Failure Modes and Mechanics of Fracture in Co-Fired Engineering Ceramics- LTCC

SAND2017-5344C

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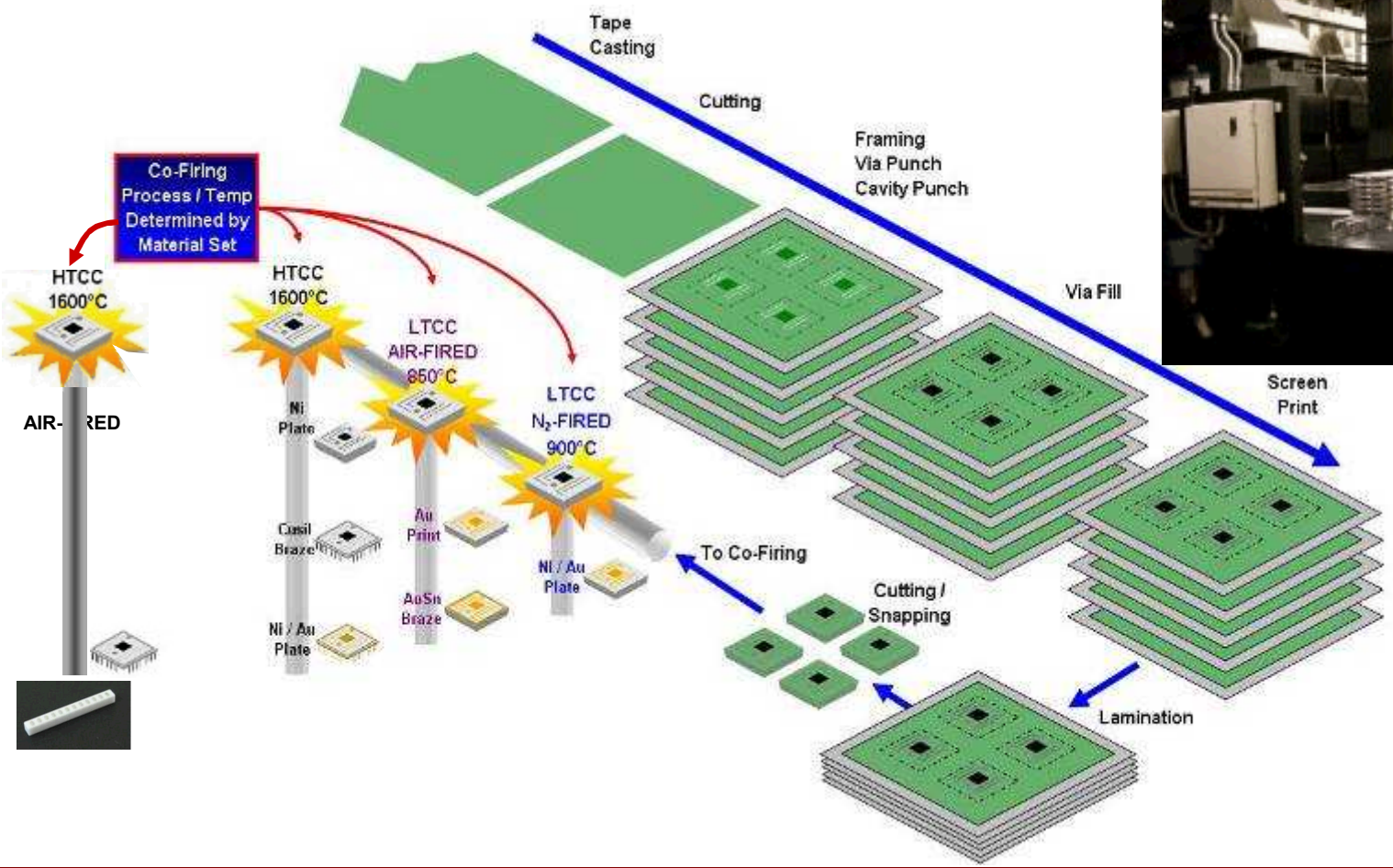
Low/High Temp. Co-fired Ceramics (LTCC/HTCC)

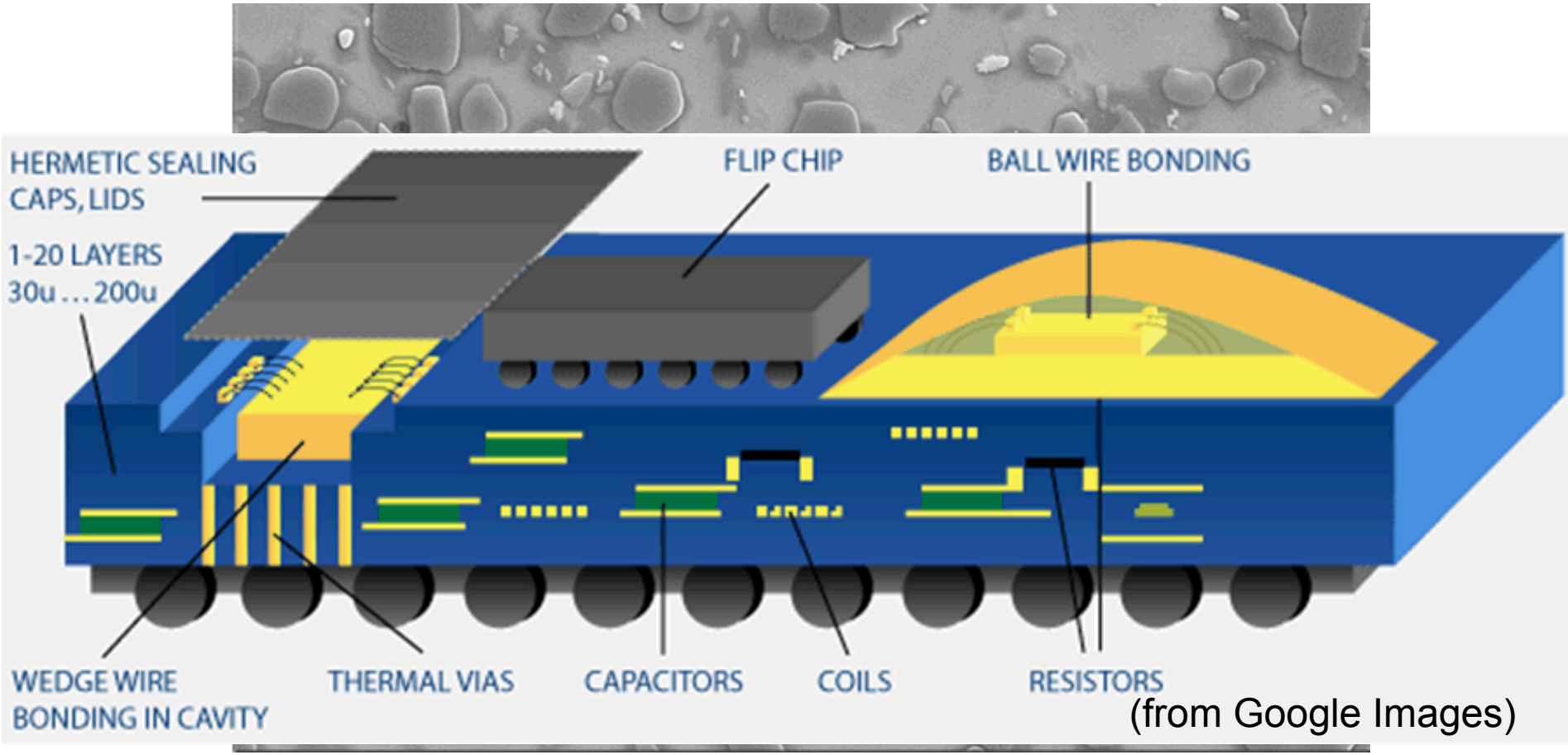
90-96% Alumina: W, Mo, Pt, Au, Ag via High Temperature Sintering
LTCC – Glass/composite ceramics: Cu, Au, Ag via Low Temperature Sintering

HTCC Belt Furnaces



Motivation

Materials Motivation: Low temp. co-fired ceramic (LTCC) is versatile glass-filled ceramic composite packaging material.

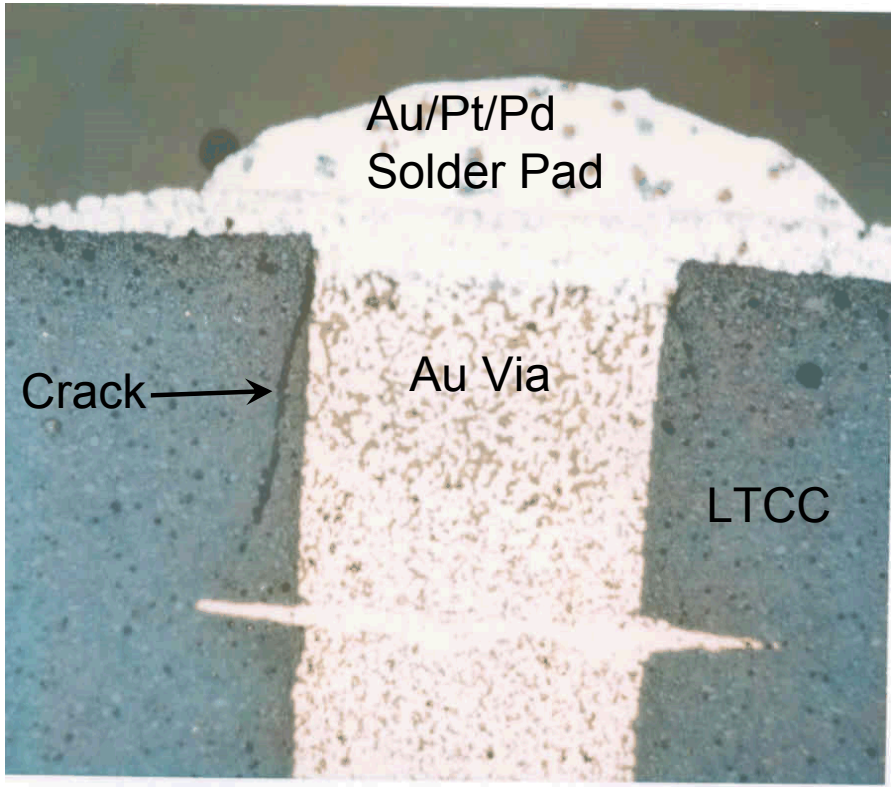


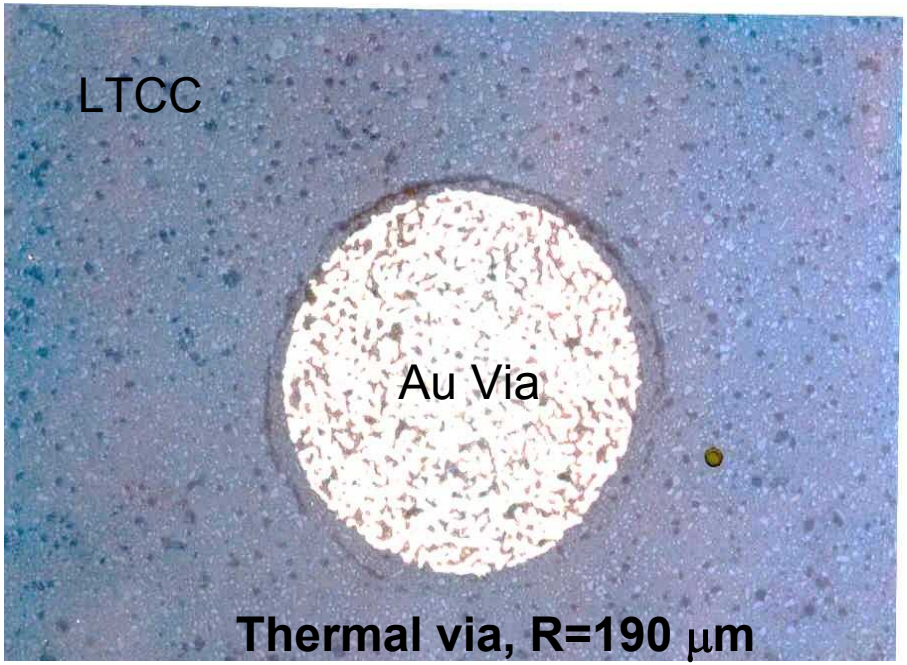
(from Google Images)

Motivation

Mechanics Motivation: Cylindrical inclusions, such as electrical vias, and metal connector pins are common features in many functional ceramic materials.

Cracking problems are sometimes observed





Outline (Part 1)

- LTCC Work:
  - Experimental Results and Fractographic Observations
  - Interfacial Fracture Mechanics for Cylindrical Inclusions
  - Stress Intensity Factors, and Strain Energy Release Rates
  - Interfacial Fracture Energy Based on Crack Kinking Arguments, & Conclusions

Outline (Part 2)

- HTCC Work

  Implantable Medical Devices

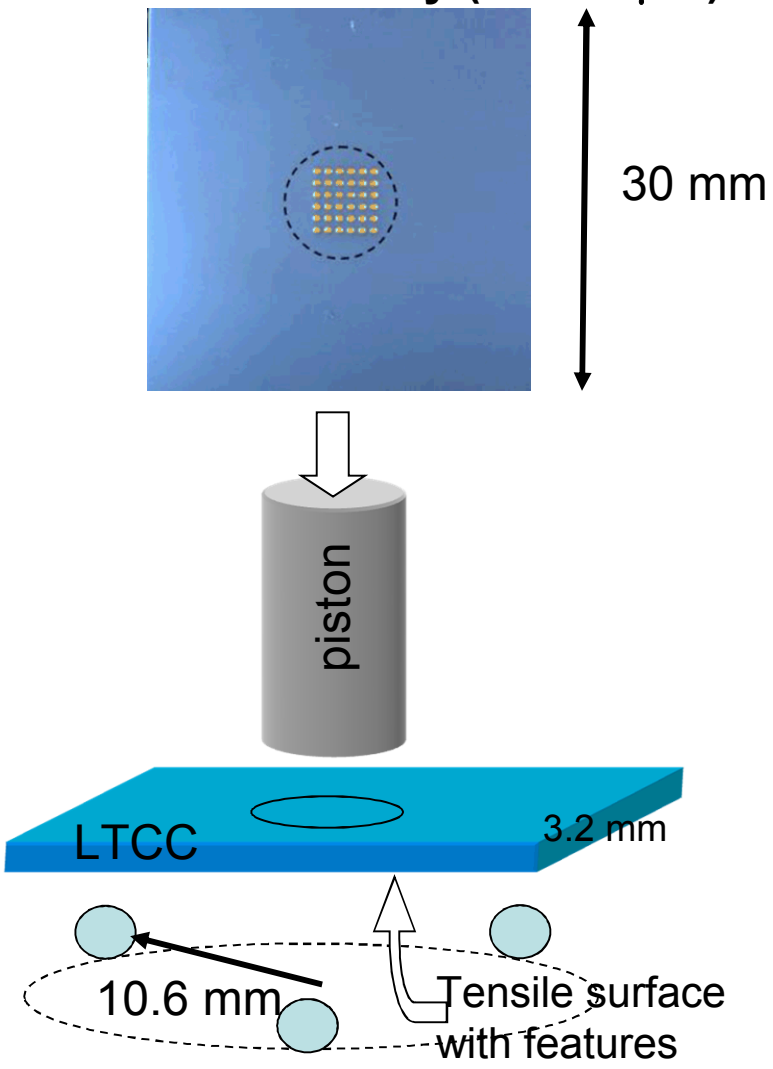
  Experimental Work
    - Mechanical Testing for Reliability
    - Test Vehicles and Approach

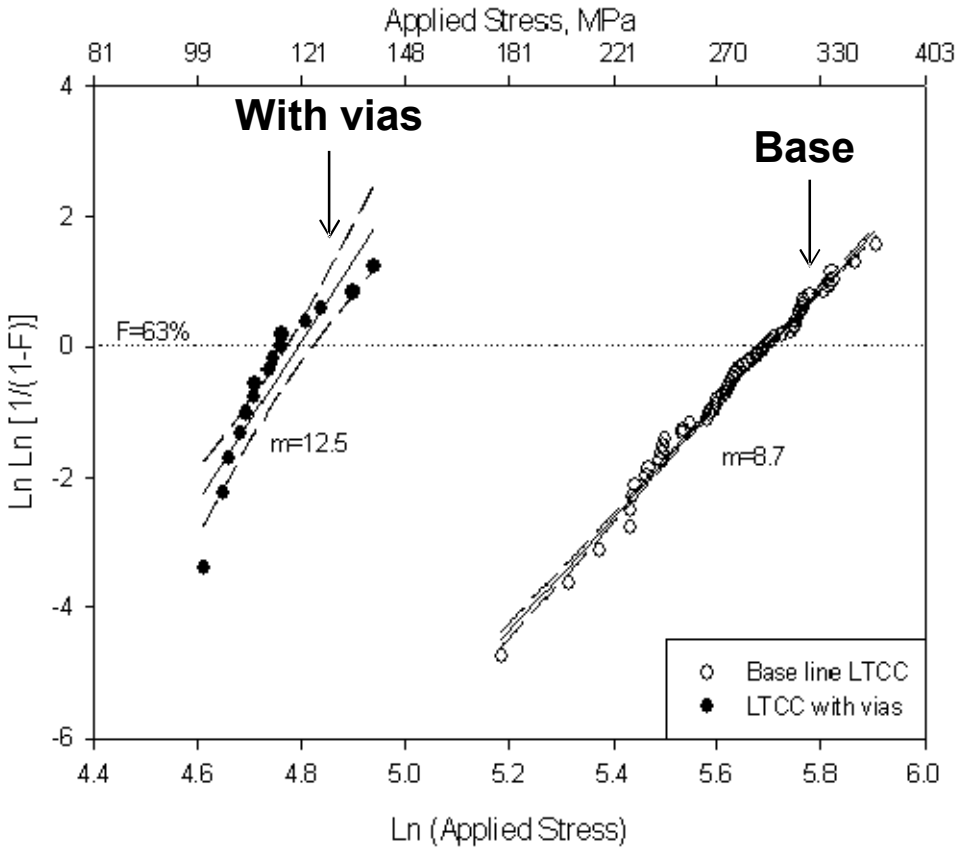
  Results
    - Iterative Materials Processing and Testing
      - Phase I, II, and III
    - Strength, Stresses and Failure Modes

  Conclusions

Test Samples and Results

Piston on RIng Strength Tests on a 6x6 via Array (R=190 μm)



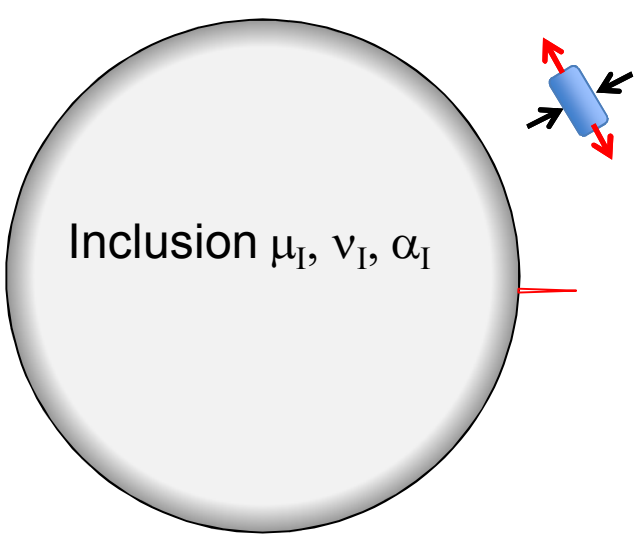


Presence of vias leads to a ~60% reduction in strength.

Why?

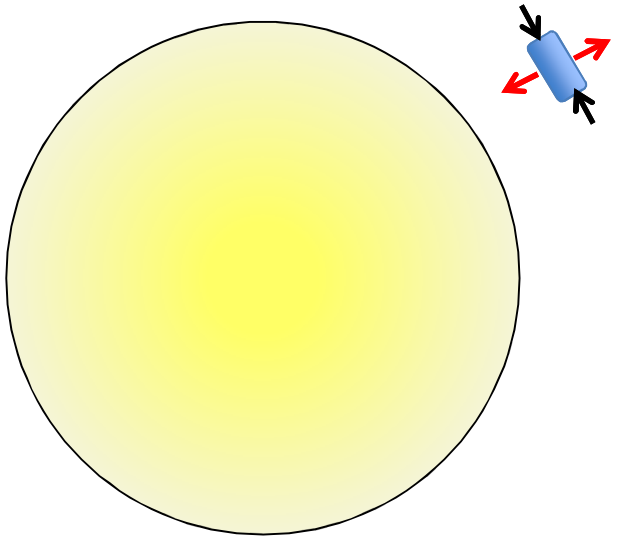
Stresses Around Inclusions

Matrix μ_M, ν_M, α_M



If $\alpha_M > \alpha_I$, circumferential tension in the matrix is generated

This can propagate a radial crack, and lead to lower strength

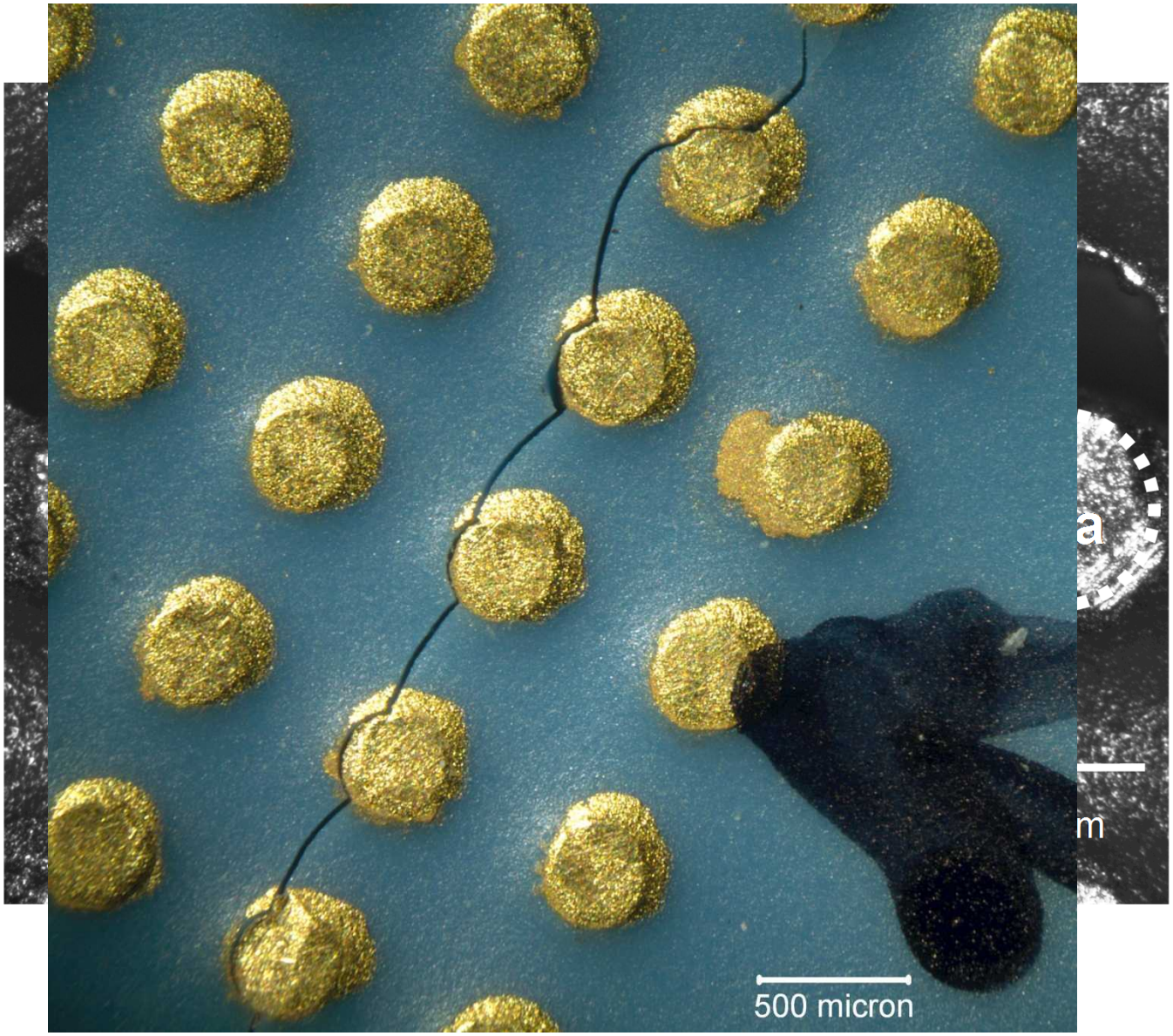


For Au-LTCC:
α_M (7 ppm) < α_I (16 ppm)

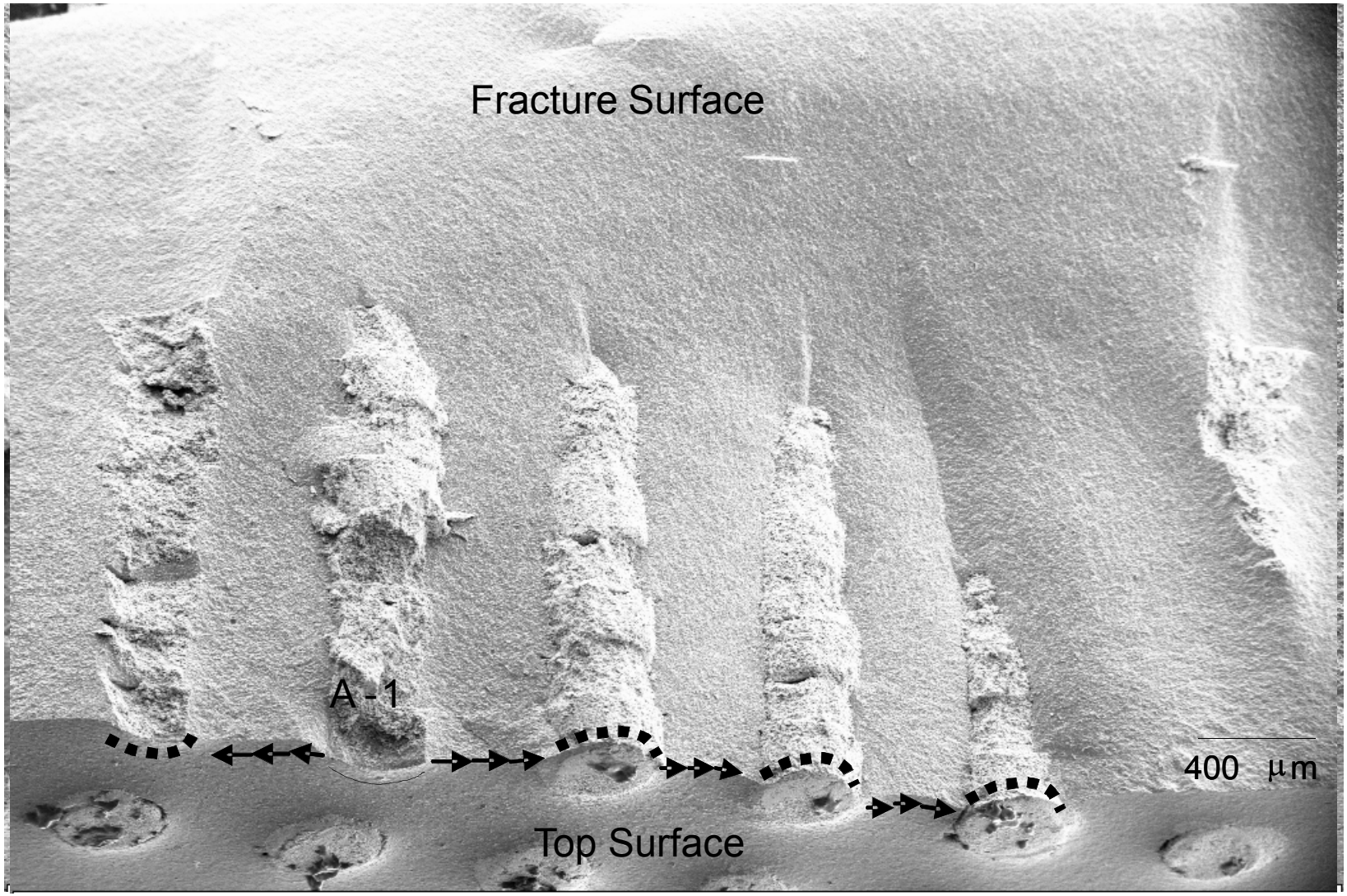
Radial tension

What is the mechanism for strength loss?

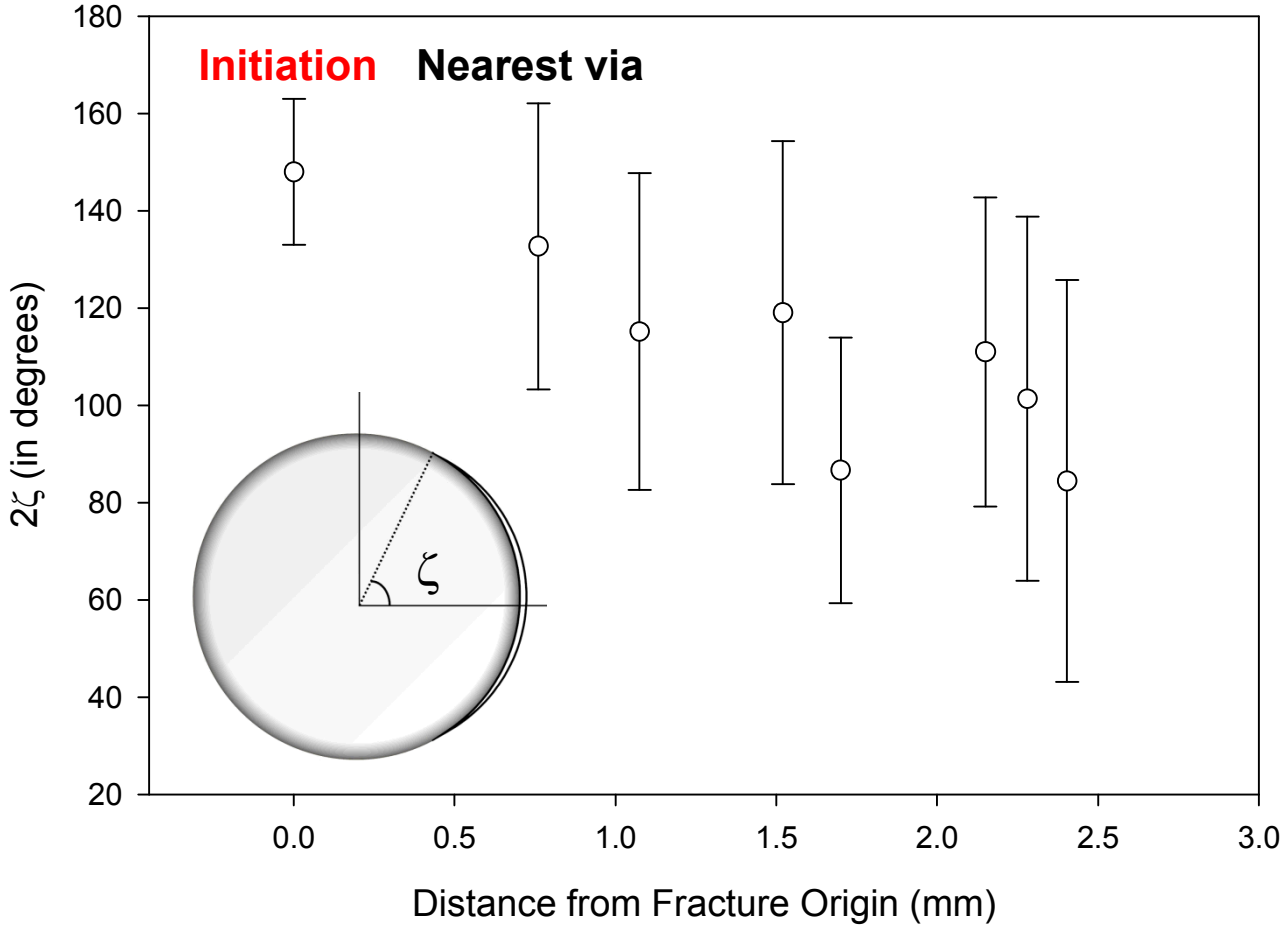
Failure Analysis



Fracture Surface Analysis

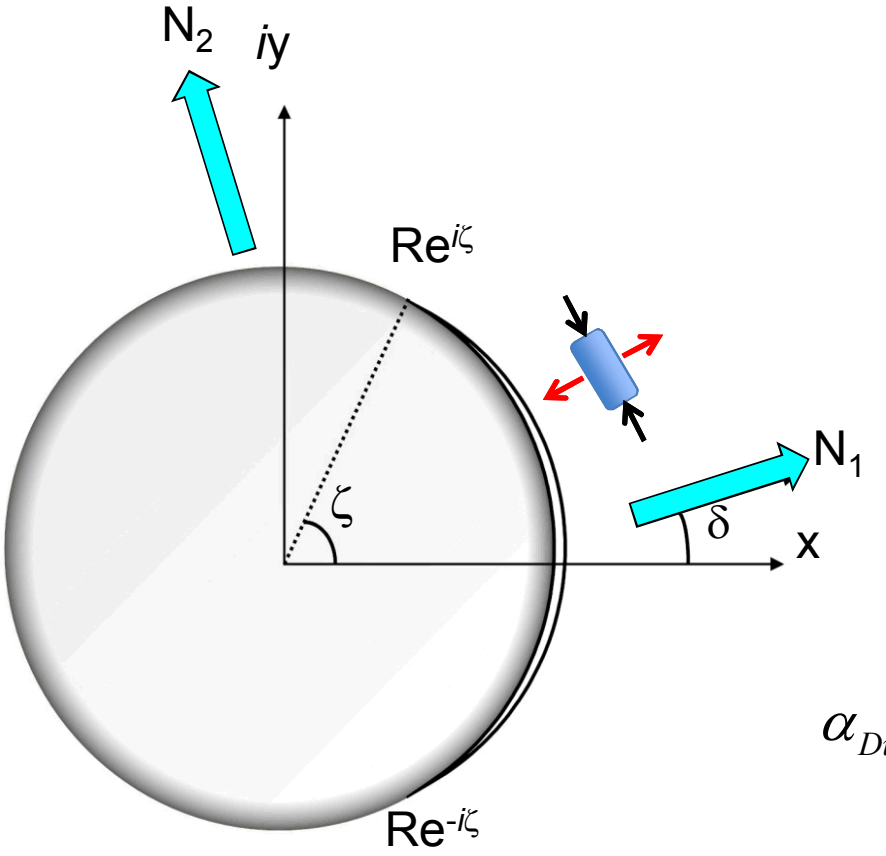


Distribution of Arc Crack Angles



The via causing fracture was identified, and the crack angle at which kinking occurred was measured. $2\zeta = 148 \pm 15^{o}$.

Interfacial Circumferential Crack Model



Driving Forces:

σ_{rr}= tensile

Biaxial loads, N_1 and N_2

Stress Intensity Factors expressed in terms of Dundur's parameters/oscillatory index

$$\alpha_{Dundur} = \frac{\mu_I\left(\kappa_M+1\right)-\mu_M\left(\kappa_I+1\right)}{\mu_I\left(\kappa_M+1\right)+\mu_M\left(\kappa_I+1\right)} = \frac{E_I-E_M}{E_I+E_M}$$

$$\beta = \frac{\mu_I\left(\kappa_M-1\right)-\mu_M\left(\kappa_I-1\right)}{\mu_I\left(\kappa_M+1\right)+\mu_M\left(\kappa_I+1\right)}$$

$$\gamma = \frac{1}{2\pi}\ln\frac{1-\beta}{1+\beta}$$

Material, #	E (GPa)	ν	μ (GPa)	α (ppm/°C)
LTCC, M	116	0.24	47	7
Gold-via fill, I	78	0.44	27	15

Calculated Values (Plane-Stress)

α_{Dundur}	β	γ	σ_{th} (MPa)
-0.1958	-0.01464	0.0046	156

Stress Intensity Factors

K due to Biaxial Loading

$$\kappa_L = \left(\overline{b_1} - \overline{b_2} e^{i\zeta}\right)\sqrt{\pi R \sin\zeta}\,(1-2i\gamma)\,e^{-\gamma\zeta}\,e^{i\left(\frac{\zeta}{2}-\gamma\ln(2R\sin\zeta)\right)}$$

$$b_1 = \frac{(1+\alpha)(N_1+N_2)-(1-\alpha^2)(N_1-N_2)(0.25+\gamma^2)\sin^2\zeta\cos 2\delta}{(3+\alpha)(1-\beta)-(1-\alpha)(1+\beta)e^{-2\gamma\zeta}(\cos\zeta+2\gamma\sin\zeta)} +$$

$$i\frac{(1+\alpha)(N_1-N_2)(0.25+\gamma^2)\sin^2\zeta\sin 2\delta}{(1-\beta)+(1+\beta)e^{-2\gamma\zeta}(\cos\zeta+2\gamma\sin\zeta)}$$

$$b_2 = -\frac{1}{2}\frac{(1+\alpha)}{(1+\beta)}(N_1-N_2)e^{2\gamma\zeta}e^{2i\delta}$$

K due to thermal expansion mismatch

$$\kappa_{\text{th}} = F_0\sigma_{th}\sqrt{\pi R\sin\zeta}\,(1-\alpha)(1-2i\gamma)\,e^{-\gamma\zeta}\,e^{i\left(\frac{\zeta}{2}-\gamma\ln(2R\sin\zeta)\right)}$$

$$F_0 = f(\alpha,\beta,\gamma) = \frac{2}{(3+\alpha)(1-\beta)-(1-\alpha)(1+\beta)e^{-2\gamma\zeta}(\cos\zeta+2\gamma\sin\zeta)}$$

$$\sigma_{\text{th}} = -\frac{4\mu_2}{1+\kappa_2}\left(\alpha'_M-\alpha'_I\right)\Delta T \text{ where } \alpha'_j = \alpha_j \text{ [for plane stress]; or } = (1+\nu_j)\alpha_j \text{ [for plane strain]}$$

W. H. Müller and S. Schmauder, Int. J. Sol. Struc., 29 (1992)

Strain Energy Release Rate

$$\mathcal{K}_{Net} = \mathrm{K}_1 + i\mathrm{K}_2$$

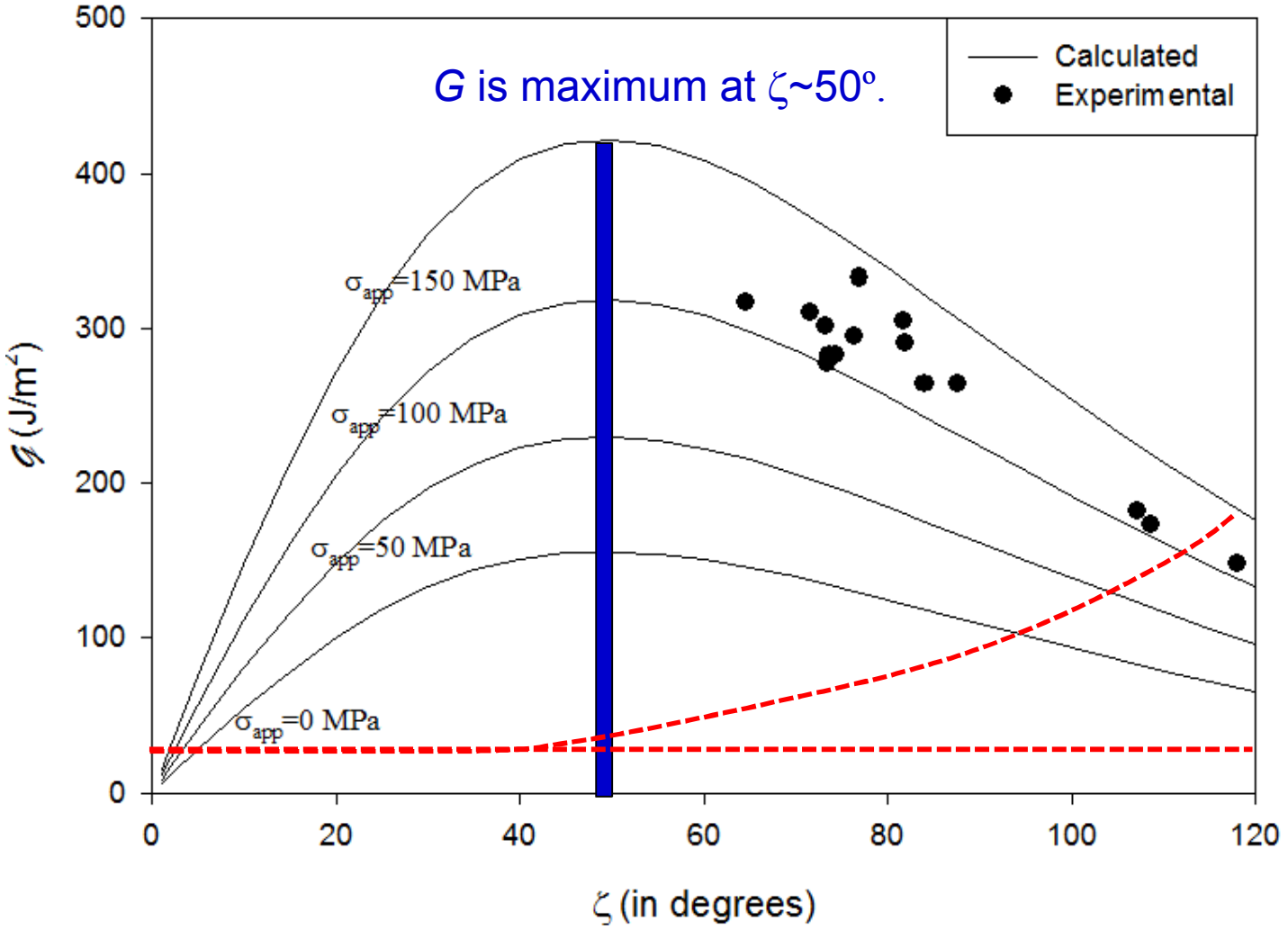
$$\mathrm{K}_1 = \mathrm{F}_1\sqrt{\pi R\sin\zeta}\left(\cos\psi + 2\gamma\sin\psi\right)e^{-\gamma\zeta}$$

$$\mathrm{K}_2 = \mathrm{F}_1\sqrt{\pi R\sin\zeta}\left(\sin\psi - 2\gamma\cos\psi\right)e^{-\gamma\zeta}$$

$$\mathrm{F}_1 = \mathrm{F}_0\left(\sigma_{app} + \sigma_{th} + \alpha\left[\sigma_{app} - \sigma_{th}\right]\right); \psi = \frac{\zeta}{2} + \gamma\ln\left(2R\sin\zeta\right)$$

$$\mathcal{G} = \frac{\mathcal{K}_{Net}\overline{\mathcal{K}_{Net}}}{4\cosh^2\pi\gamma}\left[\frac{1}{\mu_1\left(1+\nu_1\right)} + \frac{1}{\mu_2\left(1+\nu_2\right)}\right]$$

G as function of Crack Length (ζ)

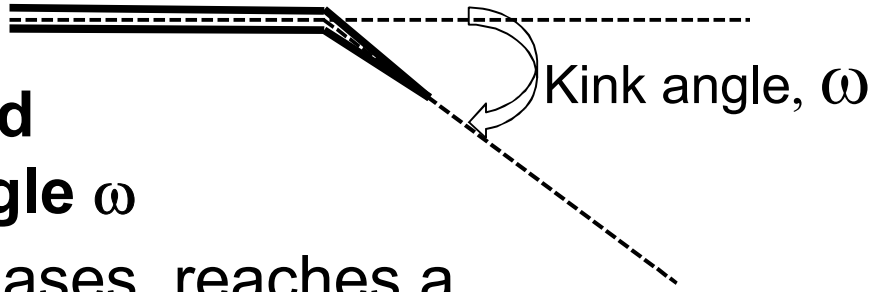


Crack kinking out of interface (into the matrix) occurs on the decreasing portion of G-curve.

Crack Kinking out of Interface

$$\frac{\mathcal{G}_{interface}}{\mathcal{G}_{\max,\omega}} > 1$$

(He et al. J. Am. Ceram Soc. 74, (1991))



- where $G_{max,\omega}$ is the maximized energy release rate at kink angle ω

- with increasing ζ, $G_{interface}$ increases, reaches a maximum, and then decreases.
- At some ζ, $G_{interface} = G_{max,\omega}$ and crack transitions to bulk

$$\frac{\mathcal{G}_{interface}}{\mathcal{G}_{\max,\omega}} = \frac{\Gamma_{interface}}{\Gamma_{substrate}}\bigg|_{Transition}$$

From He et. al, $\Gamma_i/\Gamma_s \sim 0.6$ (for $\alpha=0$), or ~0.8 ($\alpha=-0.5$)

For LTCC-AU system, $\alpha=-0.2$, Γ_s ~20 J/m^2.
Max. Γ_i ~12-16 J/m^2 – brittle interface

Conclusions

Failure Mechanism:

Crack initiation along the interface

Crack Propagation along the interface aided by the applied &

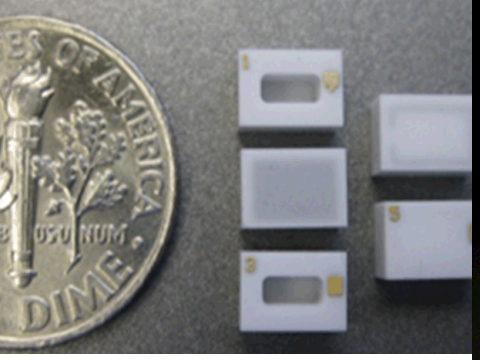
residual stress state

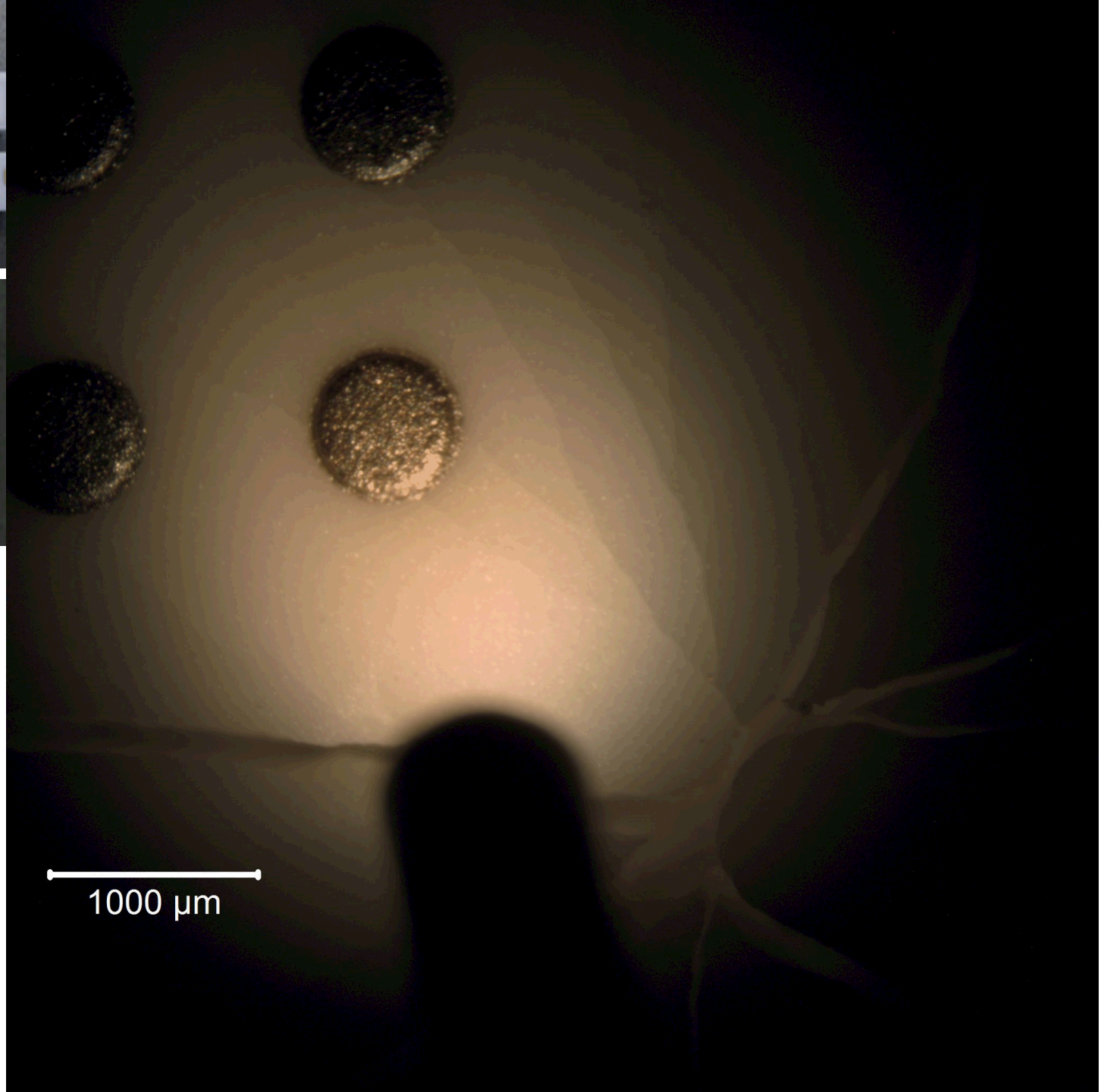
Final fracture after crack kinks into the matrix

Large crack size (~500 μm) at failure leads to lower strength

Crack initiation and growth along the interface (and not in the bulk) implies that it is weak, and brittle

Increasing Γ_i, and strength of interface will lead to higher strength


DIME


1000 µm

Presentation Outline

Introduction
- Implantable Medical Devices

Experimental Work
- Mechanical Testing for Reliability
- Test Vehicles and Approach

Results
- Iterative Materials Processing and Testing
  - Phase I, II, and III
- Strength, Stresses and Failure Modes

Conclusions

Implantable Medical Devices

Hydrocephalus
Sinus Diseases
Sinus Augmentation
Sleep Disordered Breathing
Cervical Degenerative Disc Disease
Thyroid Conditions

Parkinson's Disease
Essential Tremor
Dystonia**
Obsessive-Compulsive Disorder**

Atrial Fibrillation
Heart Failure
Congenital Heart Disease
Heart Rhythm Disorders
Angina*
Coronary Artery Disease
Heart Valve Disease

Scoliosis
Spinal Fracture
Lumbar Spinal Stenosis
Degenerative Disc Disease
Pelvic Trauma

Peripheral Vascular Disease*

Otologic Disorders
Meniere's Disease

Aortic Disease

Severe Spasticity associated with Multiple Sclerosis, Cerebral Palsy, Stroke and Spinal Cord and Brain Injuries

Chronic Pain

Nausea and Vomiting associated with Gastroparesis**

Diabetes

Overactive Bladder and Urinary Retention

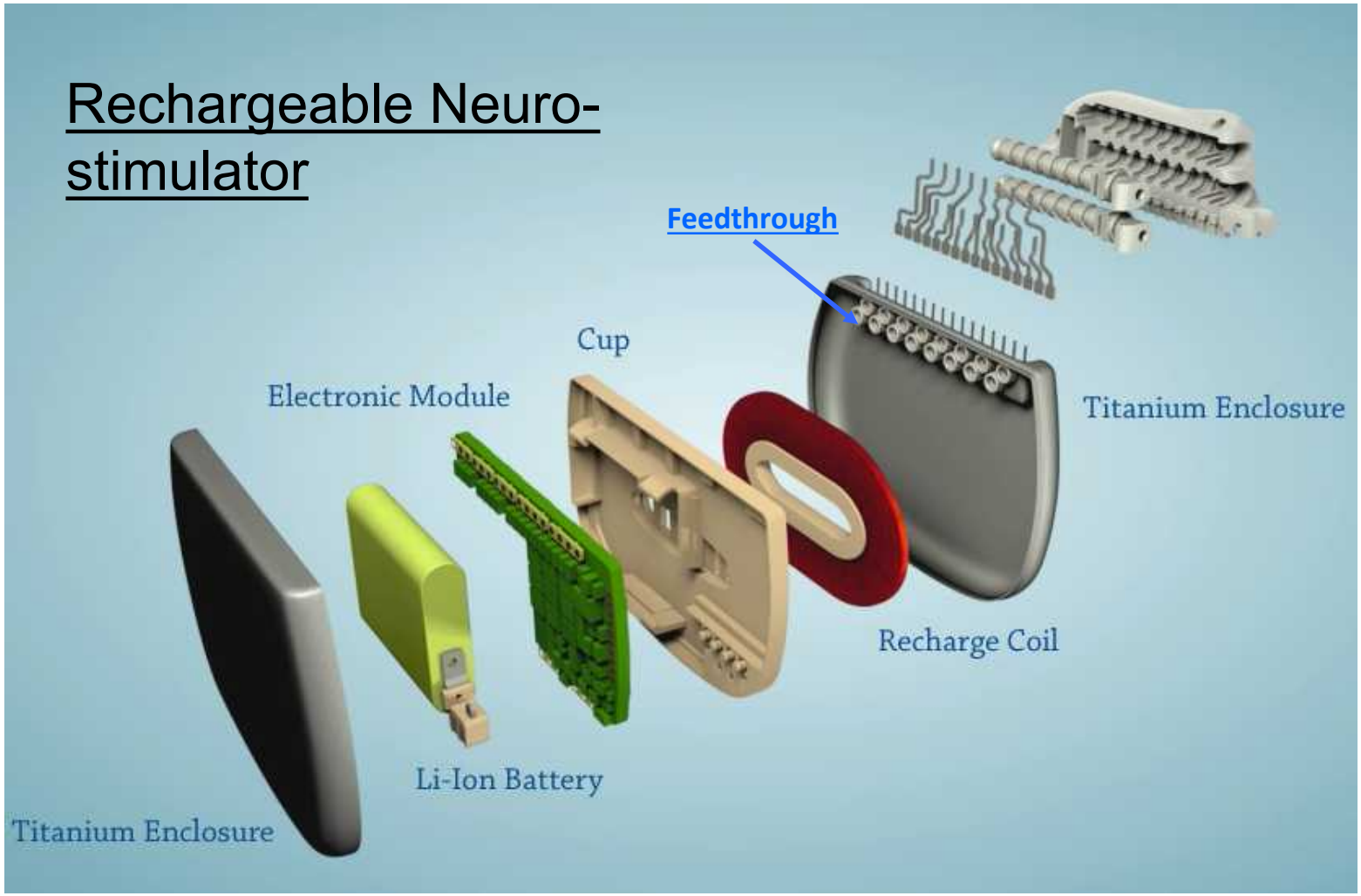
Fecal Incontinence

Tibial Fractures

* Not approved for commercial distribution in the United States
** Humanitarian Device in the United States – the effectiveness for this use has not been demonstrated

~70 B /per annum

Implantable Medical Devices

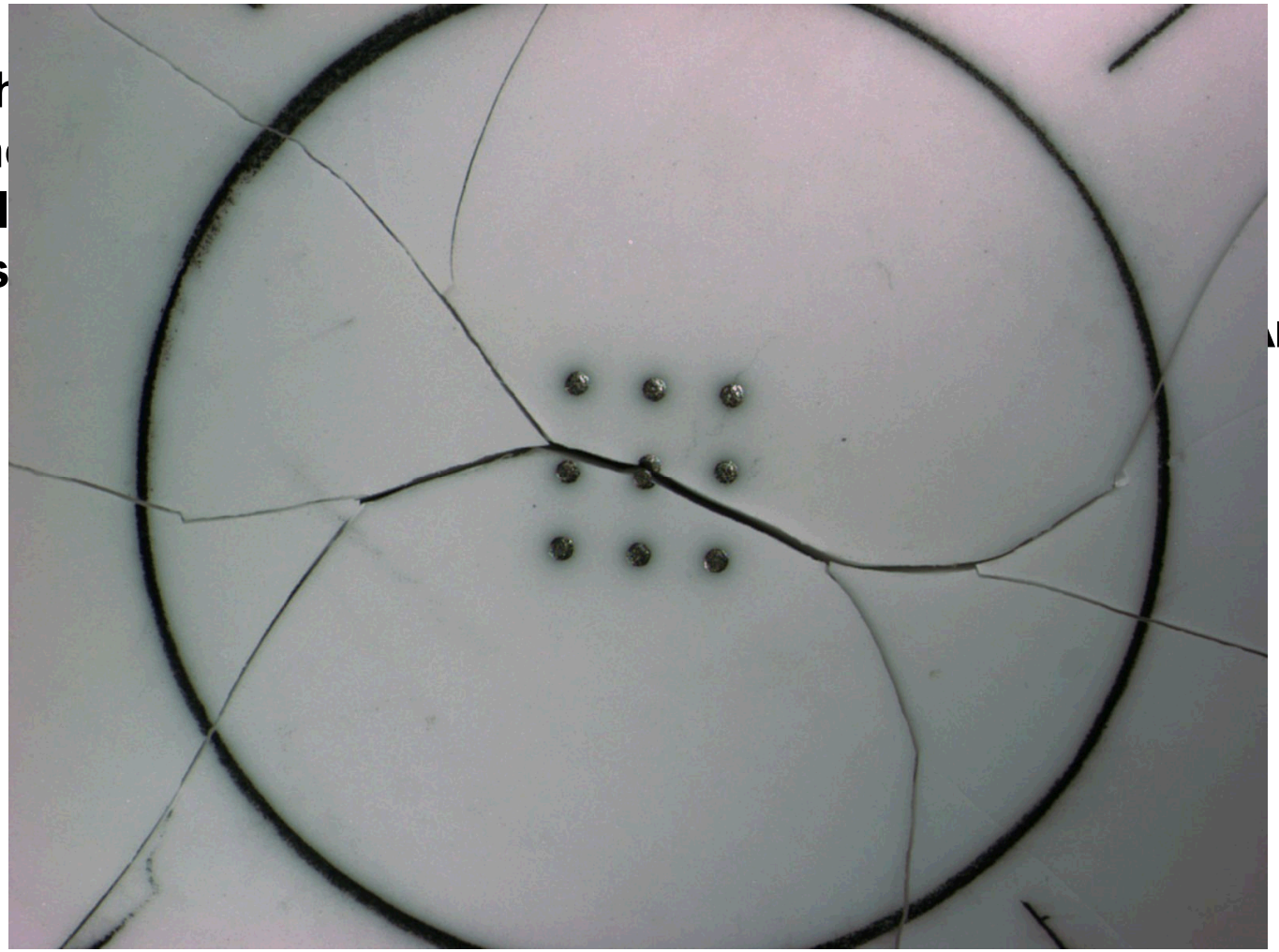


Hermetic Feedthroughs for Medical Devices

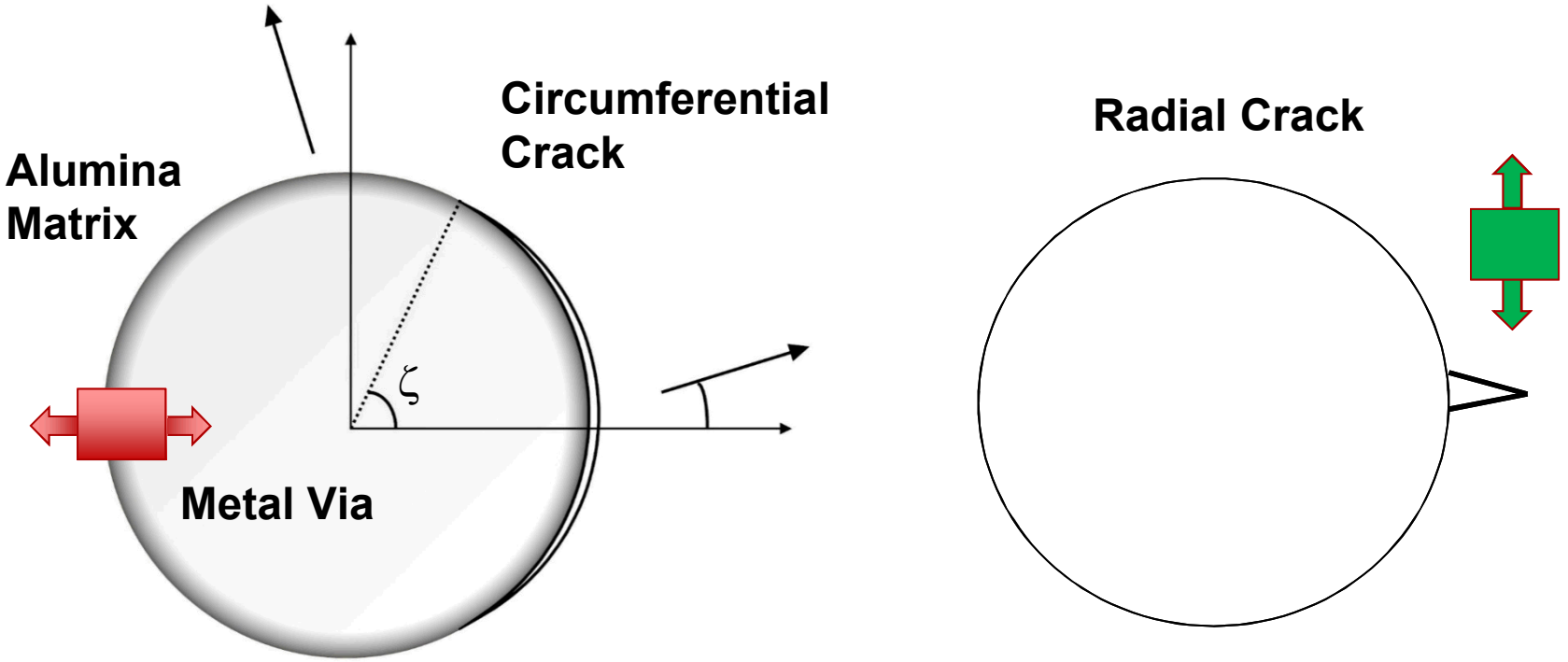
Alumina - High Temperature Co-fired Ceramic (HTCC)

Physical and electrical characteristics for high-reliability applications:

- **Mech**
- **High**
- **Easil**
- **Pass**
  - **ntennas**



Stress State Around a Via Impacts Strength



Local residual stress – Due to thermal and elastic mismatches, modified by plasticity of via material

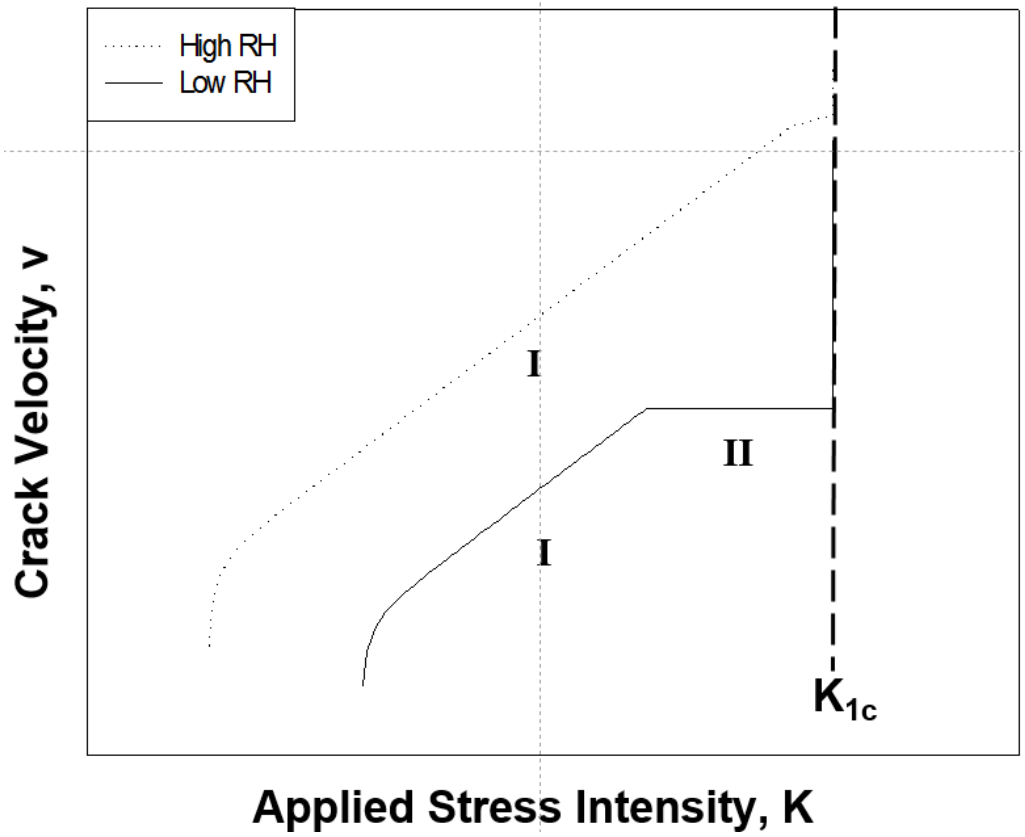
Higher thermal expansion via

~Similar expansion via + plasticity

Externally applied stresses – Thermal transients, & due to brazing/welding of material

Combination of these stresses can lead to Sub-Critical Crack Growth (SCG): can cause leaks, crack growth and failure

Sub-Critical Crack Growth (SCG)



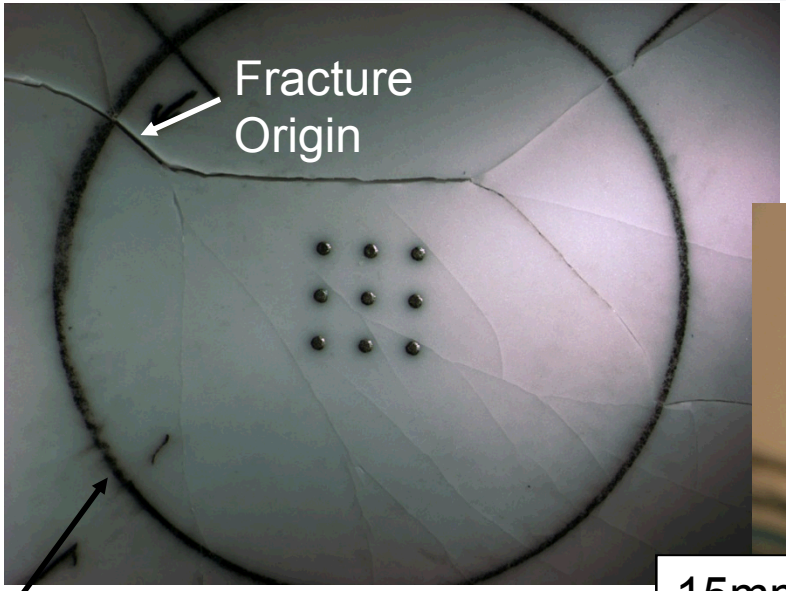
$$v = A\left(\frac{K_I}{K_{Ic}}\right)^n$$

SCG behavior was quantified by conducting strength tests as a function of loading rates *(ASTM C1368: Test method for SCG Paremeters)*

Materials with and without vias were strength tested in 20% RH, and in 0.9% saline (simulated body fluid)*

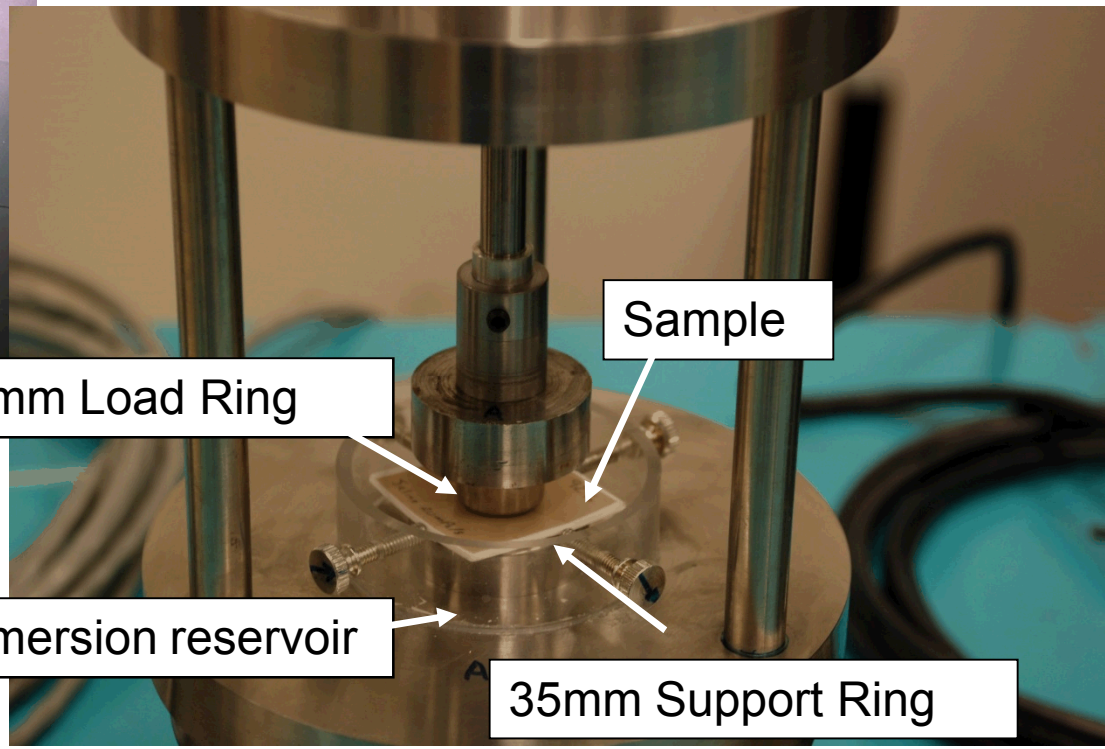
*https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3683025/

Reliability of Devices



Tensile region
(inside black circle)

(ASTM C1368 strength testing

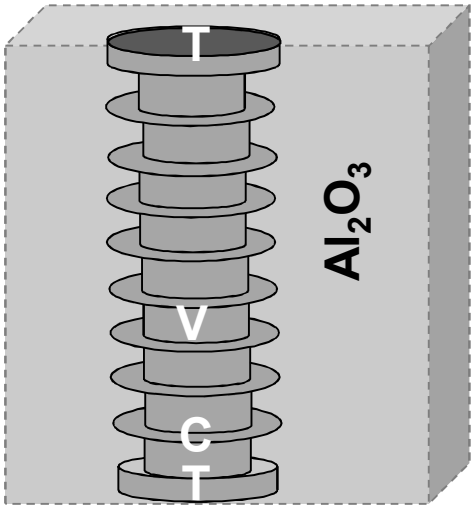


Sample Size: 40mm^2 x 2mm

Loading rings made of Tefzel material

Via Materials Optimization – Phase I

Phase I



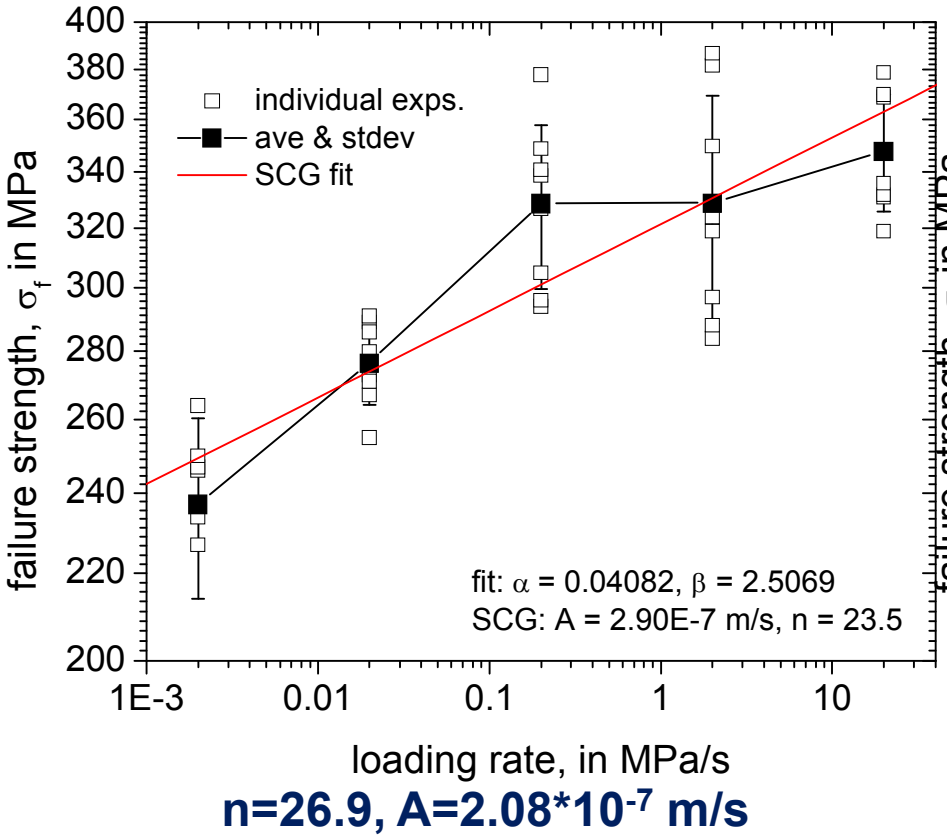
- Standard HTCC cofire process
- Commercial 92% Al_2O_3
- 0.2mm vias, 0.150mm layers
- Fired in Air atmosphere (vs N_2)

Top Pad (T)	100% Pt_f	50 Pt_f /50% Pt_c	75 Pt_f/25% Pt_c +5% Al_2O_3
Base Pad (B)	-	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Via (V)	Pt +5% (CaO, SiO_2, MgO, Al_2O_3)	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Cover Pads(C)	Pt +5% Al_2O_3	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3

Phase I – 20% RH Air

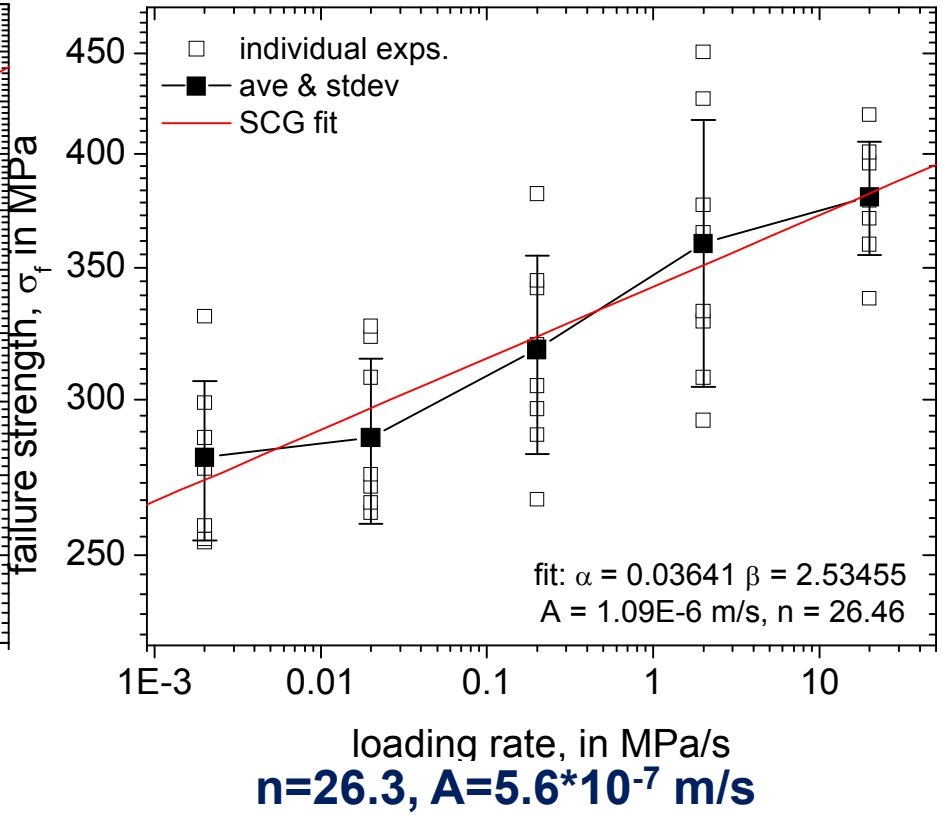
$$v = A\left(\frac{K_I}{K_{Ic}}\right)^n$$

No Vias- Base 92% Alumina



n=26.9, A=2.08*10^{-7} m/s

Alumina with Vias

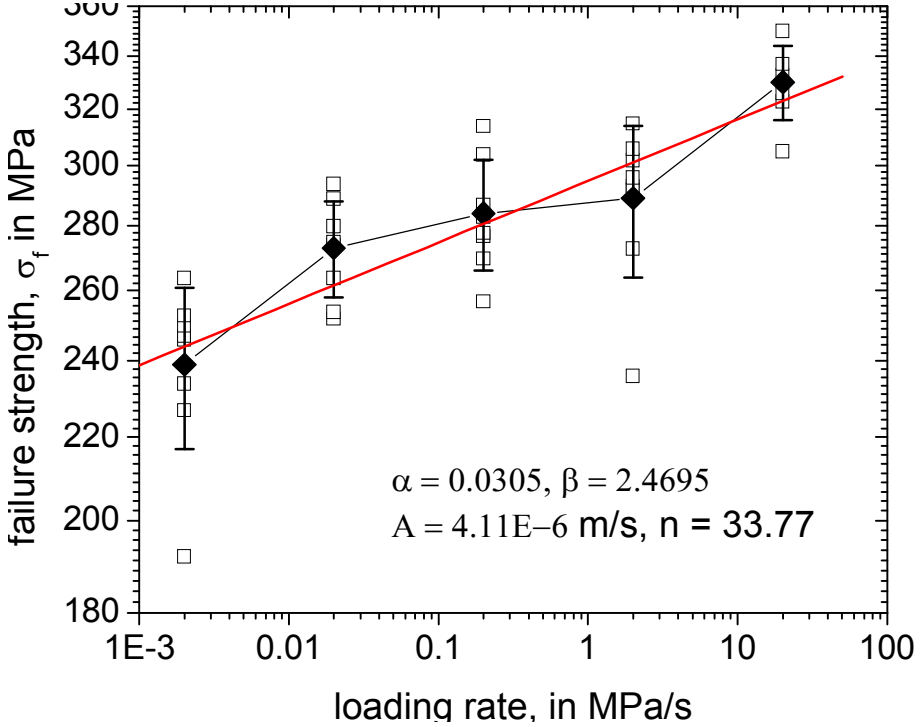


n=26.3, A=5.6*10^{-7} m/s

n values ~ those of alumina in literature
Strength Response in air is not affected by vias

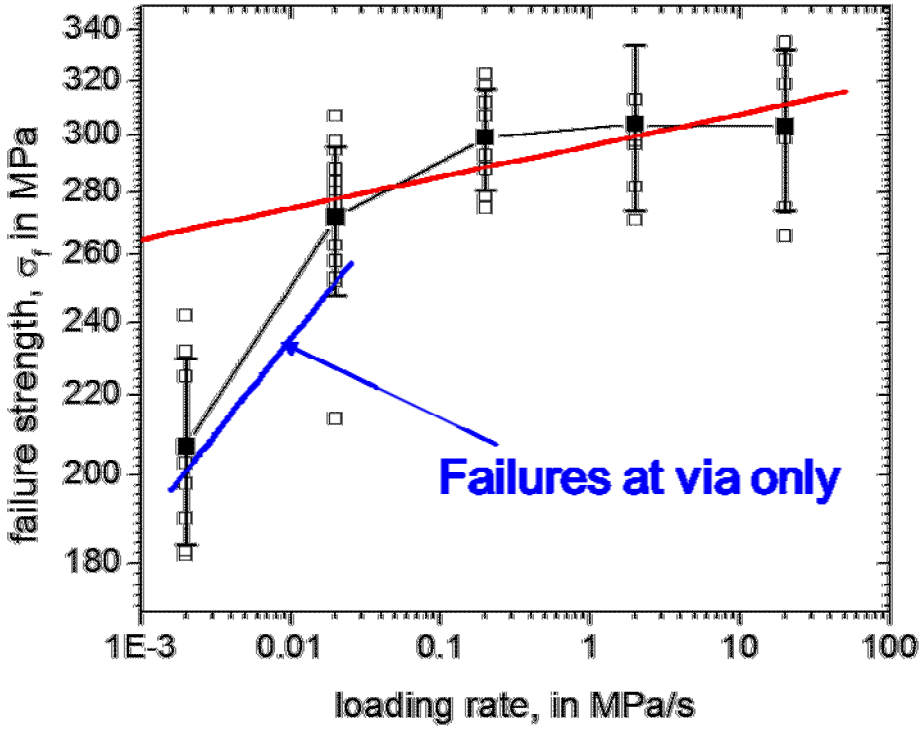
Phase I- Saline Immersion *(in vivo* simulation*)*

No Vias- Base 92% Alumina



n=36.7, A=4.54*10^{-6} m/s

Alumina with Vias



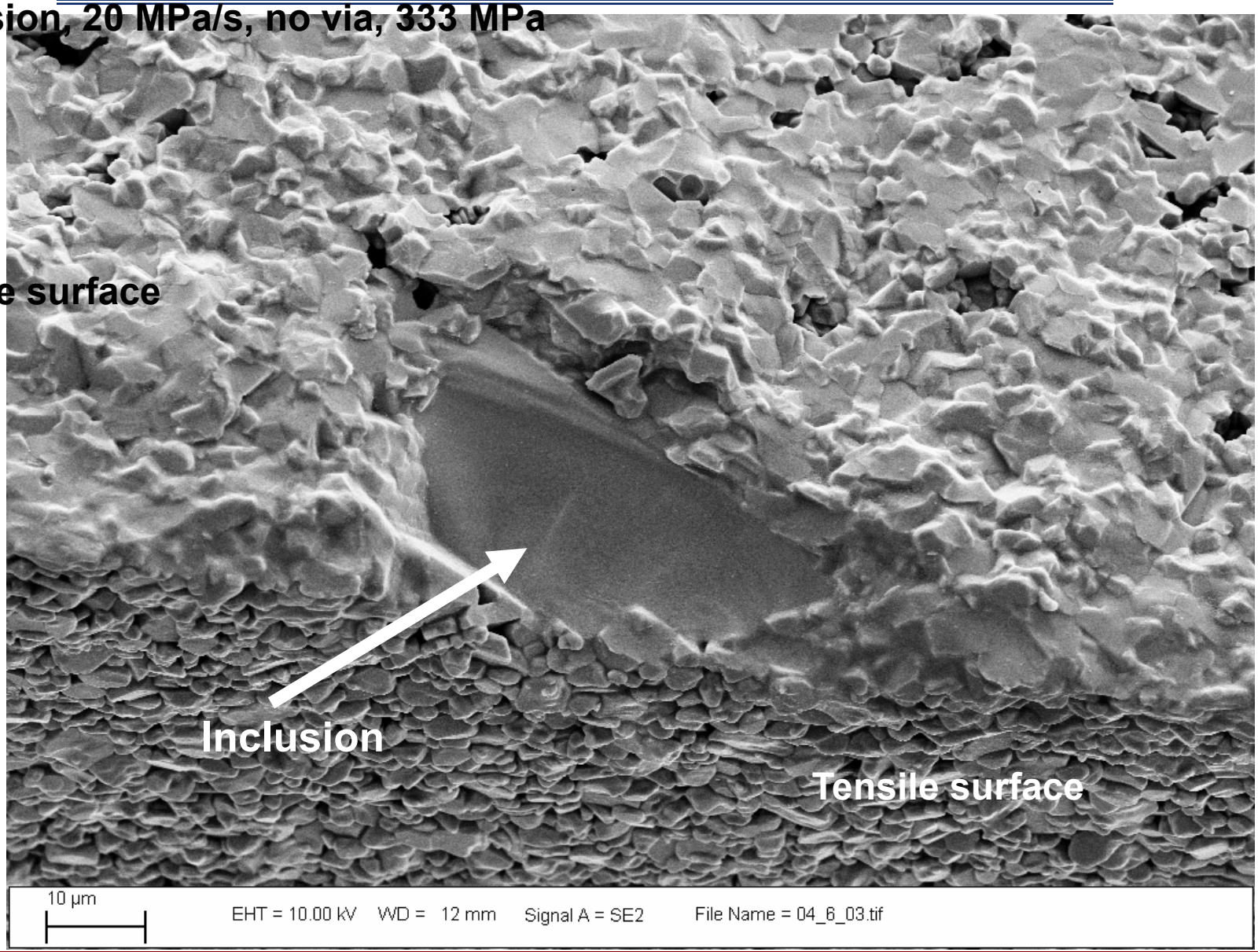
n=38.1,A=5.07*10^{-8} m/s
At Via n=9.2, A=1.0*10^{-8} m/s

Vulnerability: Slow rates and saline environment

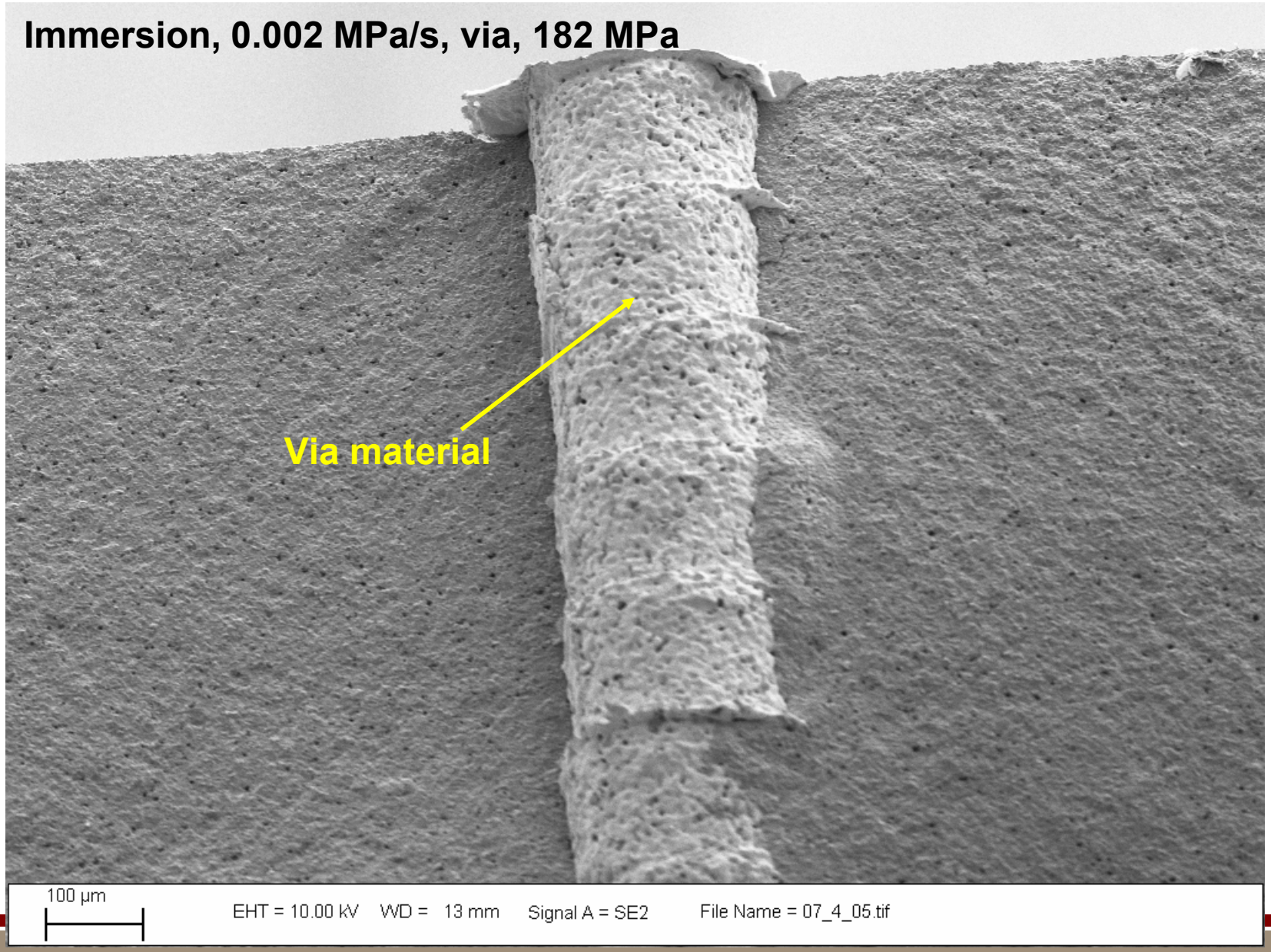
Fractography- Hard Inclusion

Immersion, 20 MPa/s, no via, 333 MPa

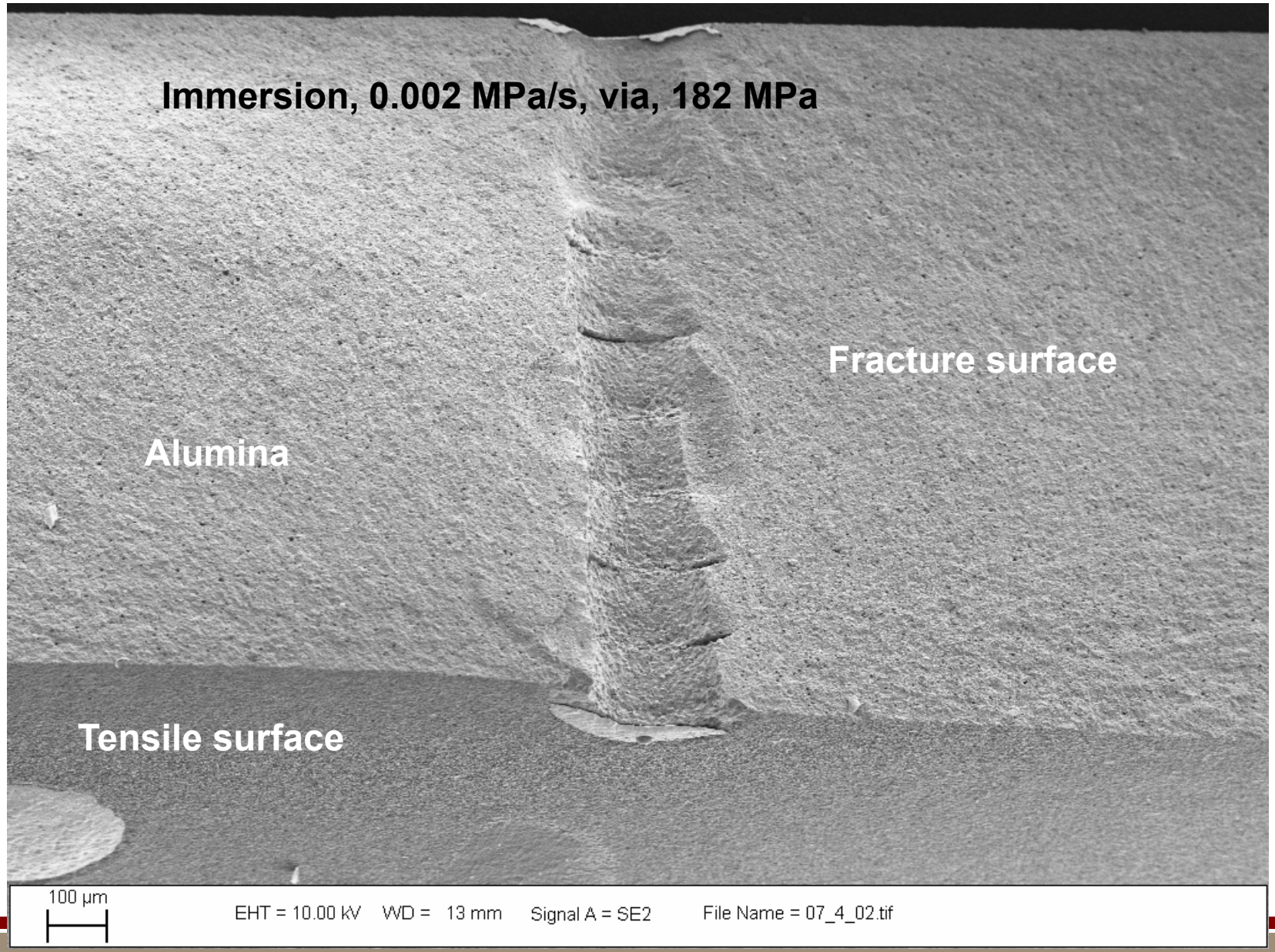
Fracture surface



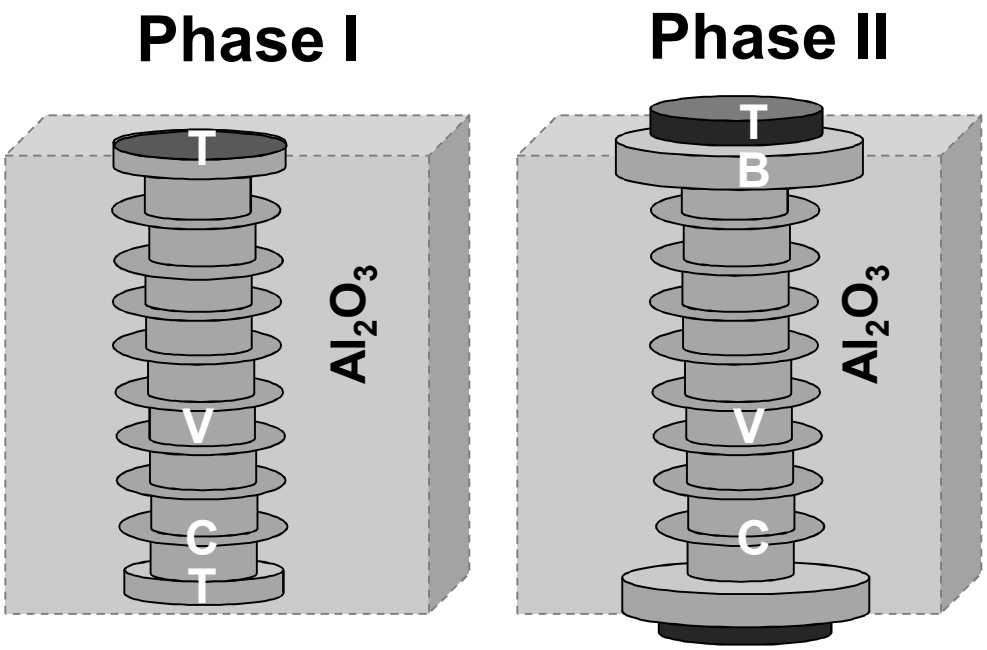
Fractography – Via Separation - A



Fractography – Via Separation - B



Via Materials Optimization – Phase II

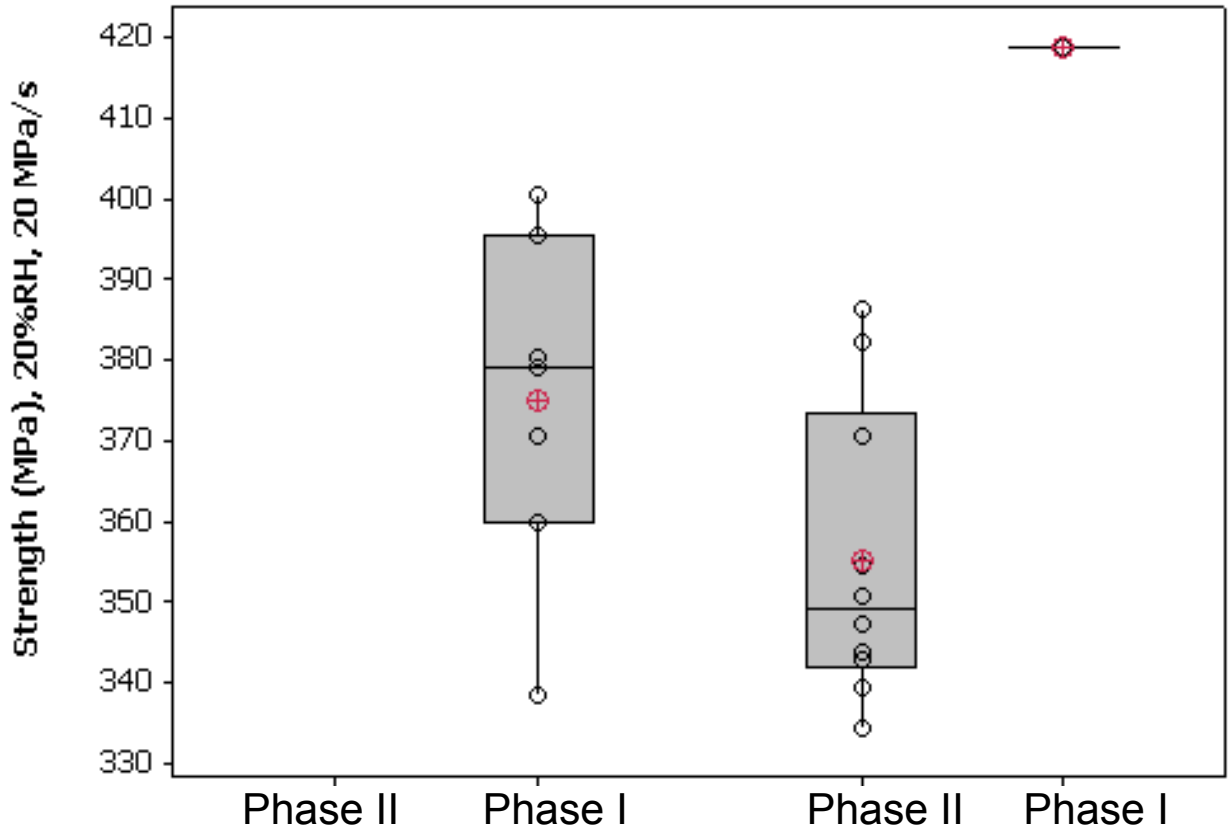


- 50/50 blend of fine/coarse Pt
- Removal of Ca/MgO/SiO_2
- Addition of base pad
- Process mods.

Top Pad (T)	100% Pt_f	50 Pt_f/50% Pt_c	75 Pt_f/25% Pt_c +5% Al_2O_3
Base Pad (B)	-	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Via (V)	Pt +5% (CaO, SiO_2, MgO, Al_2O_3)	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Cover Pads(C)	Pt +5% Al_2O_3	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3

Phase II – 20% RH, Alumina with Via

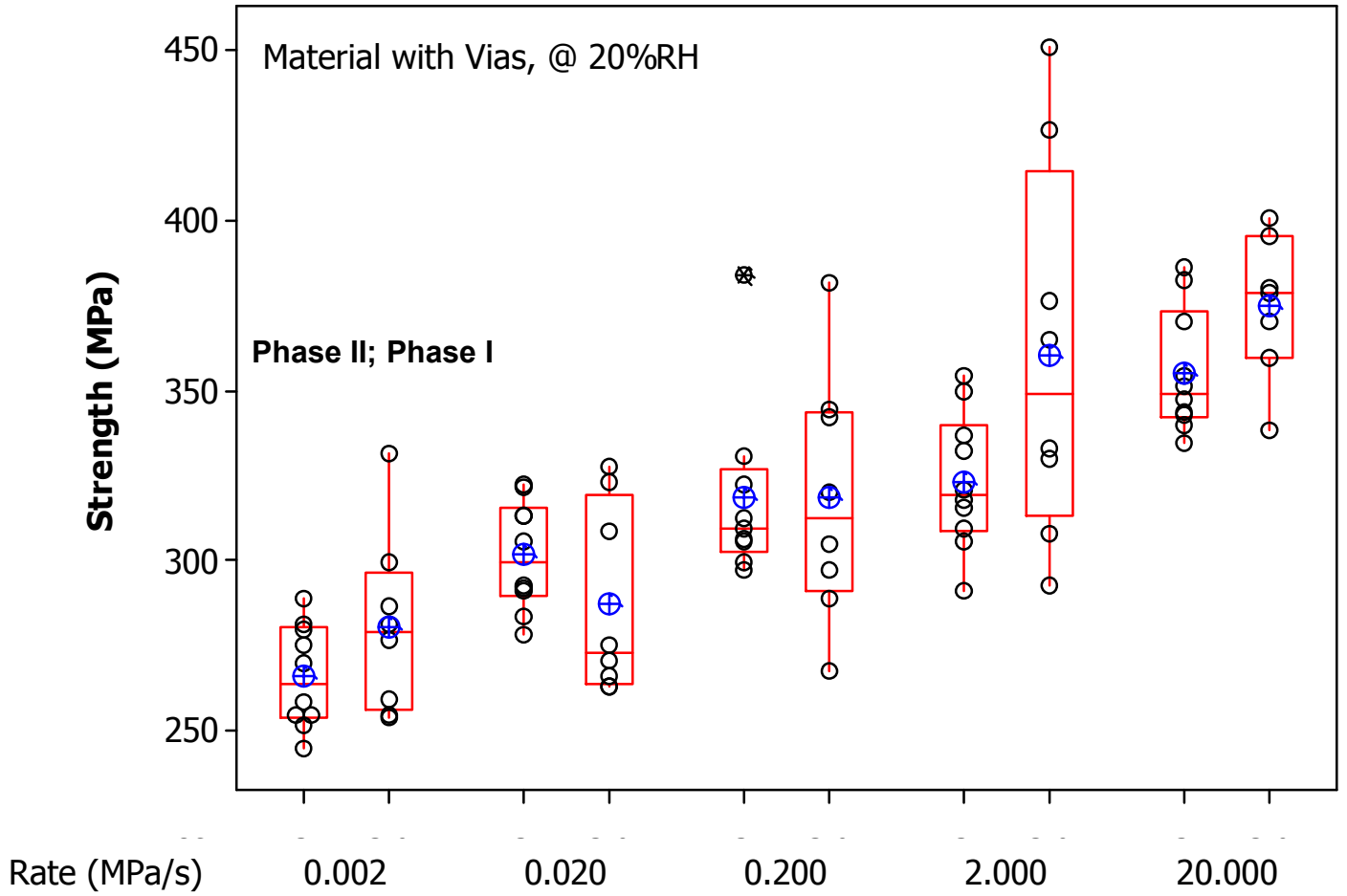
Fast testing rates (20 MPa/s), and 20% RH



The new batch of samples have lower mean strength

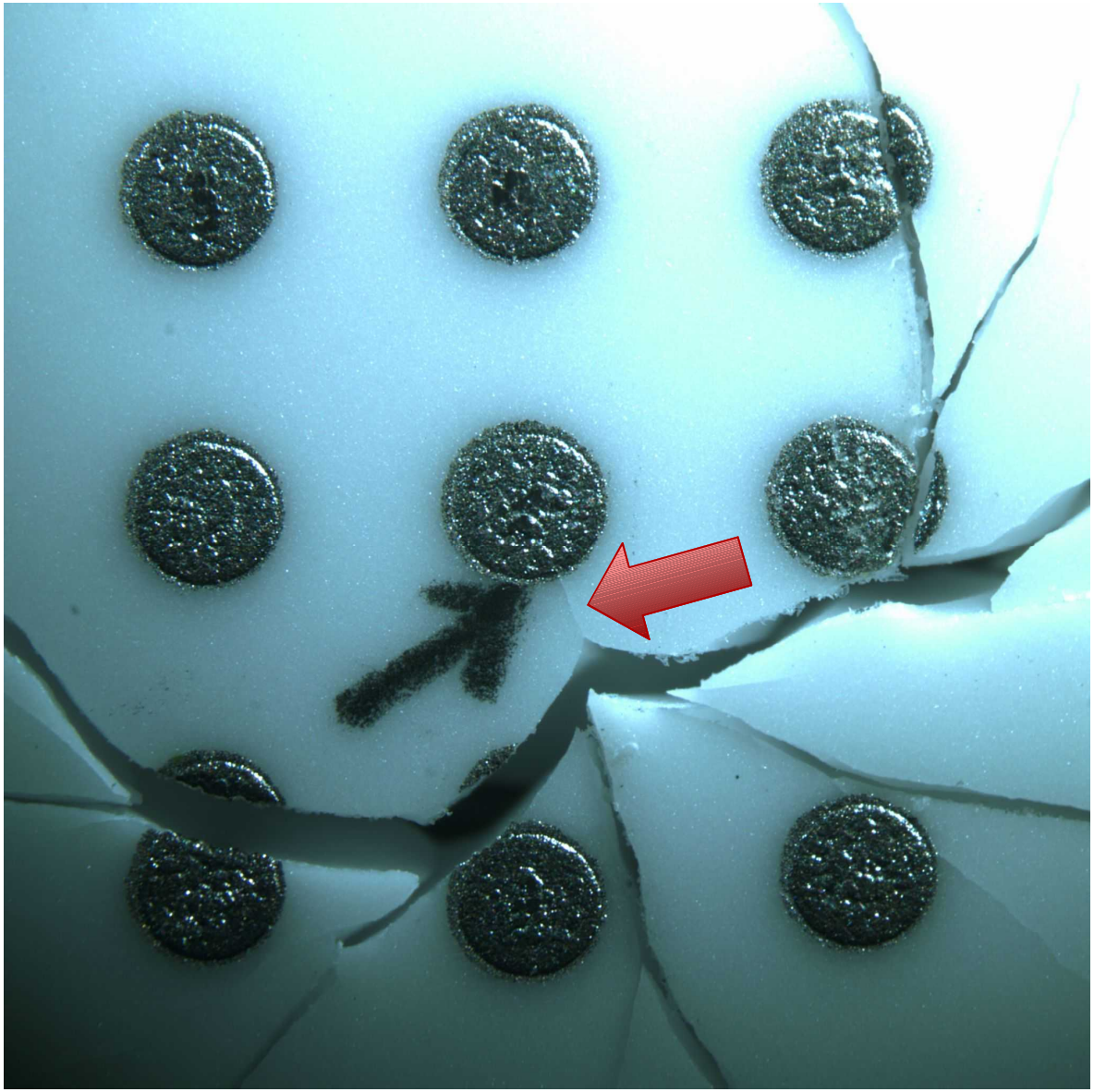
The failure origin has shifted: All failures are from the via

Phase II – Strength Lower

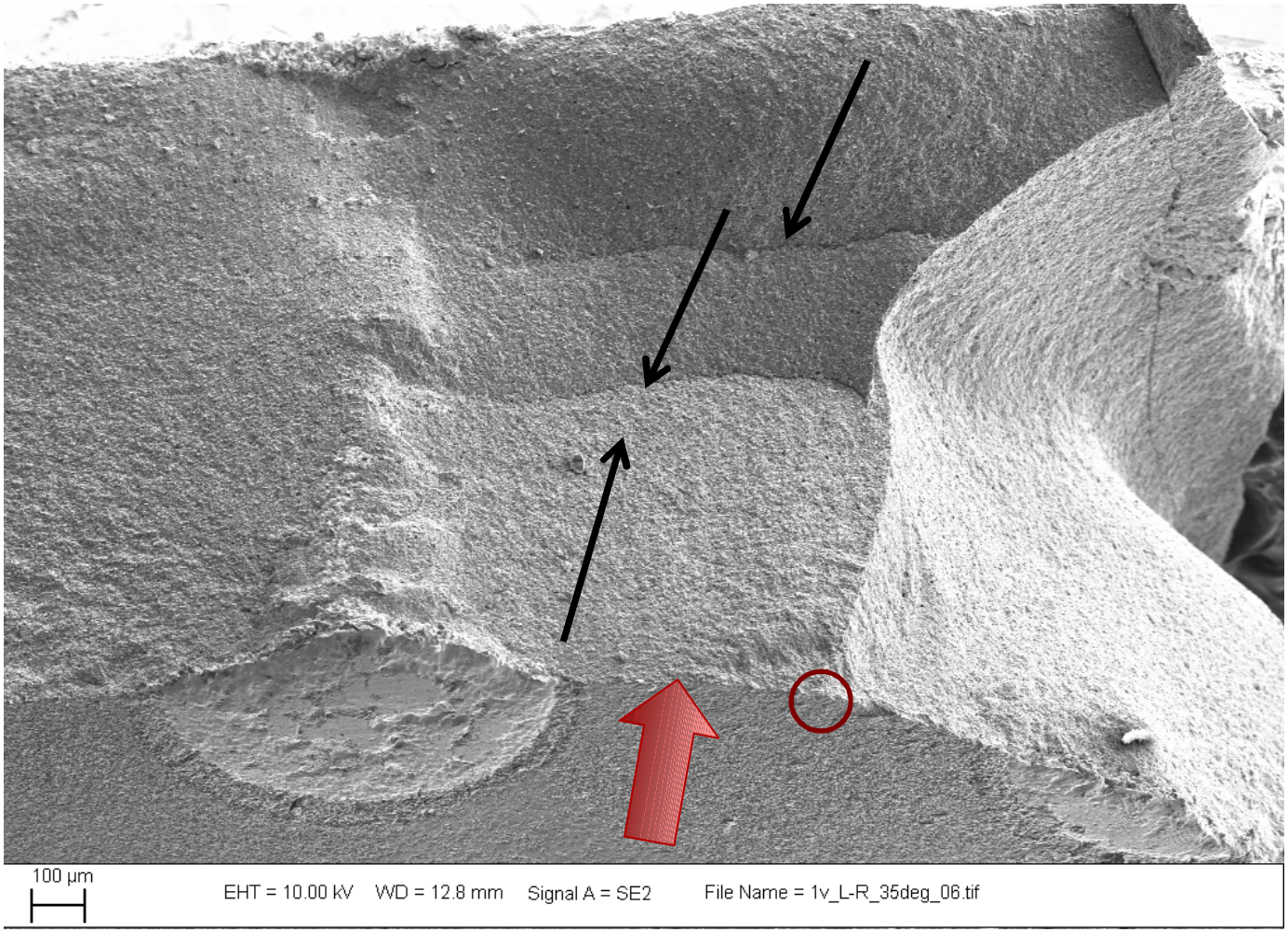


Phase II – Fractography (radial cracks)

Via 20 MPa/s
20% RH



Phase II – Fractography (radial cracks)

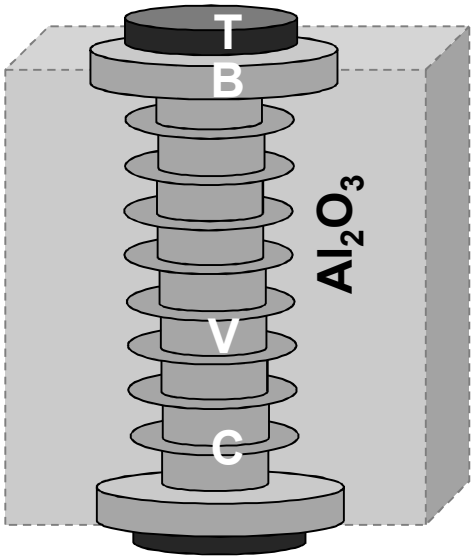


These samples must have a small circumferential tensile stress near the vias: Radial cracks and slightly lower strength Lamination ?

Via Materials Optimization – Phase III

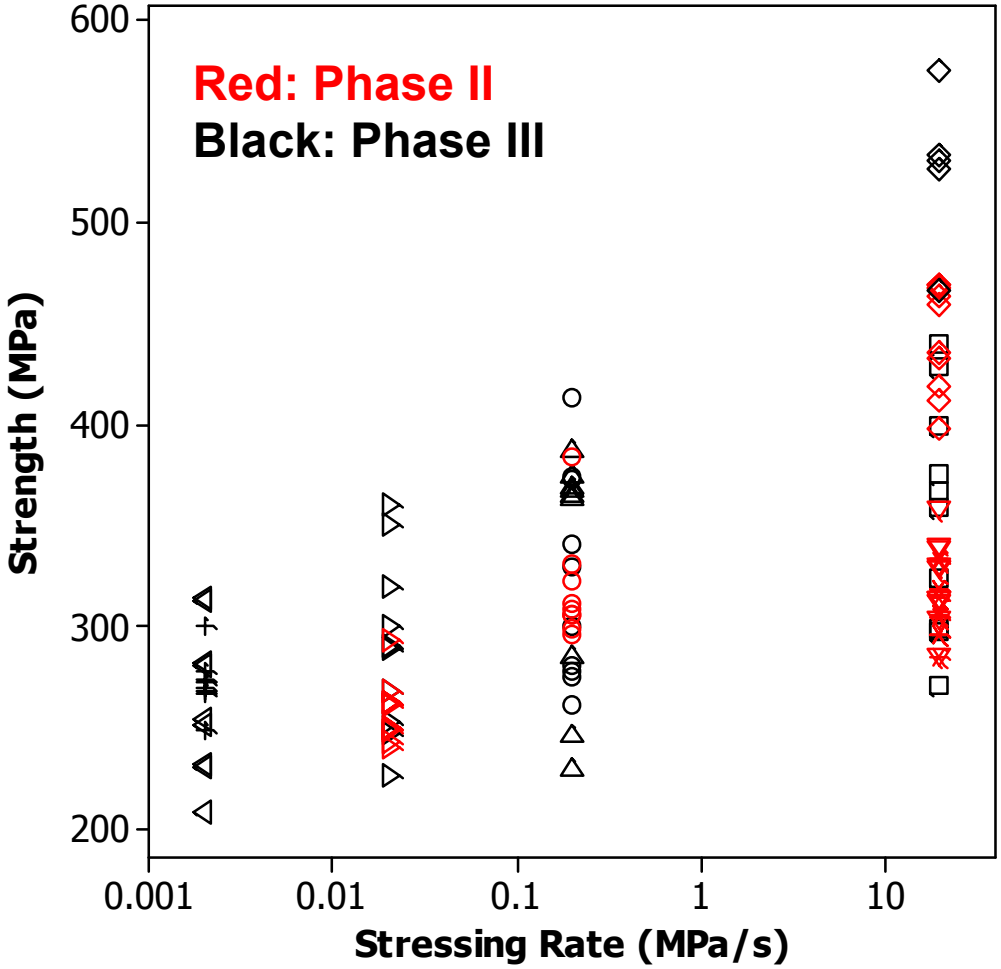
- Significant process modifications (lamination, printing, order)
- 75/25 blend of fine/coarse Pt
- Compatible metal paste vehicle

Phase III



Top Pad (T)	100% Pt_f	50 Pt_f /50% Pt_c	75 Pt_f/25% Pt_c +5% Al_2O_3
Base Pad (B)	-	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Via (V)	Pt +5% (CaO, SiO_2, MgO, Al_2O_3)	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3
Cover Pads(C)	Pt +5% Al_2O_3	50 Pt_f/50% Pt_c +5% Al_2O_3	75 Pt_f/25% Pt_c +5% Al_2O_3

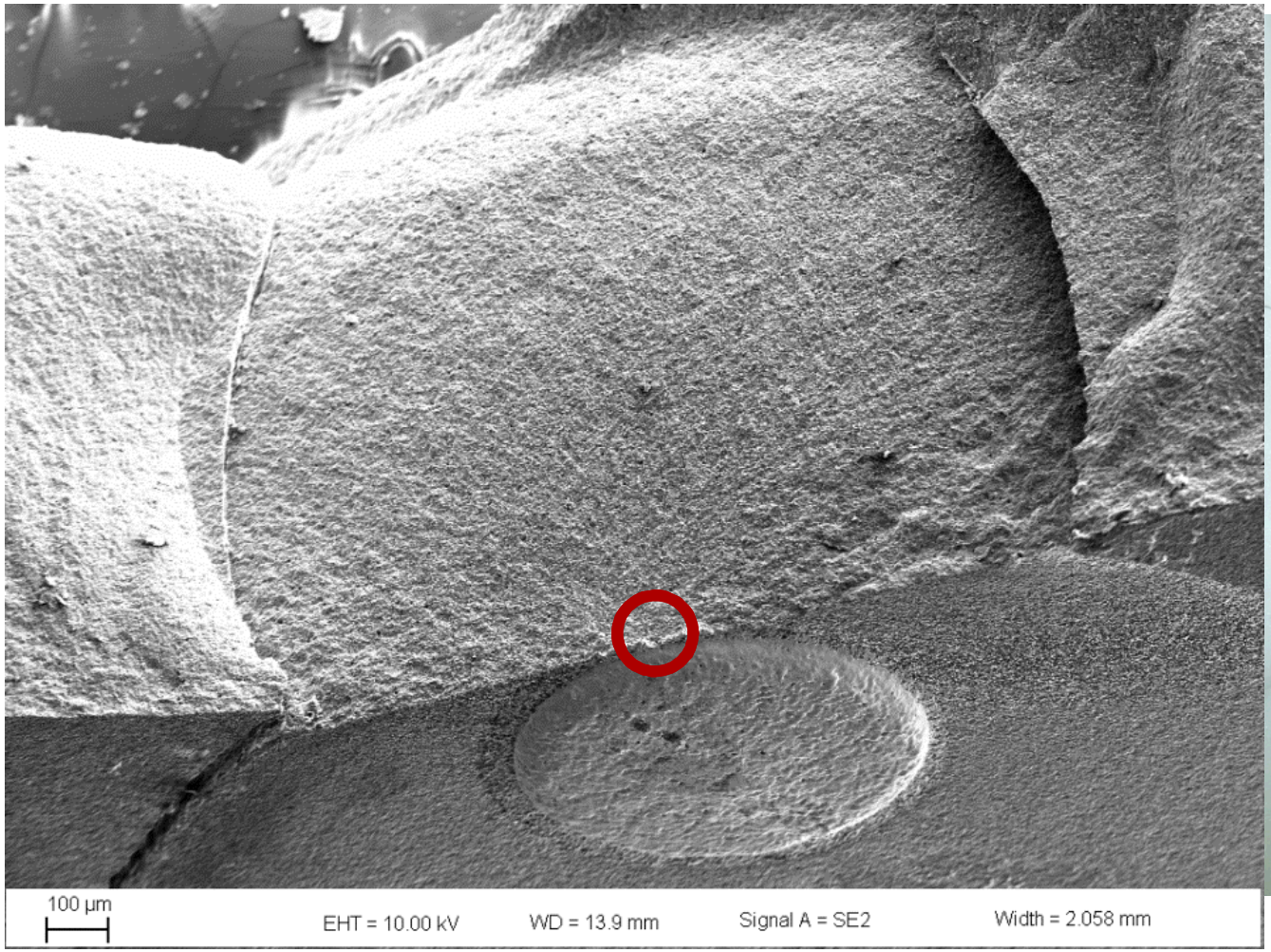
Phase III – Strength ~ base alumina

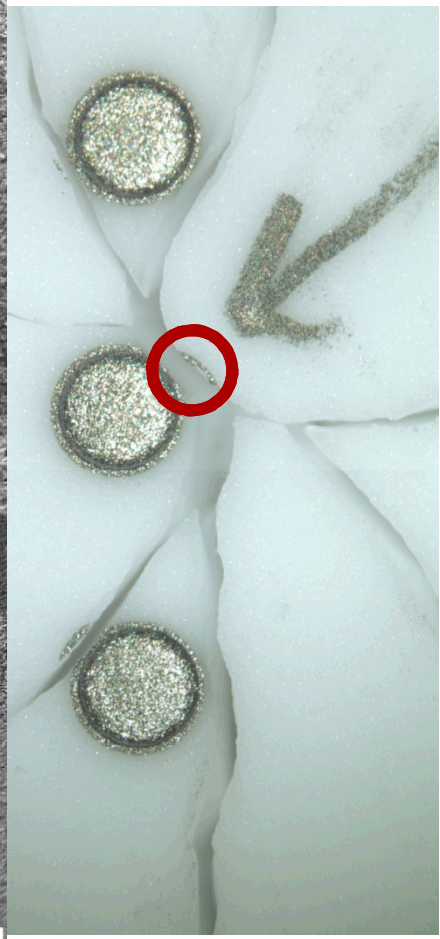


- Vias, 20%RH, 0.2 MPa/s
- Vias, Saline, 20 MPa/s
- Vias, Dry Air, 20 MPa/s
- Via, Water Imm., 0.2 MPa/s
- Via, Water Imm., 0.02 MPa/s
- Via, Water Imm., 0.002 MPa/s
- 20 MPa/s-Water-Set 2
- 0.02 MPa/s-Water Set 2
- Vias, 20%RH, 0.2 MPa/s-Set 2
- Vias, Saline, 20 MPa/s-Set 2
- Vias, Dry Air, 20 MPa/s-Set 2
- Via, 20%Rh, 0.002 MPa/s

Phase I, III ~ identical
Slightly better than Phase II

Phase III - Fractography





Conclusions

Strength:

Materials in Phase I, III had ~ identical strength; Phase II slightly lower

Notable exception of saline immersion, Phase I

- Vulnerability must be considered, tested for, and designed out prior to use

Stress State around the via (plasticity and thermal expansion considerations):

Phase I has a slight radial tension, and failure along interface in depth

- Removal of higher expansion glass phase led to redress of interfacial failure mode

Phase II has a slight circumferential tension, and radial cracking

Phase III has ~ 0 radial tensile stress

Lifetime:

Parameters extracted from these tests, and stresses use geometry, were used to calculate lifetimes > 20 years

Overall:

We can obtain material with vias that have similar lifetimes as base alumina material.

Failure Modes and Mechanics of Fracture in Co-Fired Engineering Ceramics

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Co-fired engineering ceramics can provide integration of multiple functions in one package, and lead to device miniaturization. Co-fired metals have thermal and elastic mismatches with the ceramic, producing local residual stresses which severely impact the fracture behavior and reliability. Observations and fracture analysis of a commercial low temp co-fired ceramic with gold vias show that while strength is reduced by as much as 60%, the susceptibility to sub-critical crack growth (SCG) is not lowered. A circumferential cracking mode around the vias has been observed in this system. Fracture mechanics solutions are derived to describe this failure mode, and correlated with fracture observations of crack kinking. In *in vivo* simulations of a commercial high temperature co-fired alumina ceramic-platinum via system, circumferential cracking is observed, but only at the slowest stressing rates. Processing changes made to these materials, which ultimately led to strength and SCG characteristics that were undistinguishable from the base materials, are described.

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Title: Failure analysis and sub-critical crack growth (SCG) characterization of Pt-Al_2O_3 high temperature co-fired (HTCC) ceramics

Abstract: Miniaturization and integration of multiple functions into one component is desired for device downsizing. HTCC alumina, with its high strength and bio-compatibility, provides an option for integration and higher reliability medical devices. A 92% alumina-platinum via HTCC material was characterized for failure modes and sub-critical crack growth, and modifications to processing were implemented to obtain a material with strength and SCG characteristics similar to bulk alumina. In phase I development, this material had strength equivalent to bulk alumina, except at low stressing rates in saline, body fluid-like environments, where a novel failure mode (circumferential cracking) was encountered. Processing changes implemented for Phase II materials led to failures emanating as radial cracks from the vias with slight loss of strength. Changes made to Phase III materials led to strength and SCG characteristics that were undistinguishable from the base materials. Fractographic evidence indicates that cracking originates tangentially to the via in Phase III material

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

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