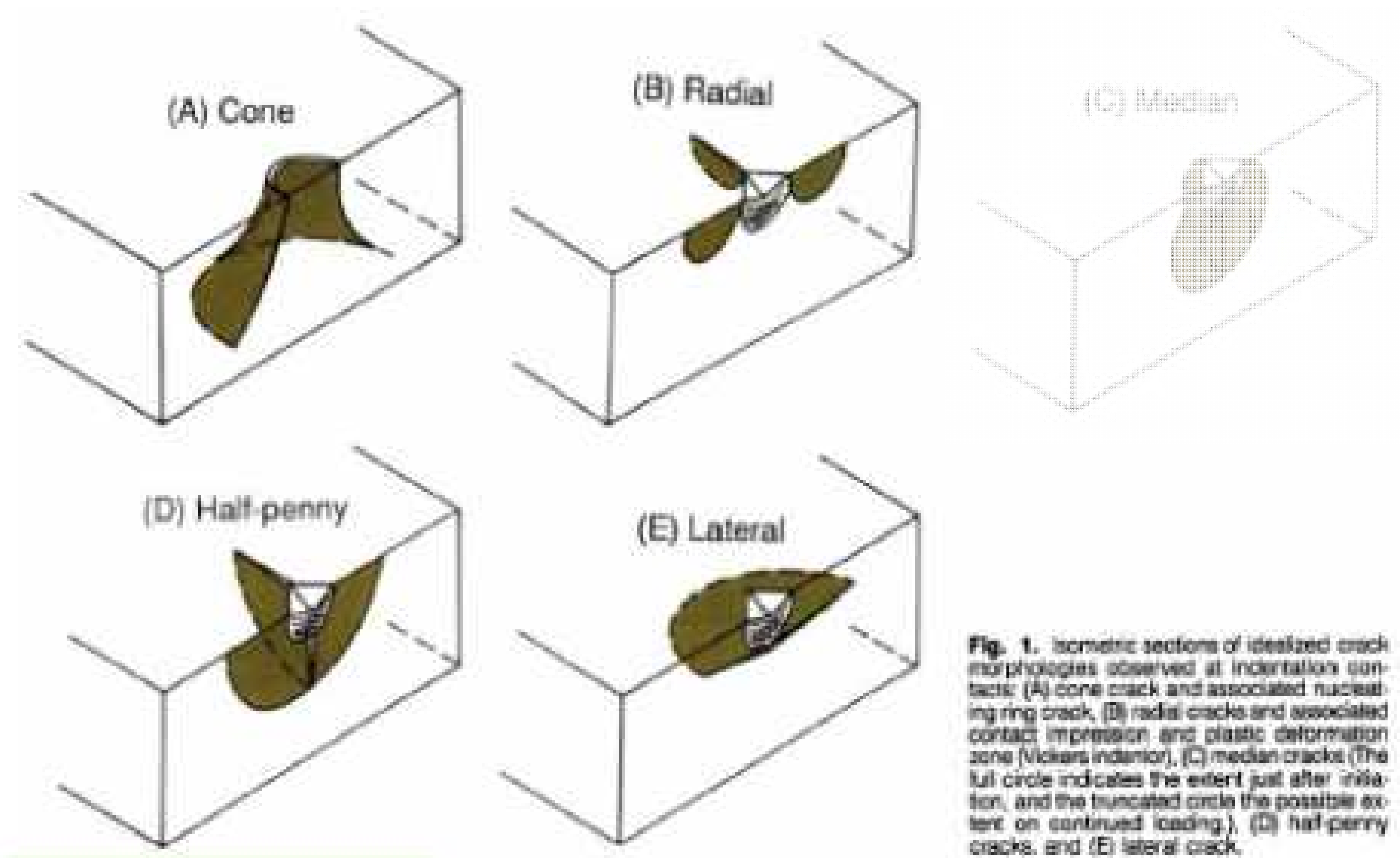

Fig. 1. Isometric sections of idealized crack morphologies observed at indentation contacts: (A) cone crack and associated nucleating ring crack, (B) radial cracks and associated contact impression and plastic deformation zone (Vickers indenter), (C) median cracks (The full circle indicates the extent just after initiation, and the truncated circle the possible extent on continued loading.), (D) half-penny cracks, and (E) lateral crack.

Cook and Pharr, J. ACerS., 1990

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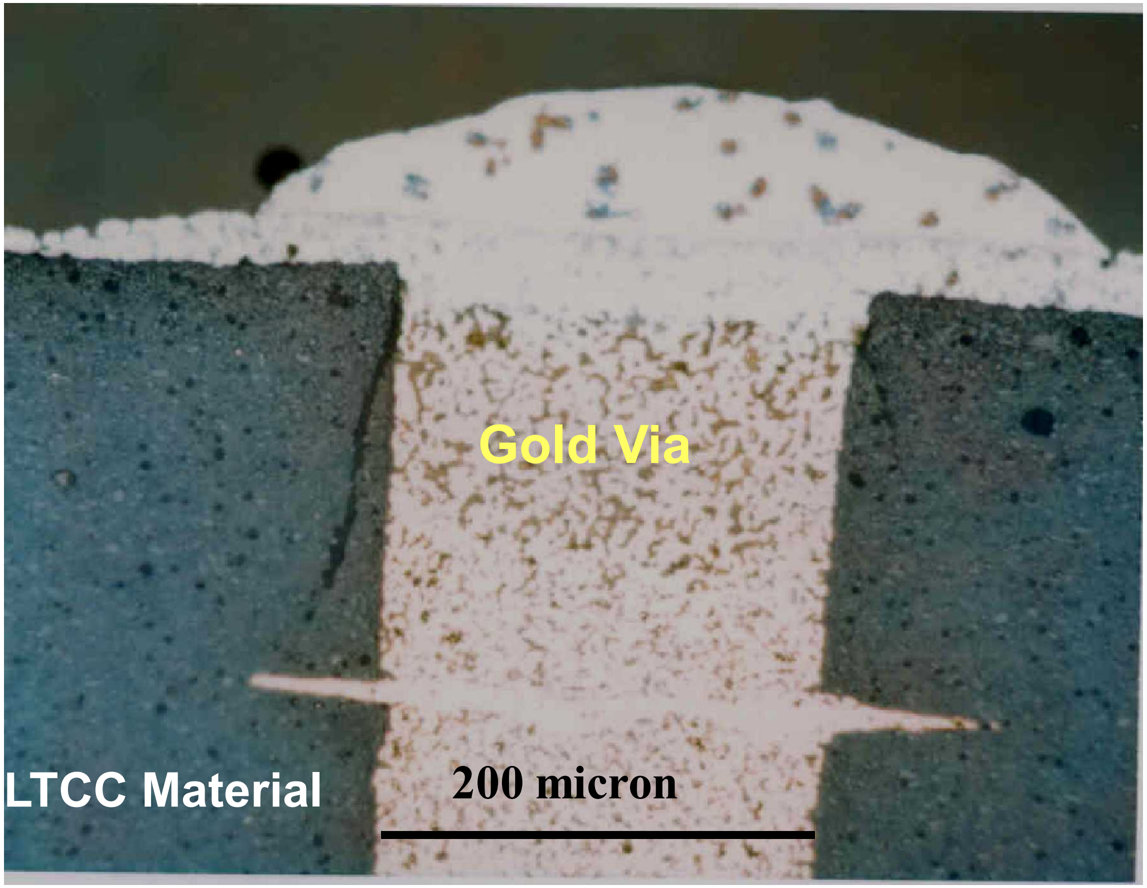
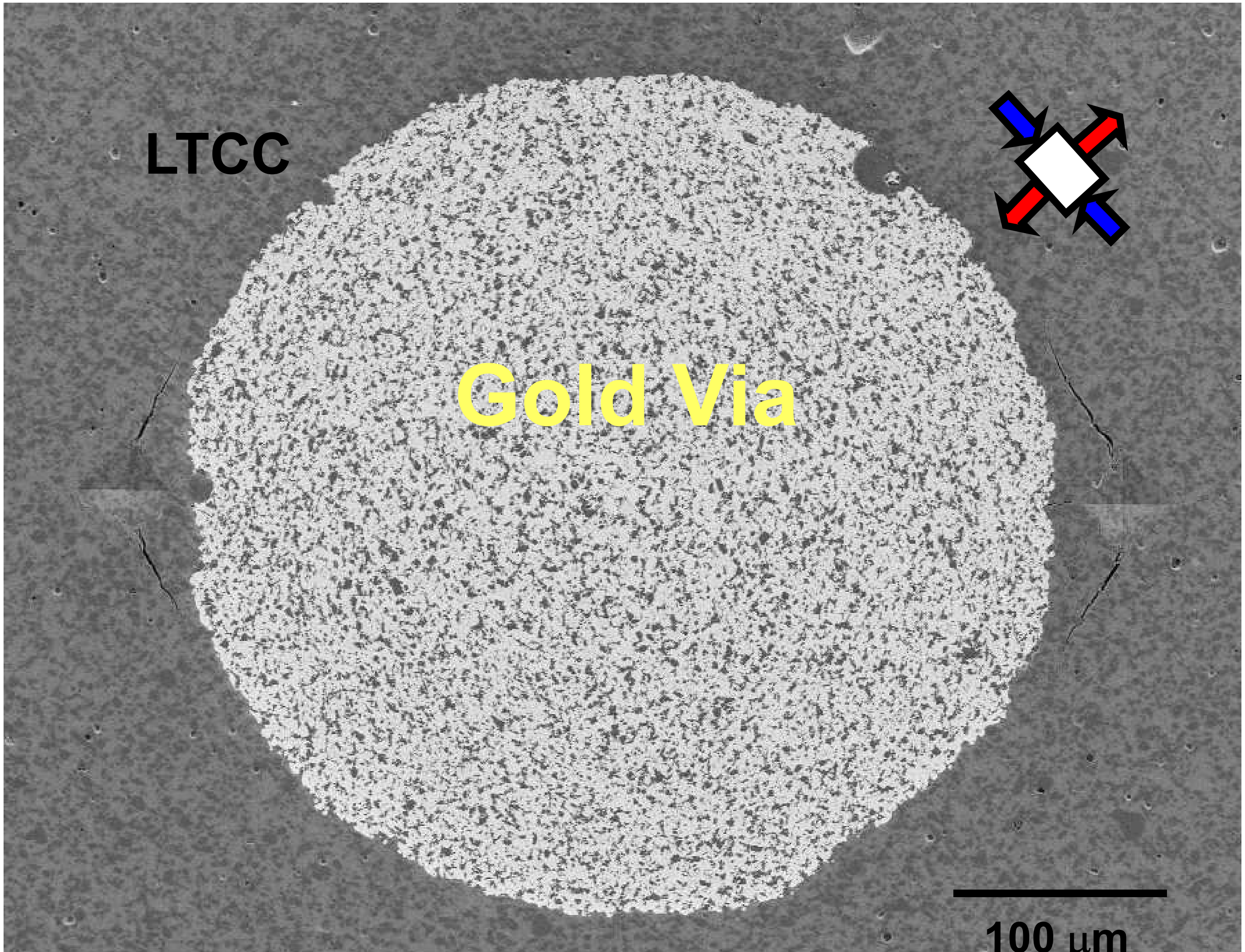
Cracks in LTCC Materials near Metal Vias



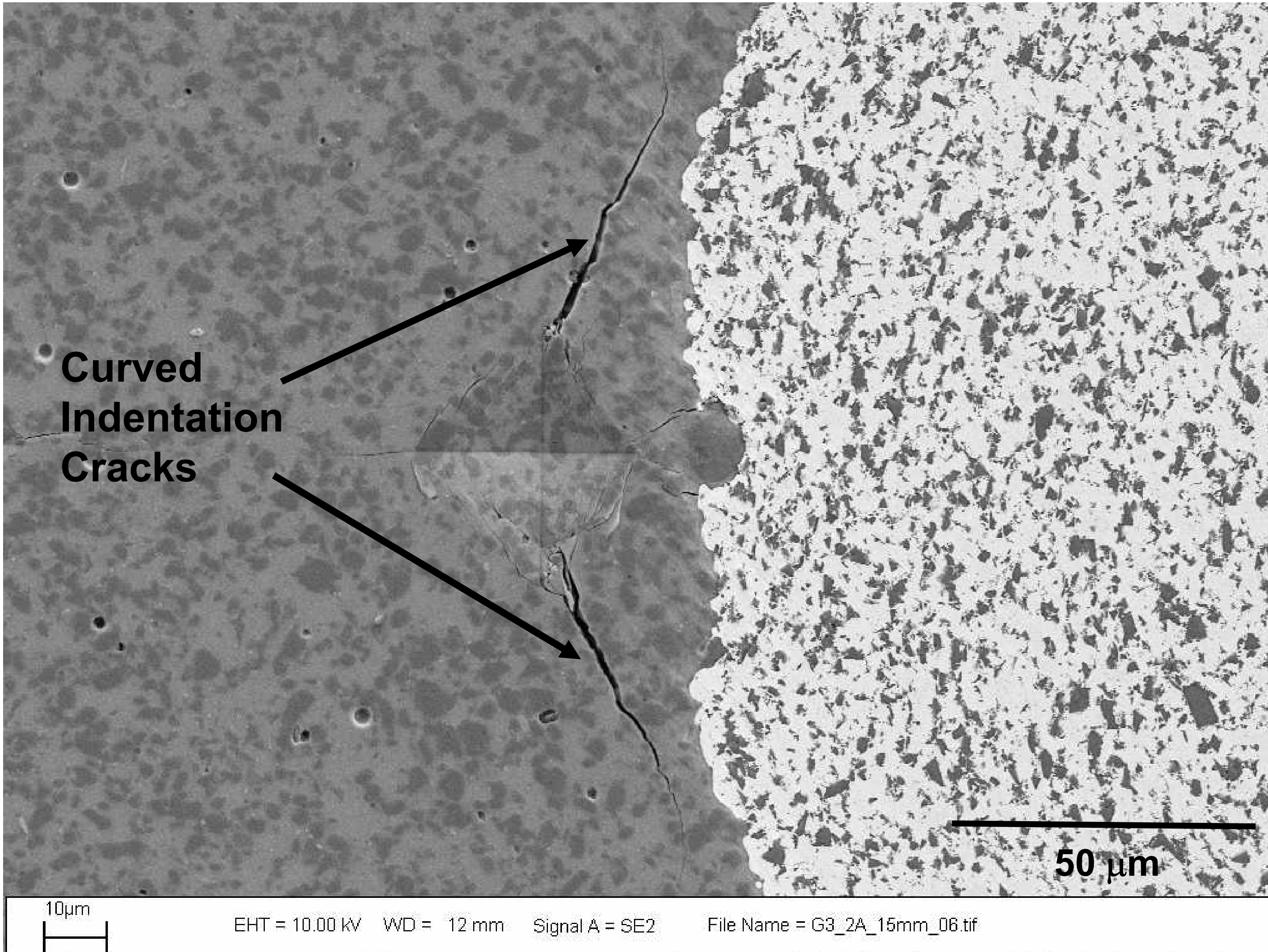
Expansion of via ~2x that of LTCC
Radial tension is expected, driving ring cracks on the surface

Curved Cracks Near Vias

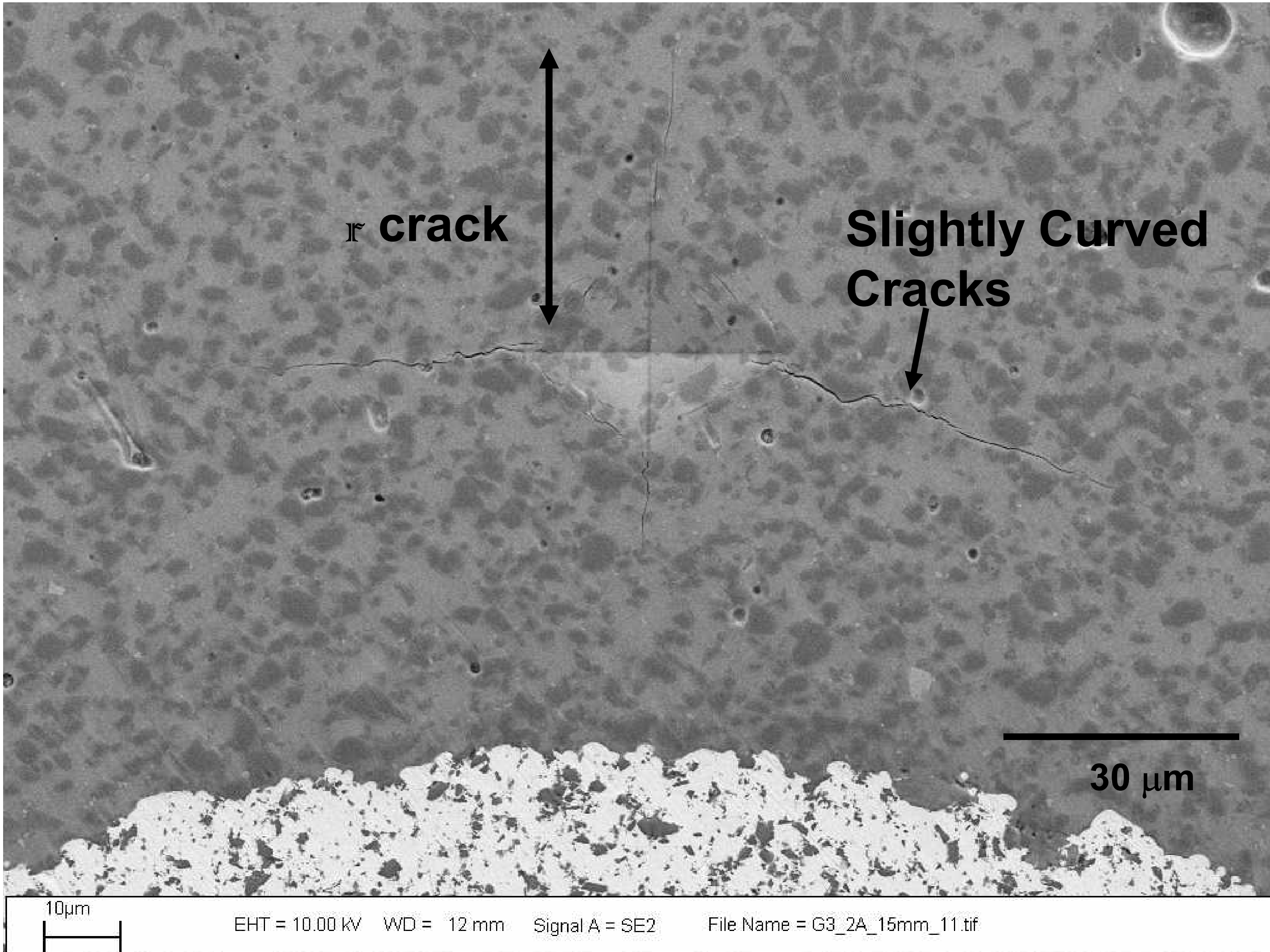


Stress states generated during cooling
Radial tension = hoop compression

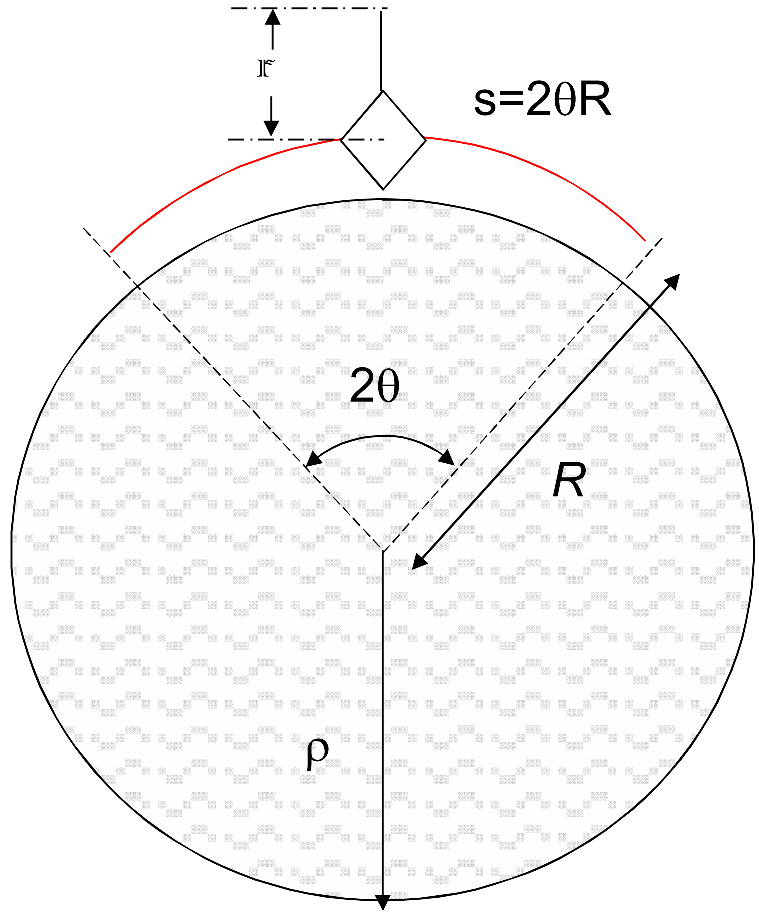
Curved Cracks Near Vias



Curvature Decreases further from Via

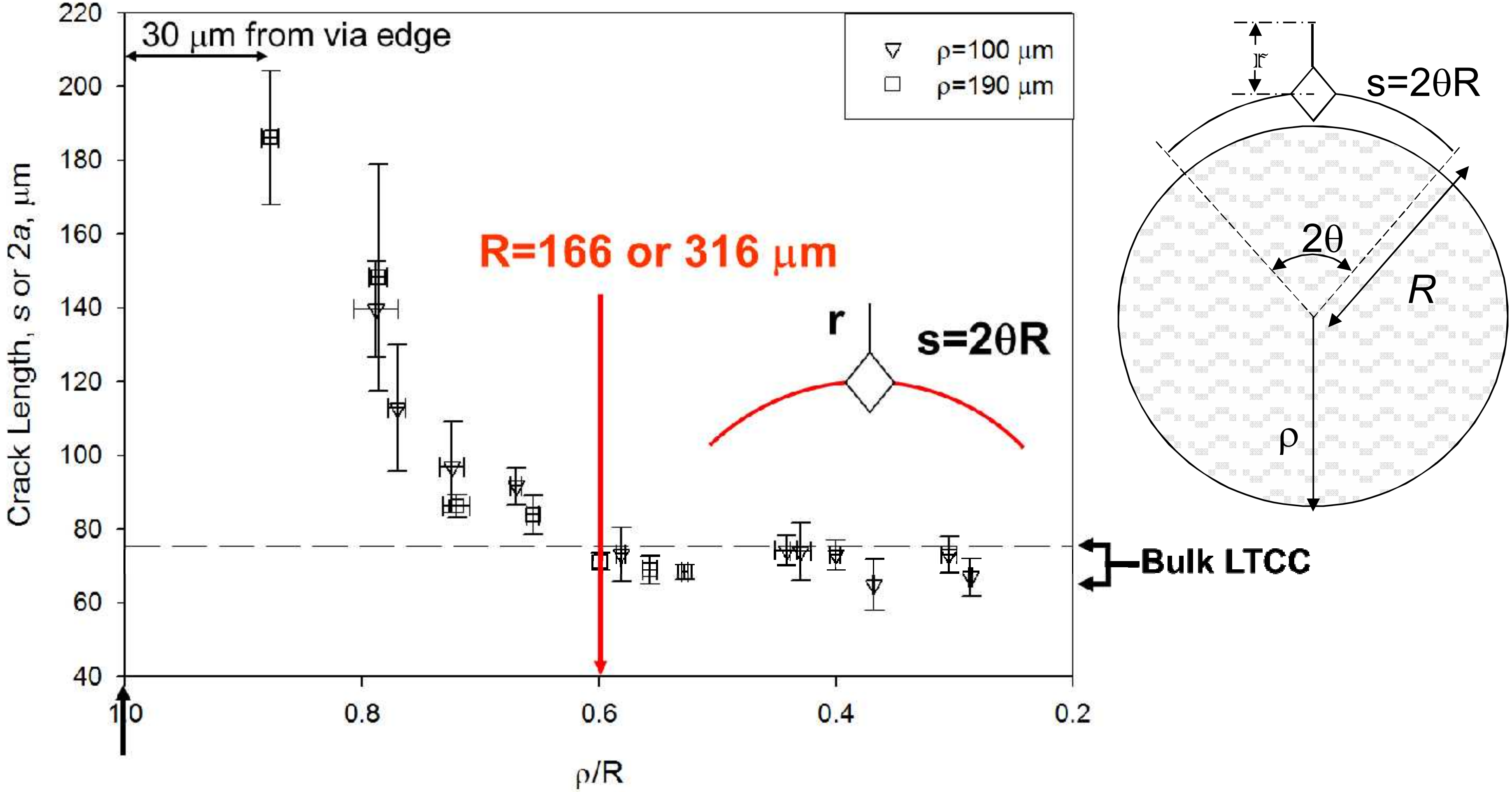


Idealization



Arc crack around the via under mixed mode loading

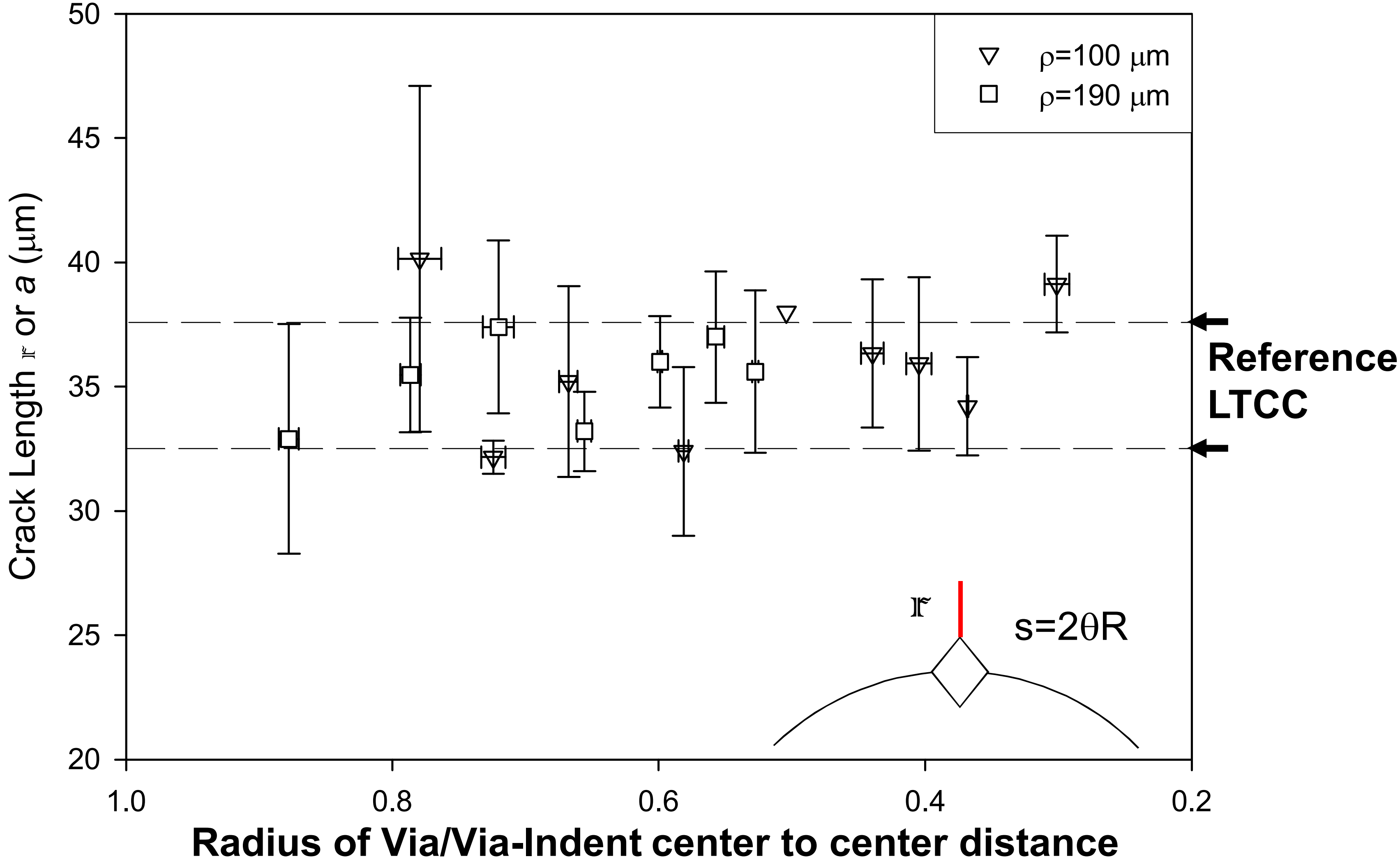
Crack Length Measurements



Radius of Via/Via-Indent center to center distance

Map of tensile stress distribution near via

Crack Length Measurements



No compressive hoop stress !

Effects leading to Δc near interface

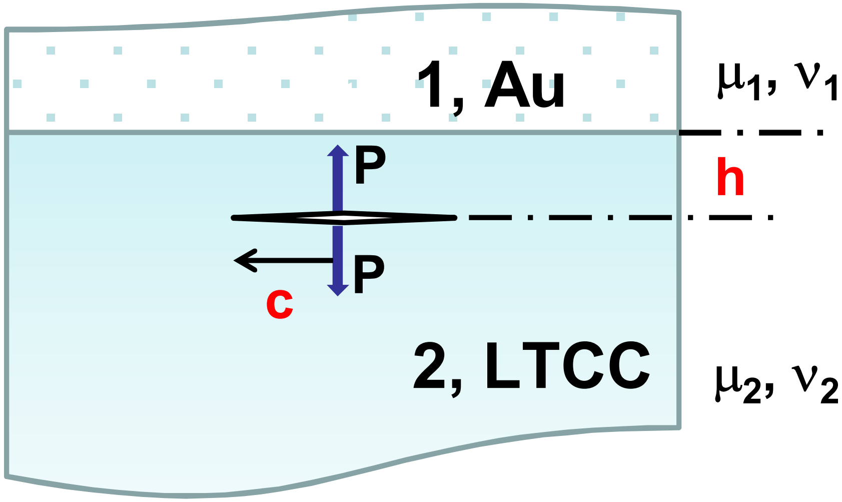
- Stress intensity increment due to elastic mismatch

- Stress intensity increment due to stress due to thermal mismatch between Au and LTCC

Unknown: stress intensity factor due to indentation loading on a curved crack

Major assumption: Indentation crack approximated by a 2-d crack

Sub-interface Crack Problem



Dundur's parameters, κ=f(ν)

$$\alpha = \frac{\mu_1(\kappa_2+1) - \mu_2(\kappa_1+1)}{\mu_1(\kappa_2+1) + \mu_2(\kappa_1+1)} \sim \frac{E_1 - E_2}{E_1 + E_2}$$

Measure of elastic mismatch, α=-1 free edge, α=0 identical, α=1 rigid

$$\alpha_{Au-LTCC} = -0.2$$

- **A center point loaded crack in a semi-infinite material 2***
- **The crack of length c is at a distance h from edge/interface**
- **When h□c**

$$K_I = K_{I,0} = \frac{F}{\sqrt{\pi c}};\ K_{II} = 0$$

***Lardner et al., Int. J. Frac., 1990, *Lu and Lardner, Int. J. Sol. Struc., 1992**

The sub-interface crack was modeled by continuously distributed edge dislocations, and using the stress field for a single dislocation the boundary value problem is solved. The K's are obtained in terms of the dislocation density functions which are calculated numerically

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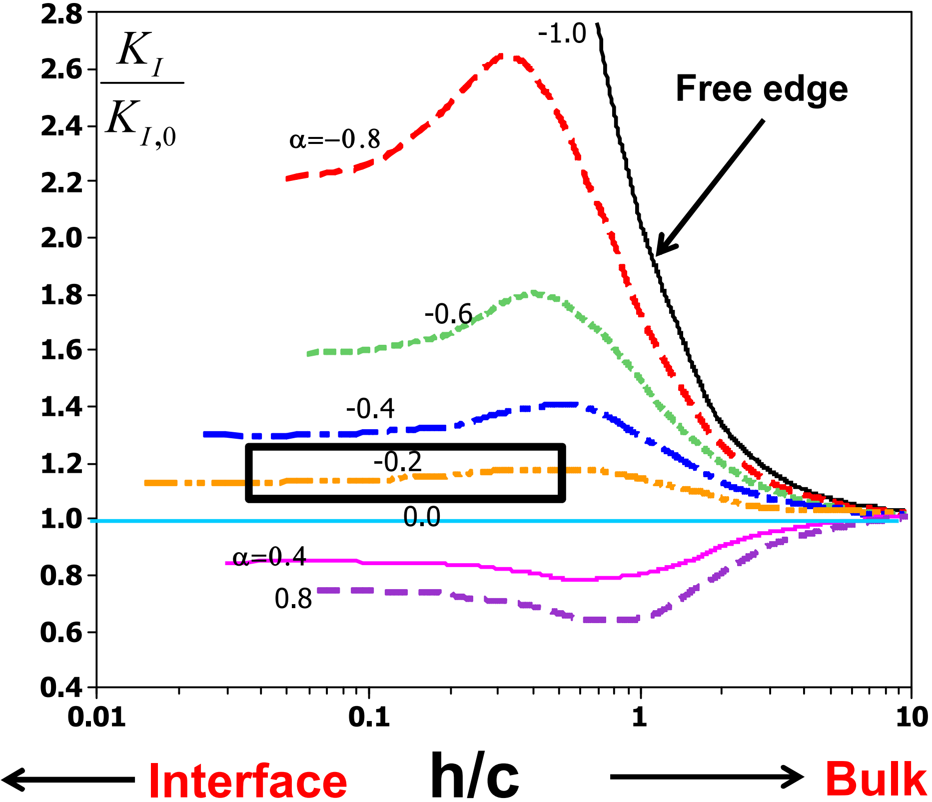
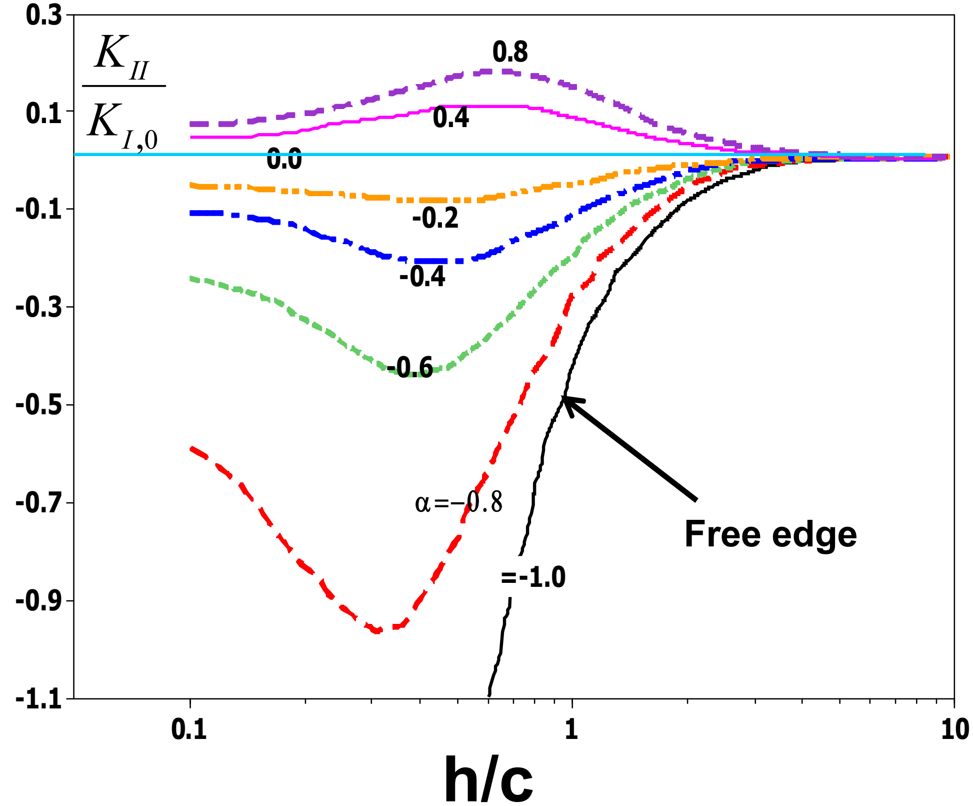
K solutions as a fn (Dundur's parameter, α)

Lu and Lardner, Int. J. Sol. Struc., 1992

Normalized Mode I, K_I / K_{I0}



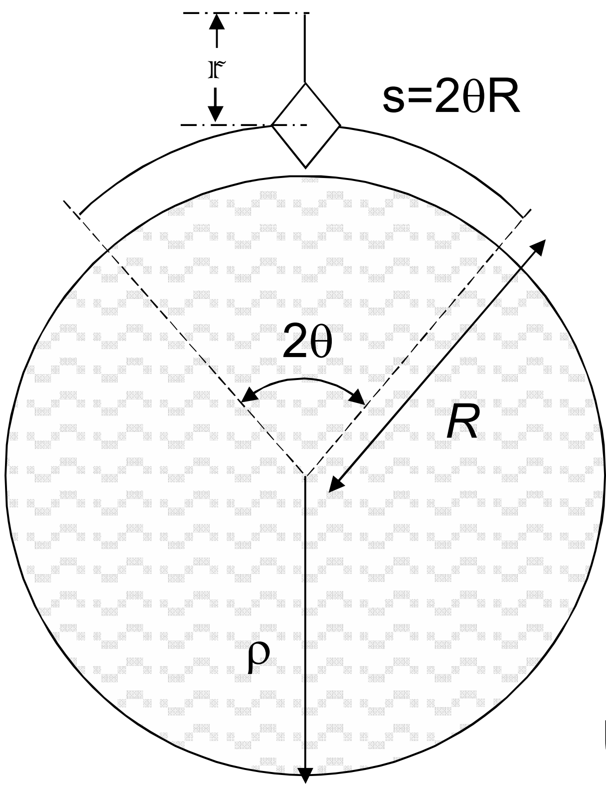
Normalized Mode II, K_{II} / K_{I0}

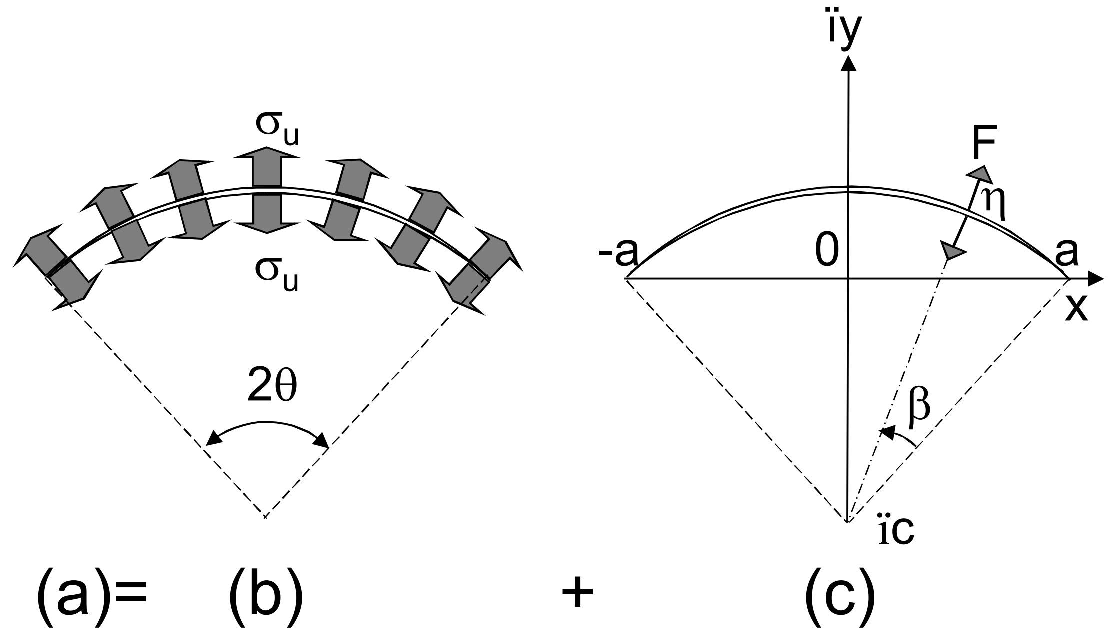


There is ~ a 10% increment to the crack length due to elastic mismatch
This leads to ~ 20% increment to the calculated stress intensity factors
Measured crack lengths are up to 1.5 x baseline sizes.
So effect due to elastic mismatch is ignored in what follows

Fracture Mechanics Idealization

Loading acting on arc crack





Uniform loading due to Stress from via **+** **Point Load due to Indentation Impression**

Stress Intensity Factors

$$K_{I-u} = \frac{\sigma_u \sqrt{\pi R \sin\theta}}{1+\sin^2\frac{\theta}{2}} \cos\frac{\theta}{2}$$

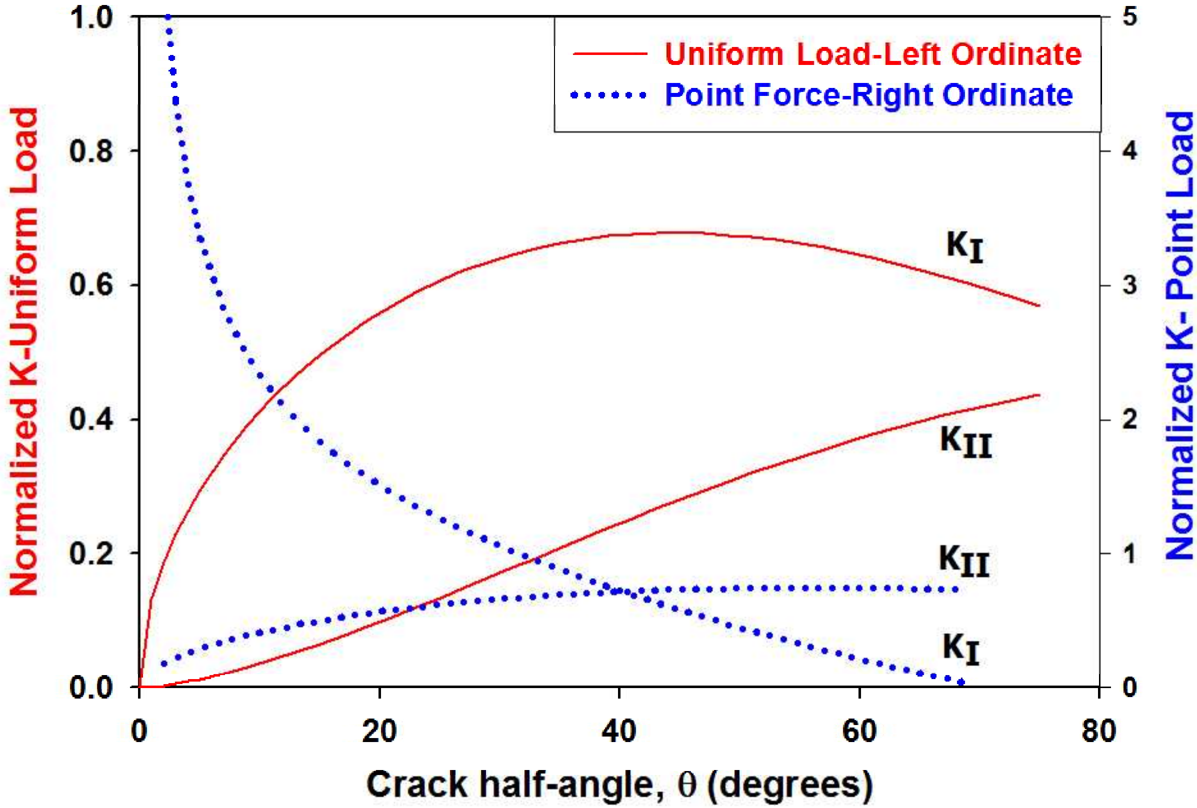
$$K_{II-u} = \frac{\sigma_u \sqrt{\pi R \sin\theta}}{1+\sin^2\frac{\theta}{2}} \sin\frac{\theta}{2}$$

Uniform Loading

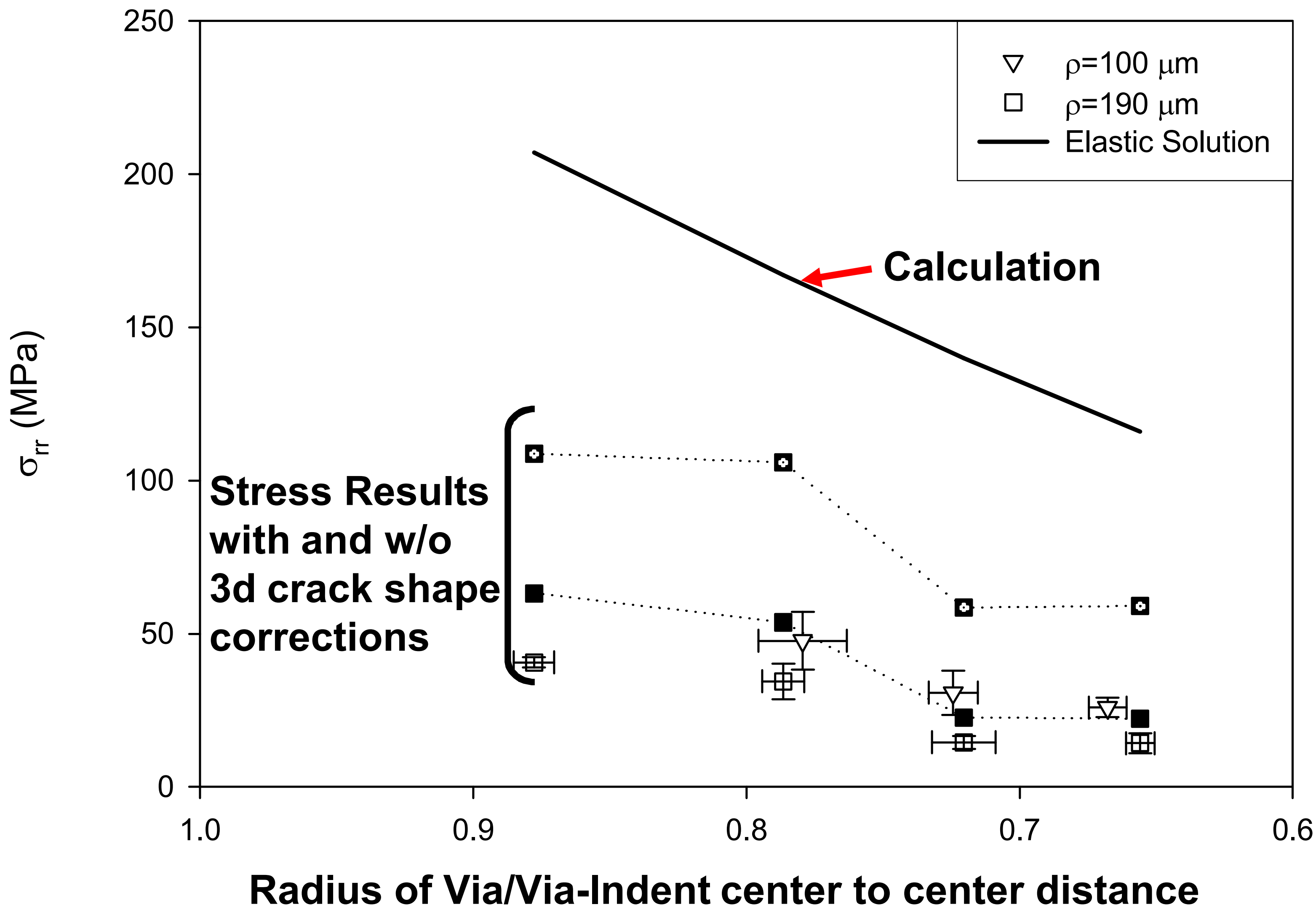
$$K_{I-p}\Big|_{\pm a} = \frac{F}{\sqrt{\pi R \sin\theta}} \left[\frac{\cos\theta}{2} - \frac{1}{2} + \frac{2\cos^4\frac{\theta}{2}}{(3-\cos\theta)} \right]$$

$$K_{II-p}\Big|_{\pm a} = \frac{F}{\sqrt{\pi R \sin\theta}} \left[\frac{\sin\theta}{2} + \frac{2\cos^3\frac{\theta}{2}\sin\frac{\theta}{2}}{(3-\cos\theta)} \right]$$

Point Loading



Stress Calculations



Stresses significantly lower than calculated

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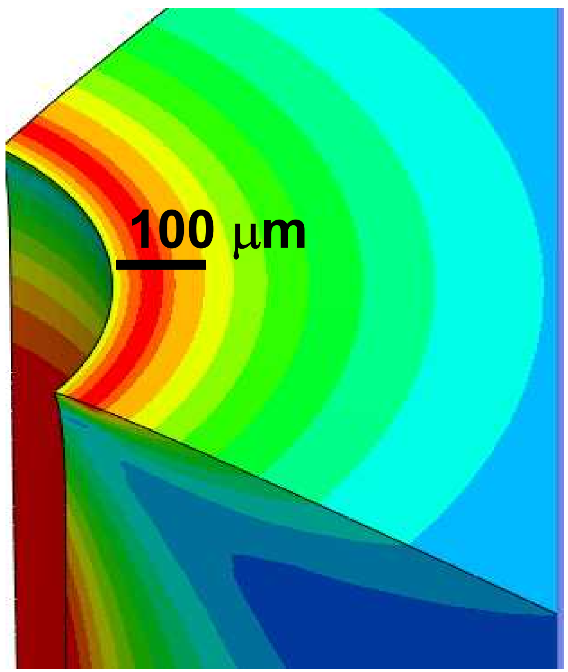
Conclusions

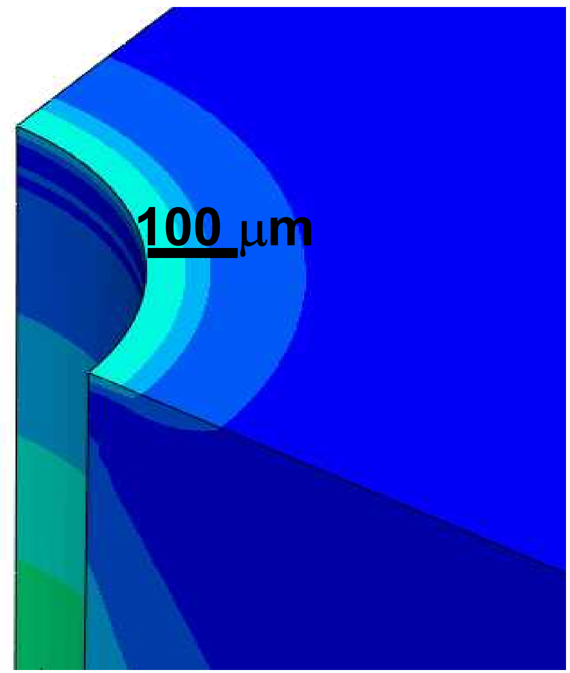
- **Cause of discrepancy: Plastic deformation in gold via**

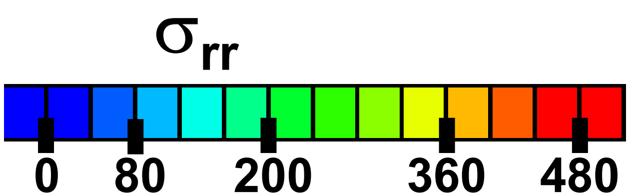
Stress Distributions in LTCC for two via material models

Elastic Via — **Model A**



Elastic-Plastic Via — **Model B**





Peak Stress:

Model A ~550 MPa
Model B ~160-120 MPa

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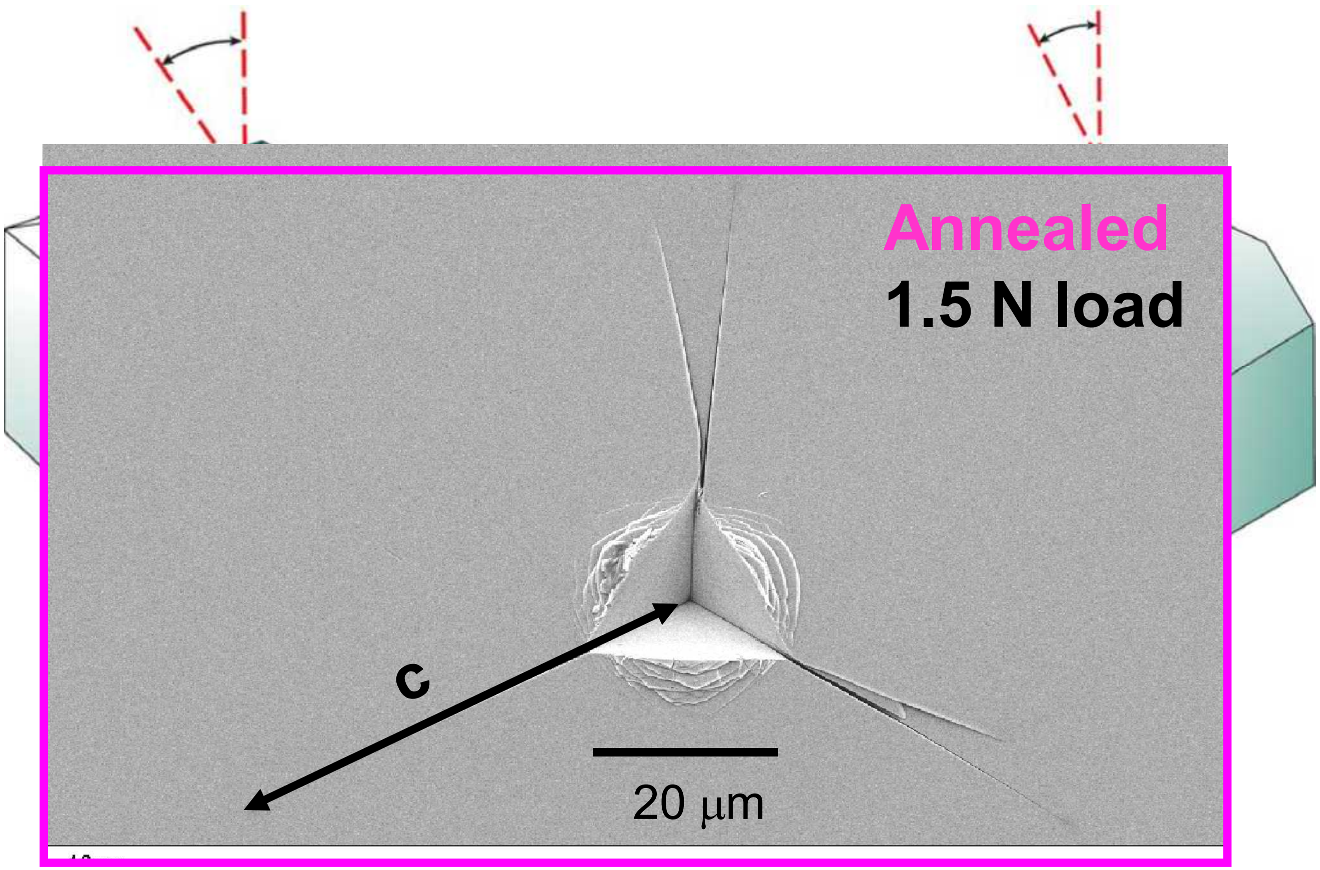
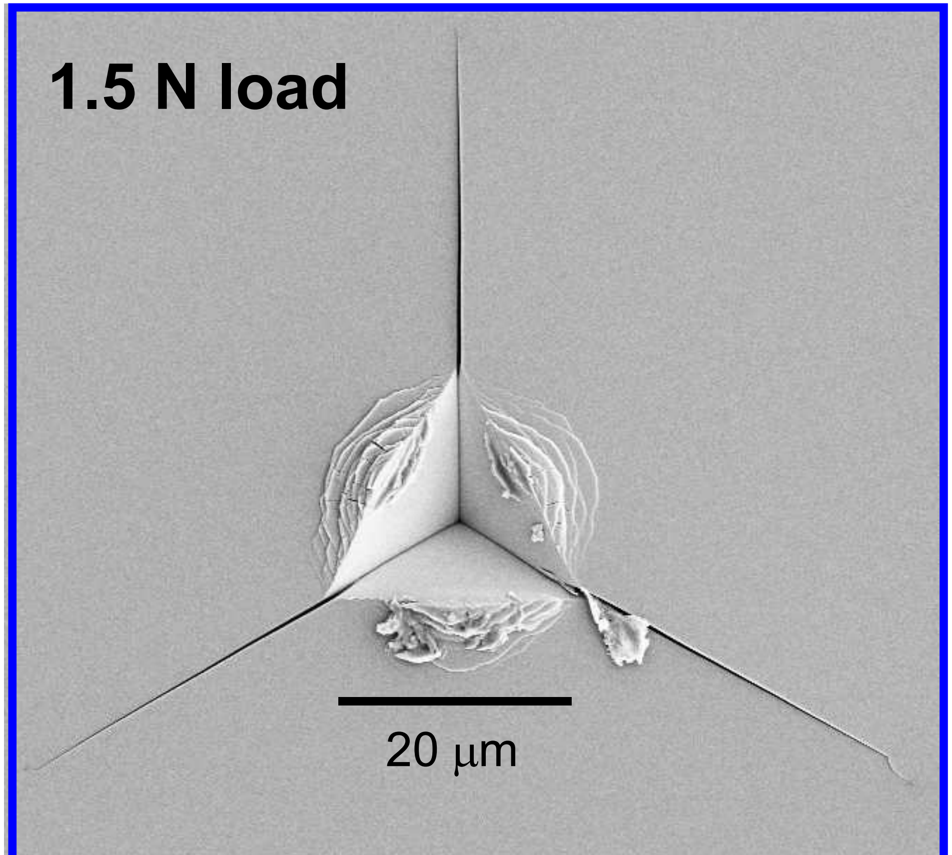
Cube Corner Indentation

Cracks develop at low loads & small impression size
Allow stress measurement over small volumes

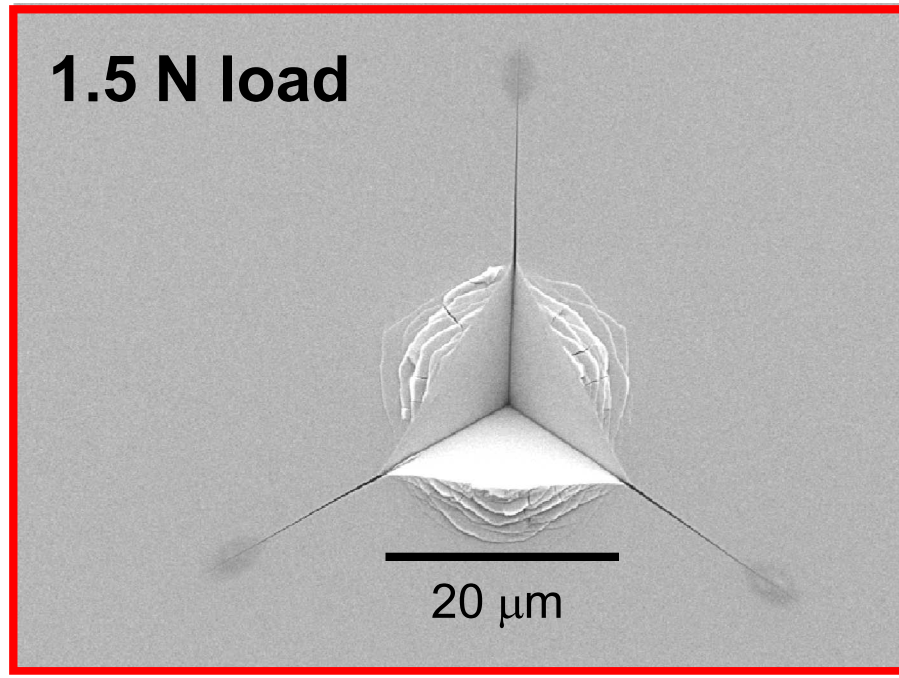


Indentation on Two Stressed Glass Surfaces

Heat Strengthened (partial temper)



Fully Tempered



Crack sizes are significantly smaller

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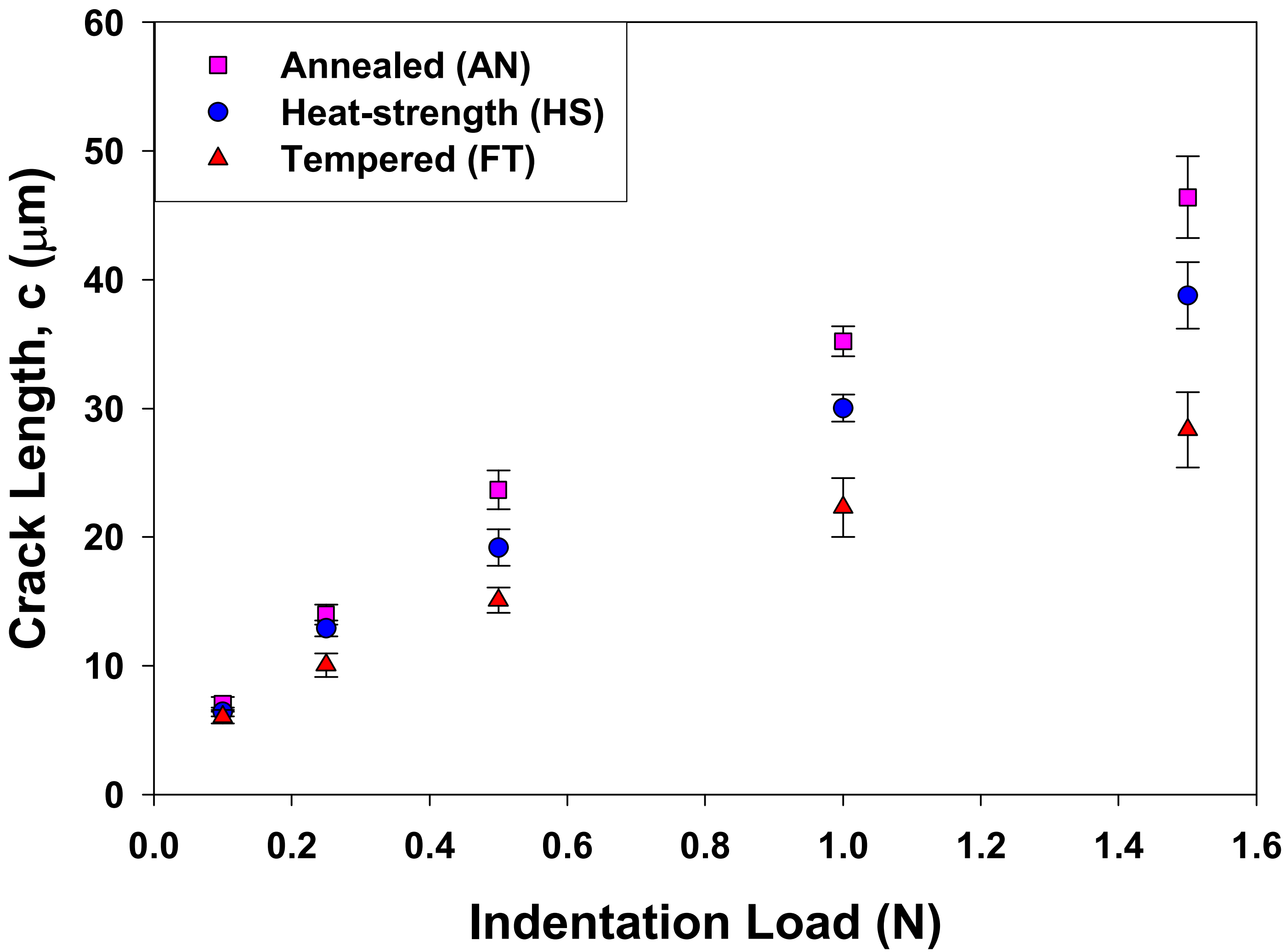
Crack Lengths Lower on Stressed Glasses



Crack length difference increases with increasing load/with increasing crack length

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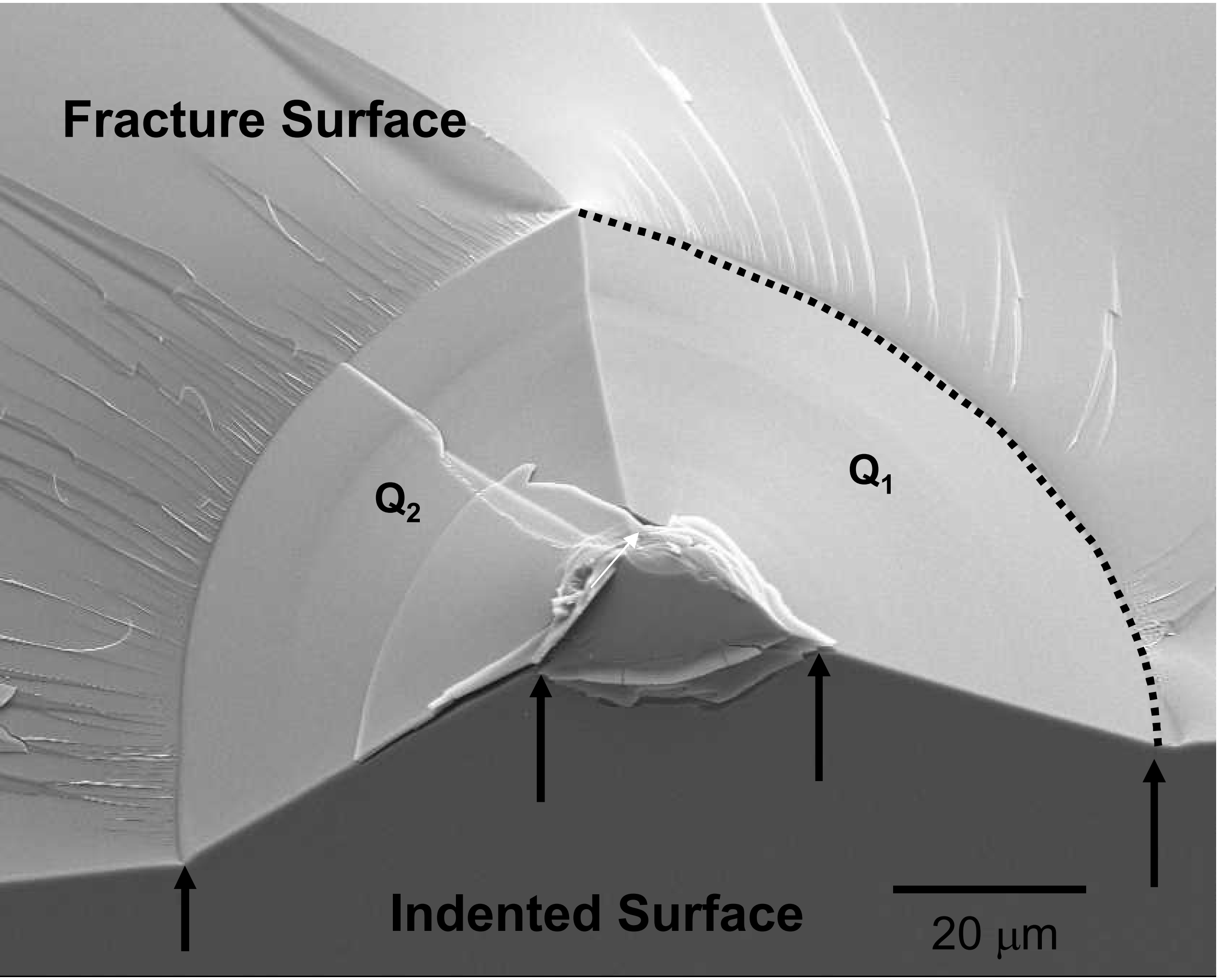
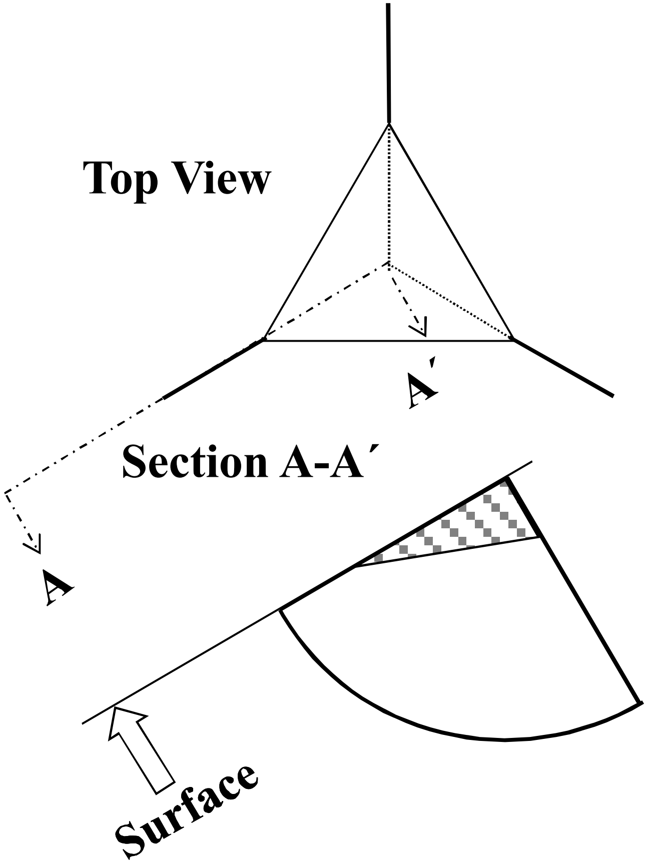
Quarter Penny Crack: High Load

Annealed: 2 N Load





Stress Intensity Superposition

$$K_{Net} = \chi \frac{P}{c^{3/2}} - 2f(\alpha)|\sigma_S|\left(\frac{c}{\pi}\right)^{1/2}$$

Elastic-plastic Mismatch Term:

– χ is ~ 2 times that for Vickers

-Half-penny crack assumption

Residual Stress, σ_s, term:

-f(α) for quarter-penny using a weight function approach~1.13

- Kese and Rowcliffe, f(α)~0.53

$$\frac{P}{c^{3/2}} = \frac{P}{c_0^{3/2}} + \frac{2f(\alpha)|\sigma_S|\left(\frac{c}{\pi}\right)^{1/2}}{\chi}$$

Residual stress obtained from slope

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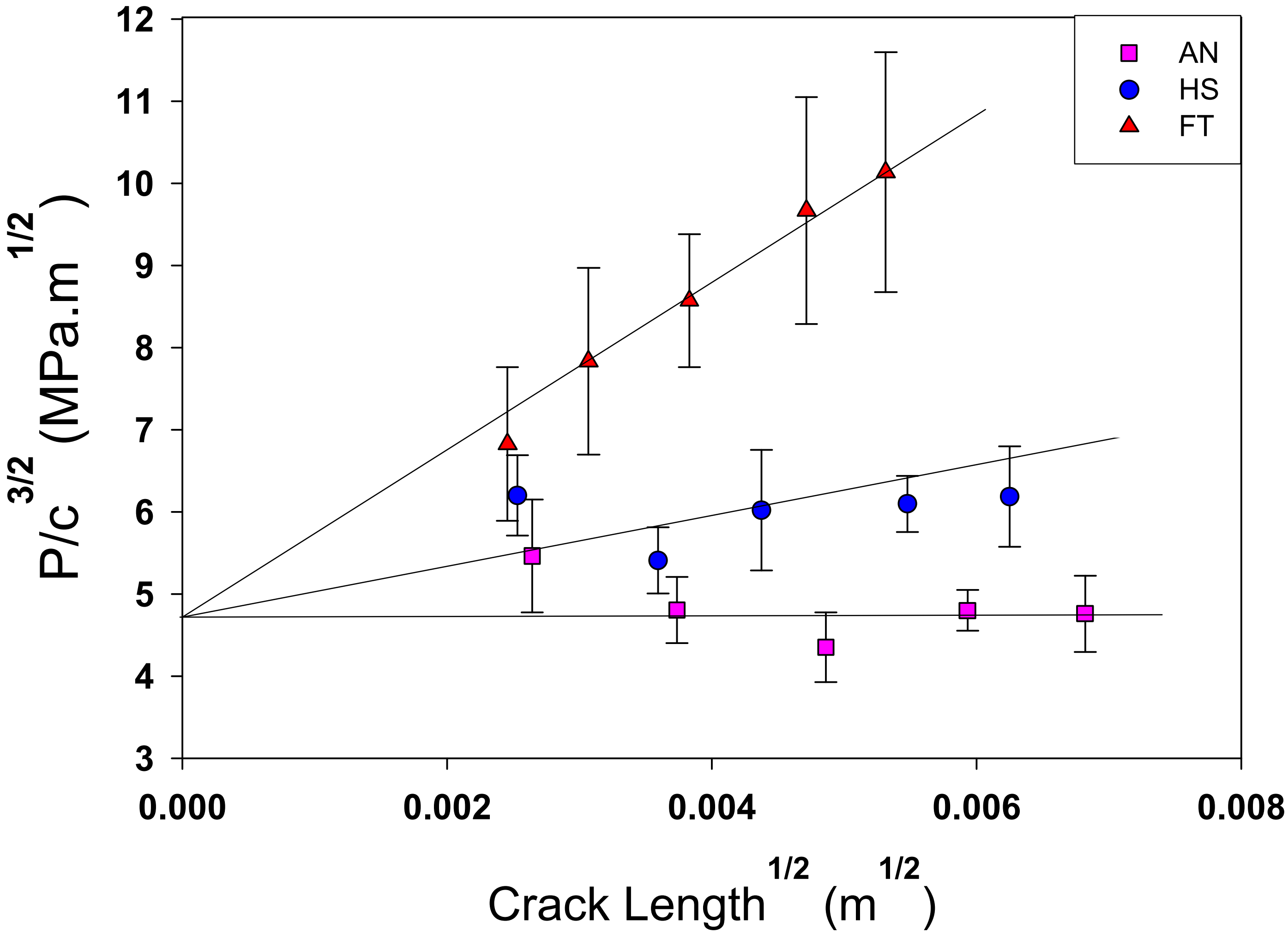
Stress Results Obtained



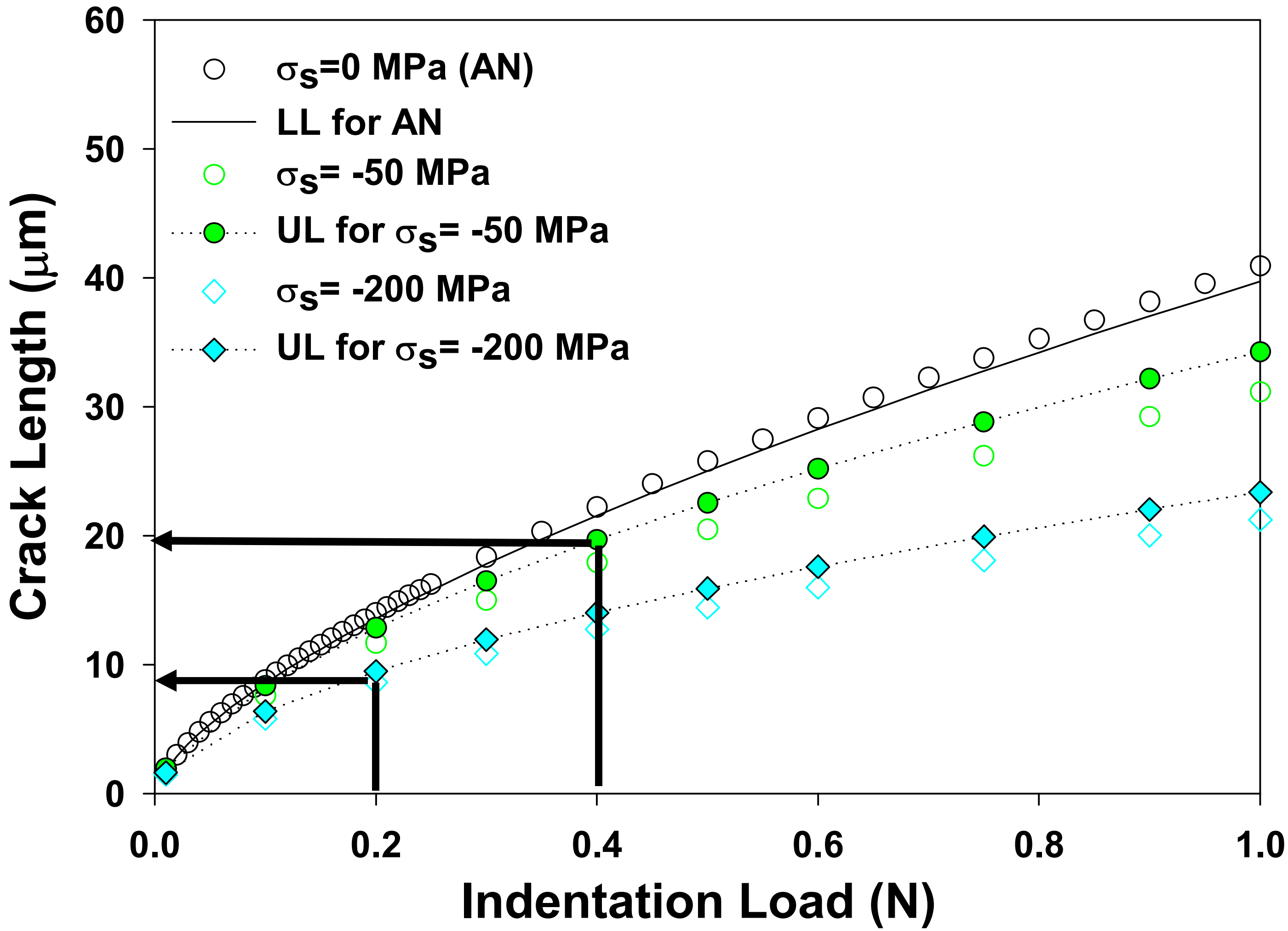
Heat Strengthened: -30 MPa

Tempered: -110 MPa

Higher stresses can be resolved over a smaller volume

-30 MPa stress resolvable over 25 μm^3

-110 MPa stress resolvable over 20 μm^3



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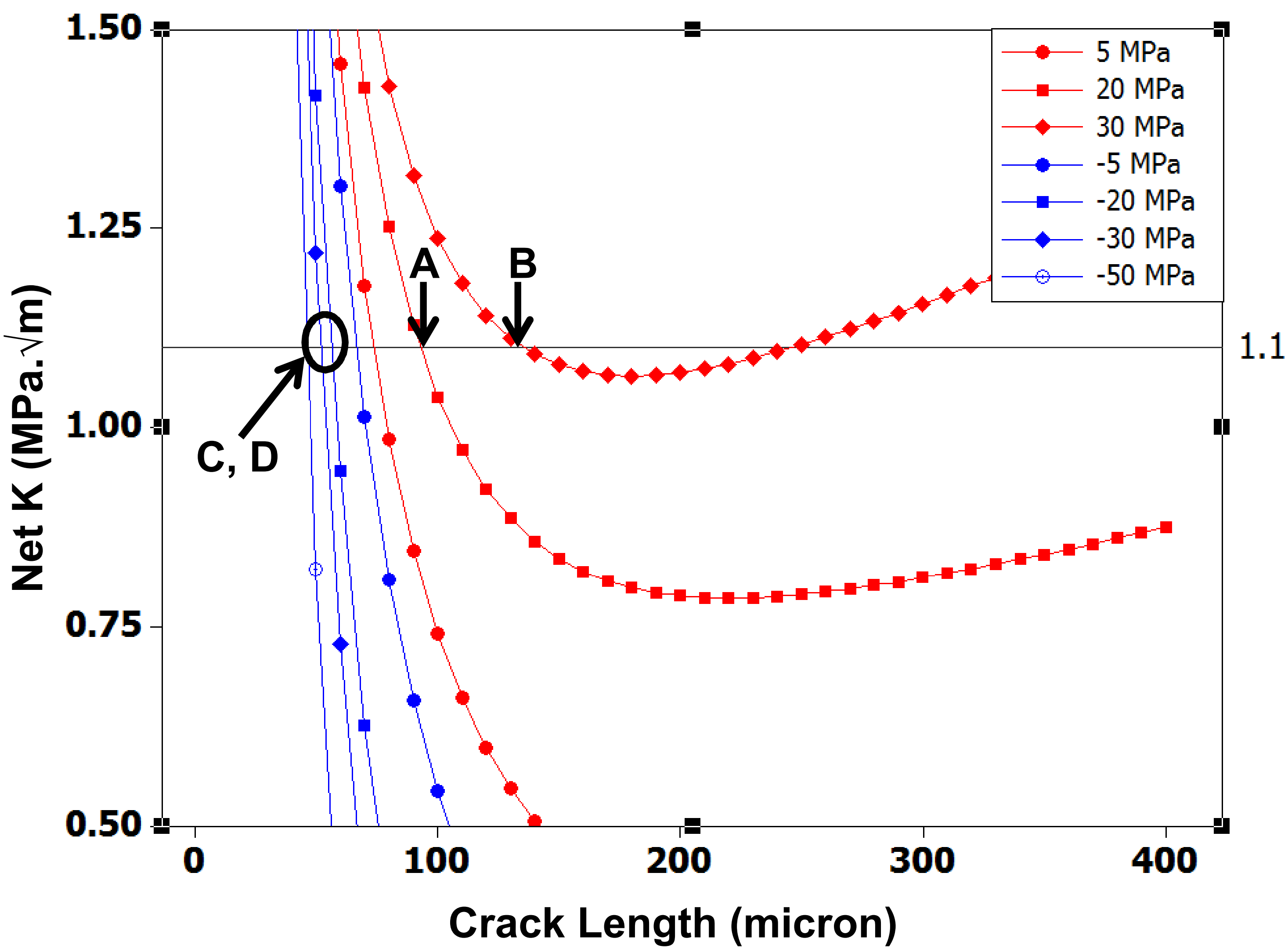
Resolution lower for compressive stress



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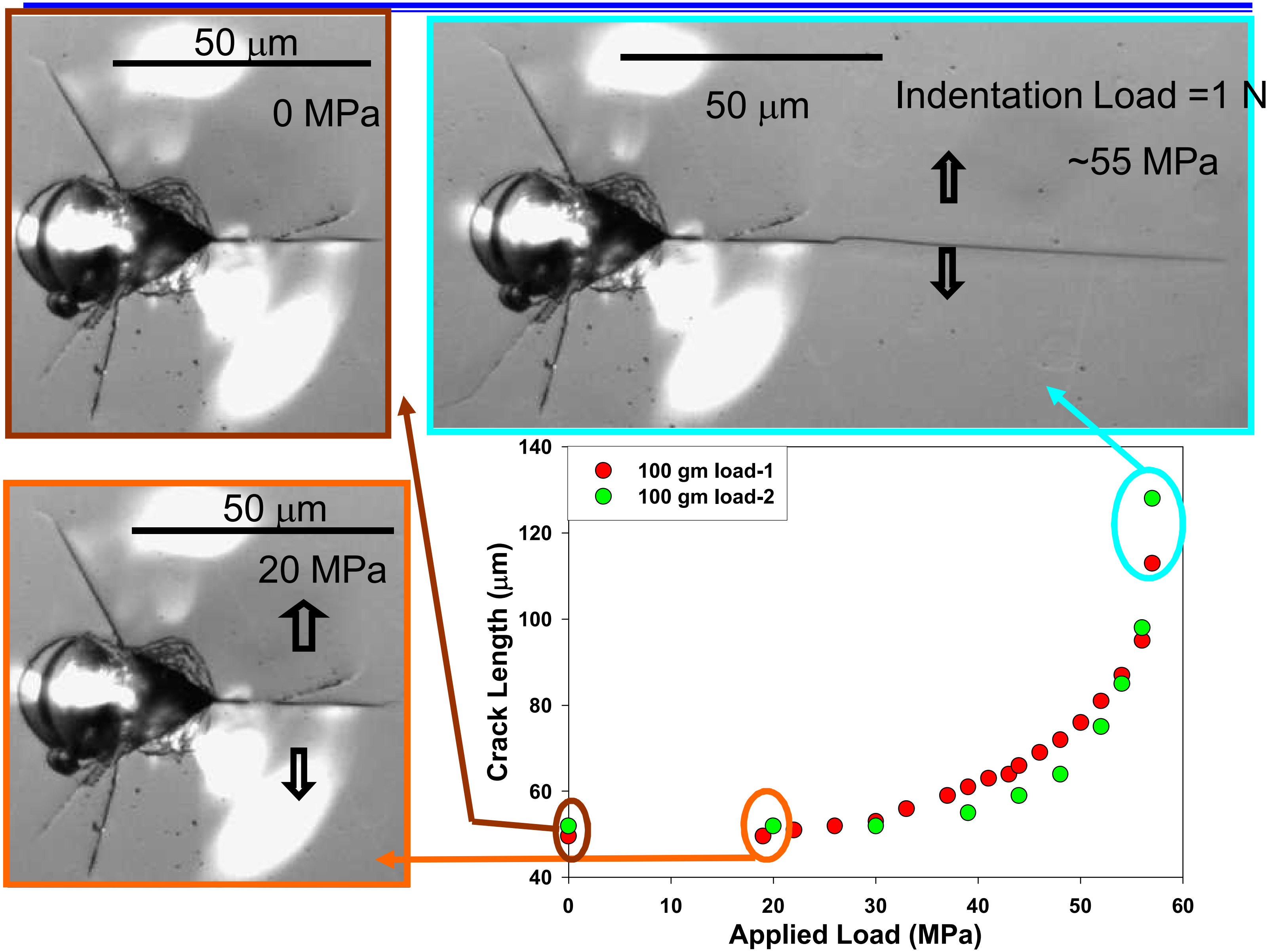
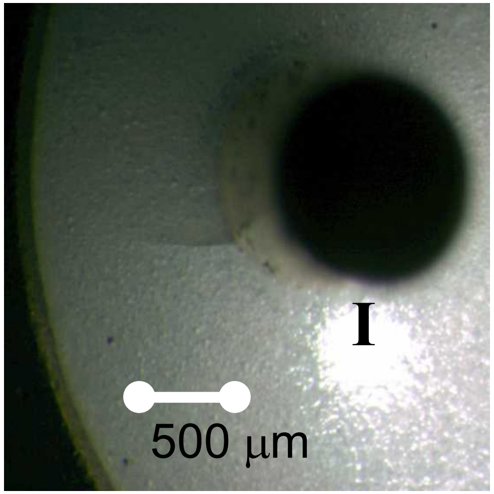
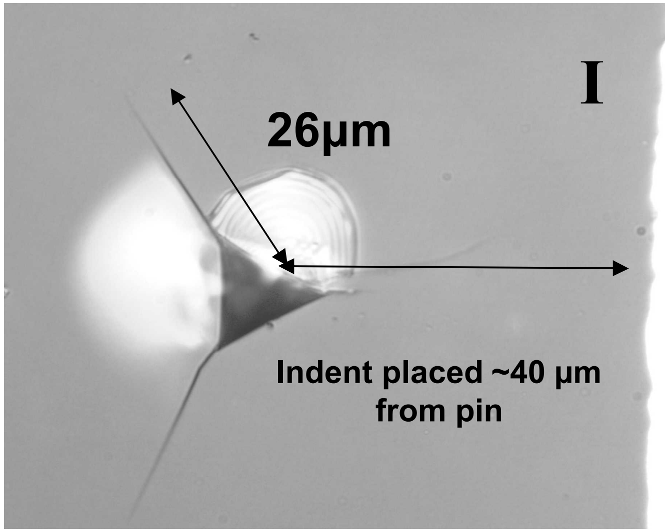
Crack Extension Studies

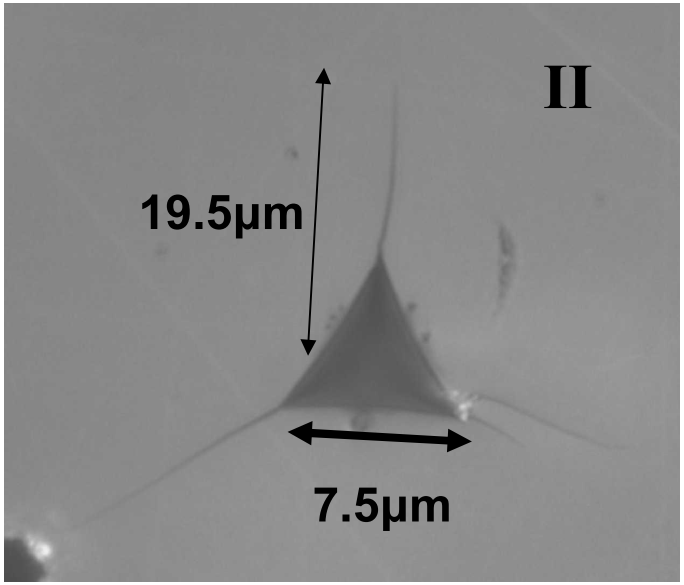


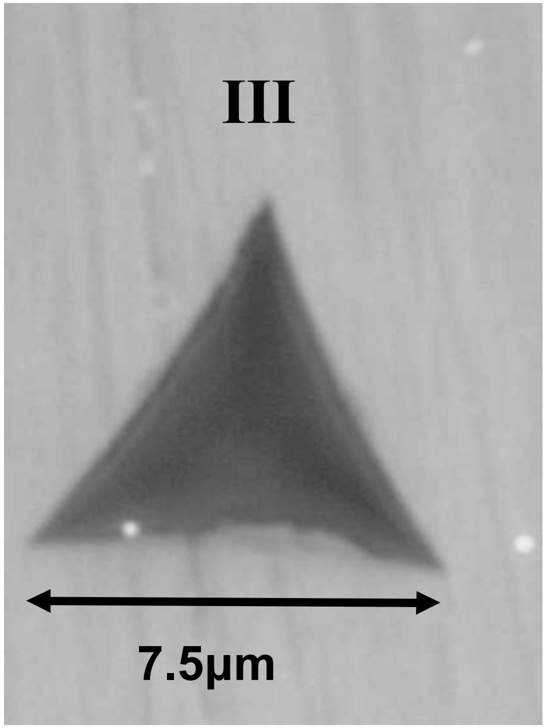
Crack-grain boundary interactions could be studied

Successful Use of Cube Corner in Glass-to Metal Seal Design and Production



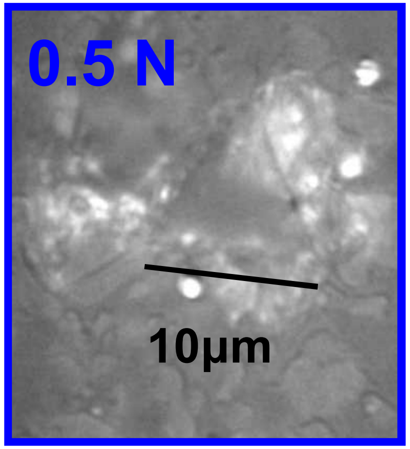


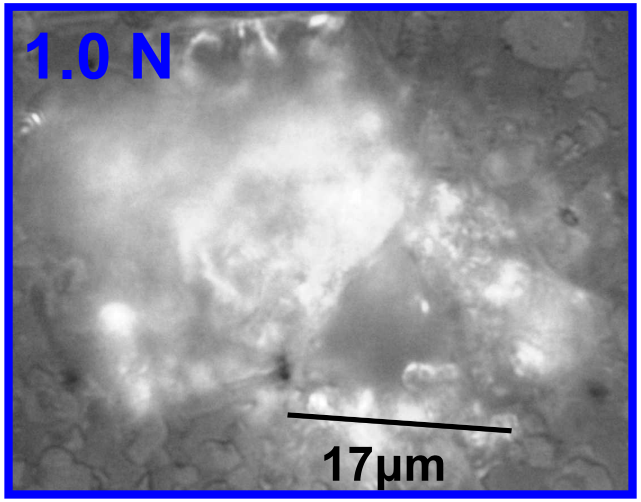


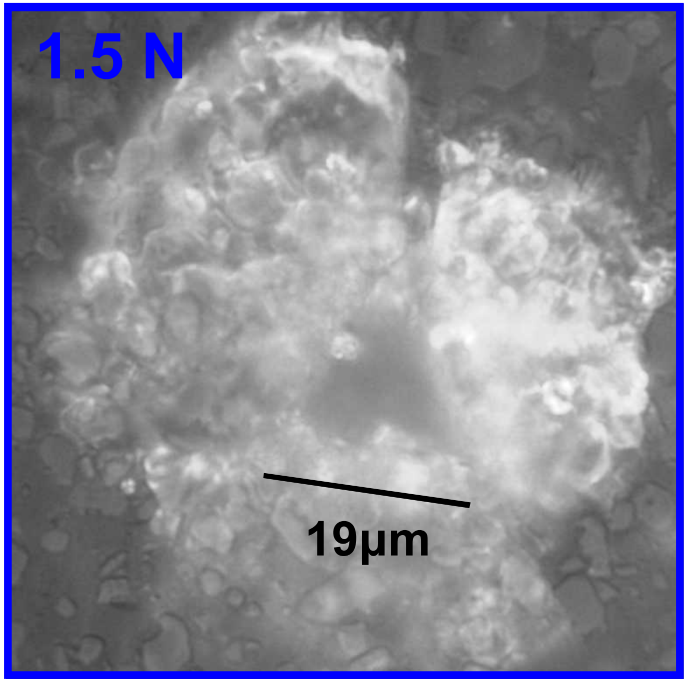


Limitations of use of Cube Corner

LTCC: Chipping







Massive chipping in other polycrystals as well

Conclusions

-Cube corner indentation appears to be a good technique for measuring stresses in glasses

-As compressive stress magnitude increases, volume in which stresses can be sampled decreases

- Compressive stress measurements in ~10μm^3 appears possible

-Polycrystalline measurements may not be possible

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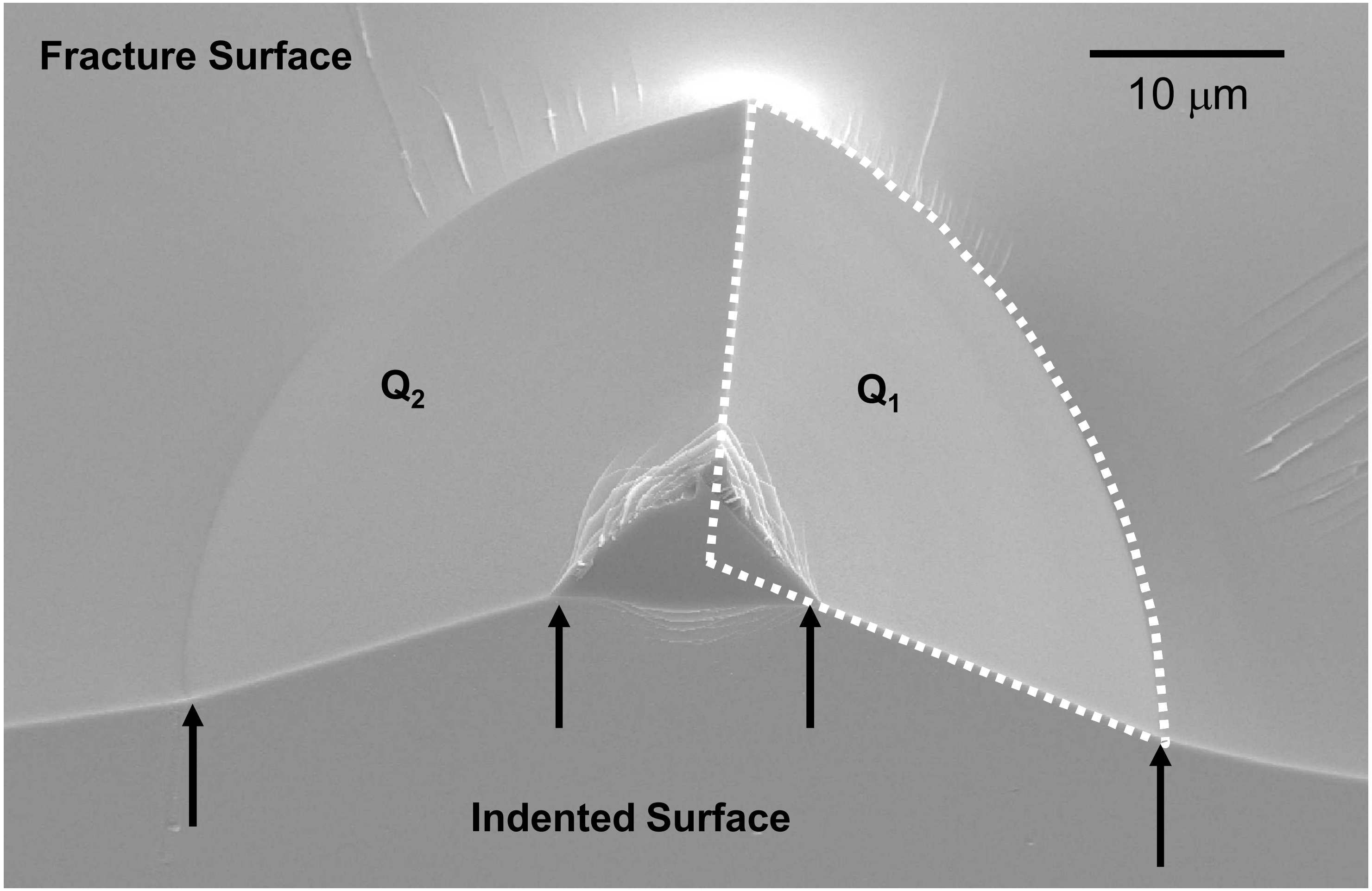
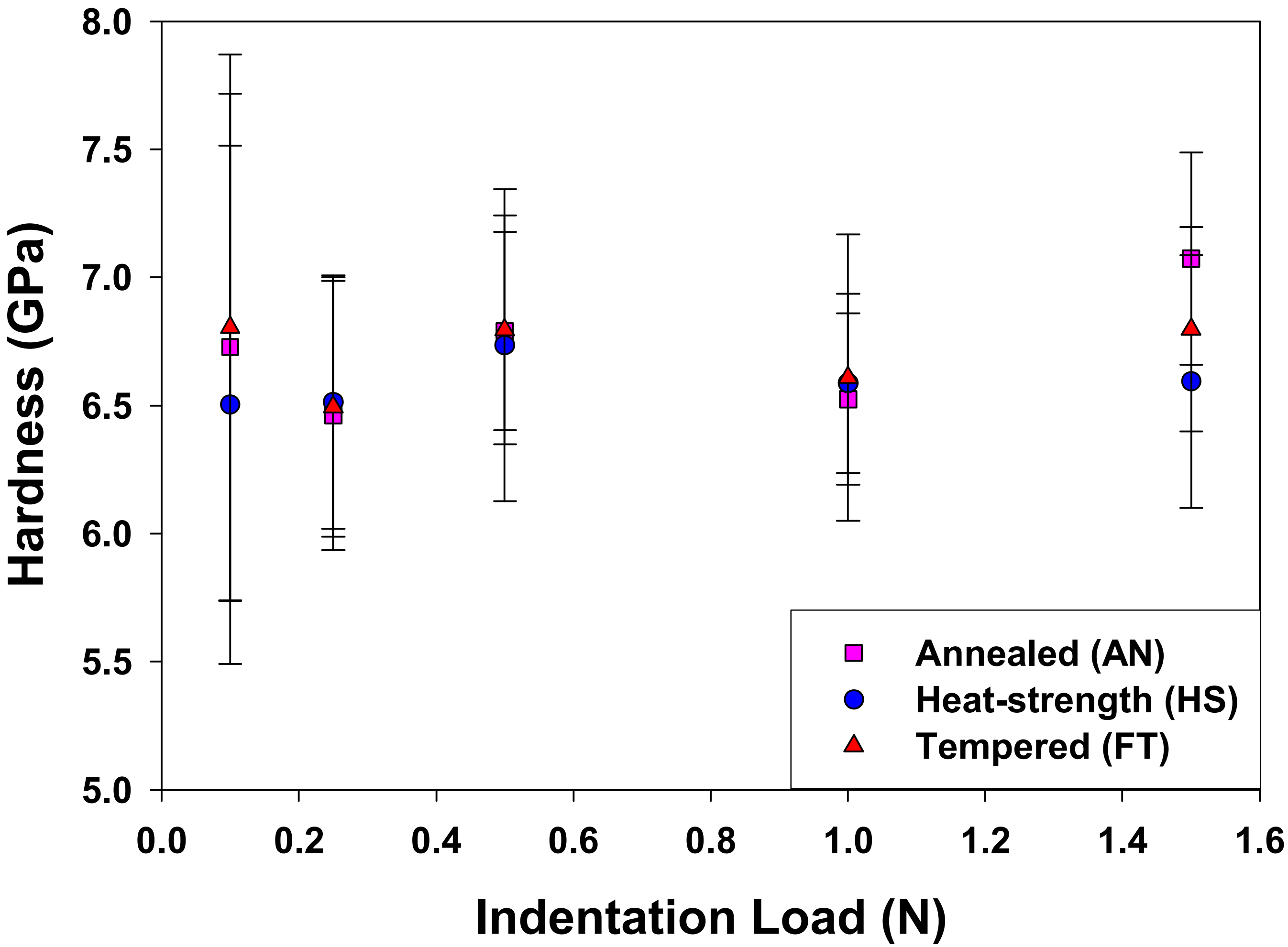
Precise information about the thermal environments during manufacturing and temperature-dependent mechanical/thermal properties are needed for accurate finite-element stress predictions in multi-material systems. For many engineering materials, these properties and proper constitutive behavior are unknown. Stress measurements are imperative prior to component deployment. Indentation cracks have been used to estimate stresses in bulk materials. Practical implementation shows at least two limitations: (1) near interfaces, indentation cracks are curved, and (2) stresses are sampled over the entire crack length (~ 100 microns). We present a fracture mechanics approach for stress estimation from measurements of curved crack lengths near interfaces. Next, the use of a (sharp) cube-corner indenter that generates cracks at extremely low loads to sample stresses across ~10 micron regions is described. Lastly, a nano-indentation approach that may allow sampling stress across ~5 micron regions is discussed. The use of proposed approaches is demonstrated in successful component designs.

Quarter Penny Crack: Lower Load

Annealed: 0.5 N



Hardness Values Unchanged



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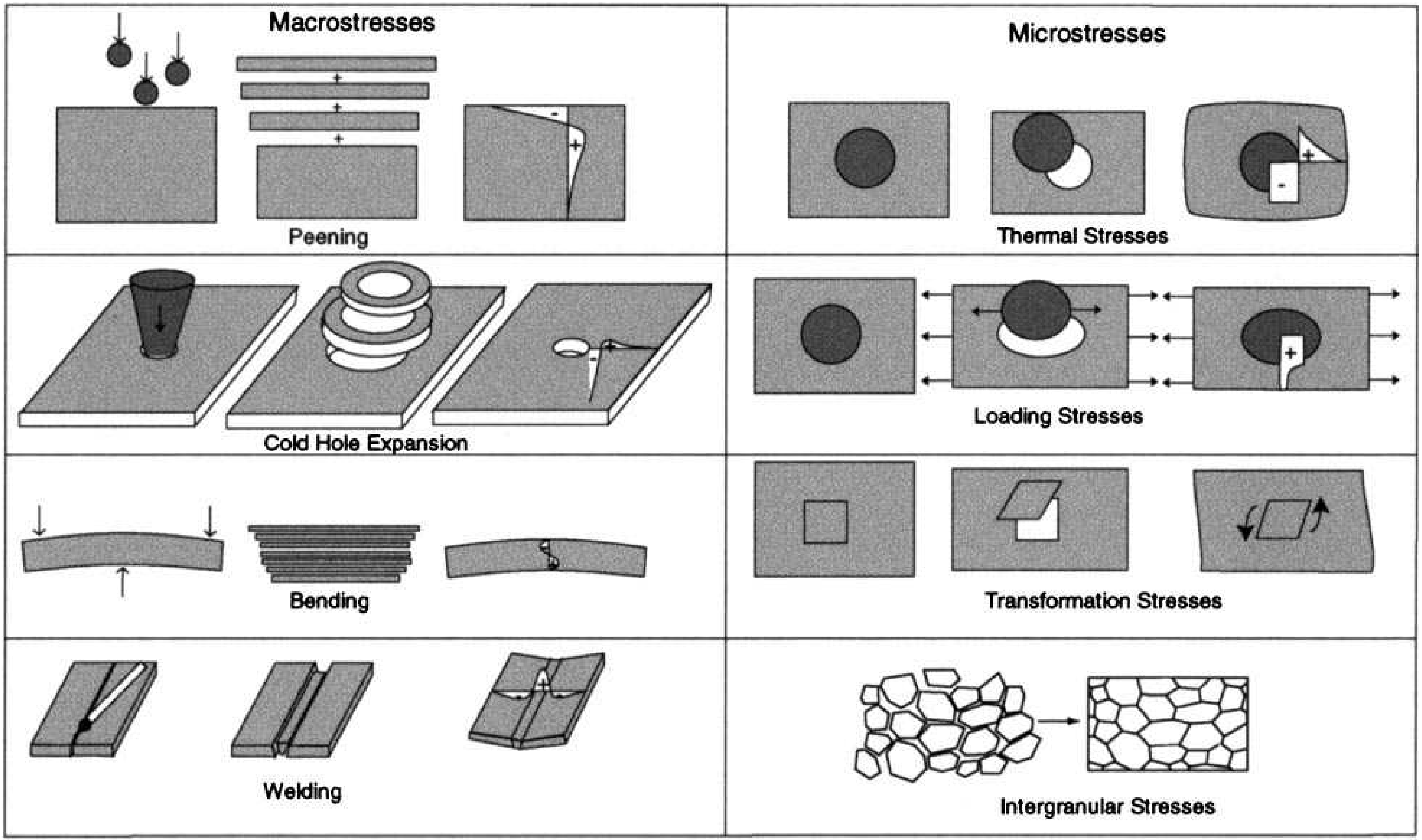
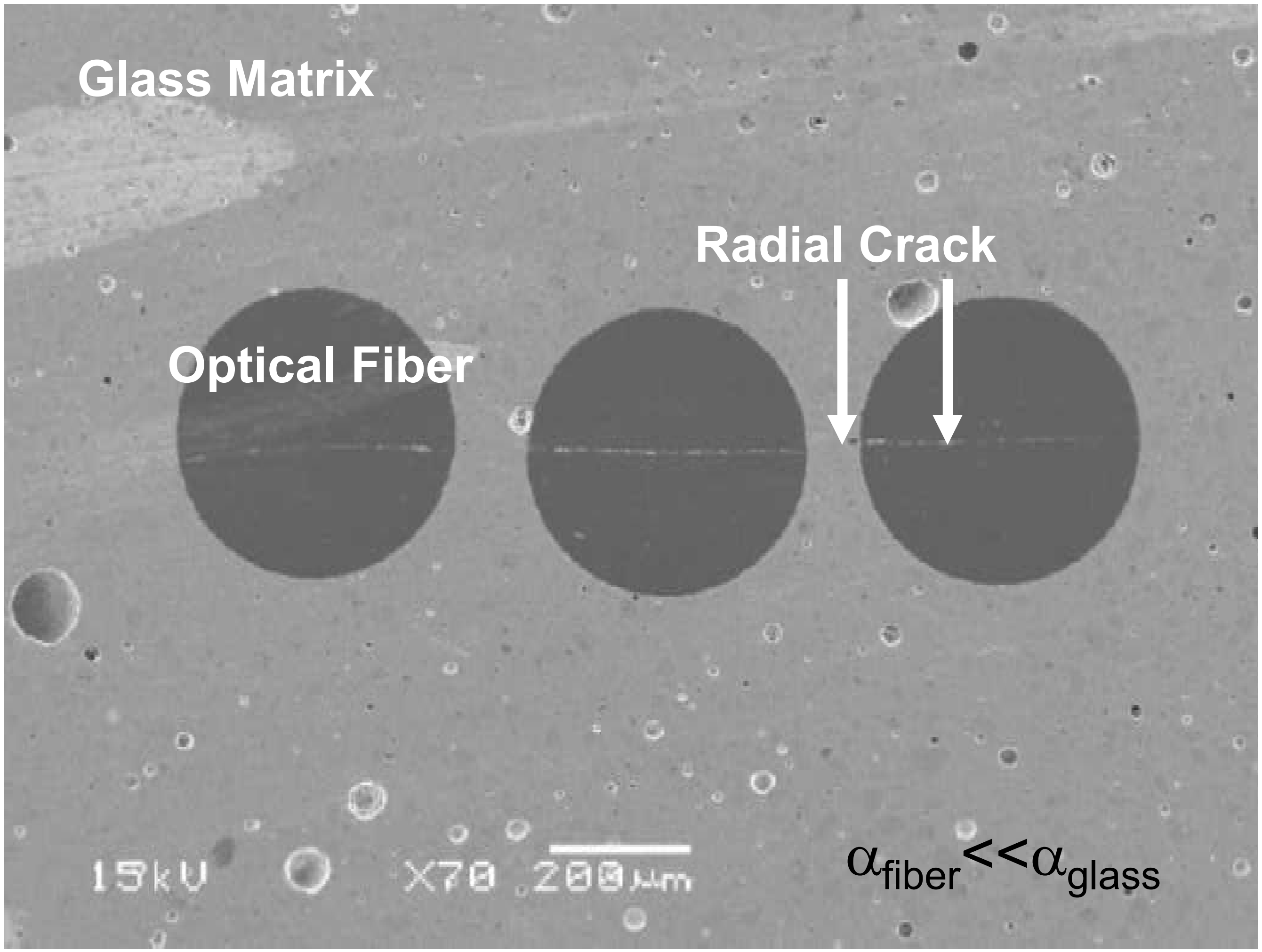
Residual stresses arise from misfits...

... between different regions or different phases when they are bonded together (figure from Withers and Bhadeshia, Mat. Sci. and Tech., 2001)



Radial Cracks Within and Outside Fiber

- Loss of power-transmission functionality



All glass seal