The Role of Circumferential Cracking In Fracture Originating From Cylindrical Inclusions

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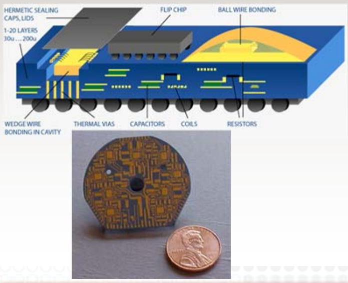
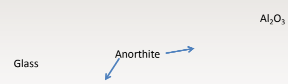
Materials Motivation: Low temp. co-fired ceramic (LTCC) is versatile glass-filled ceramic composite packaging material. Cracking problems are sometimes observed during production and use.

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

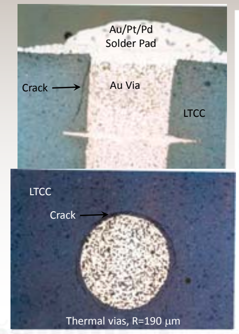
Schematic of Technology



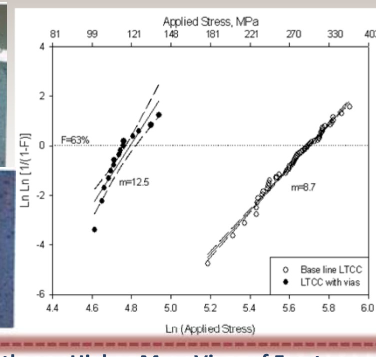
LTCC Microstructure



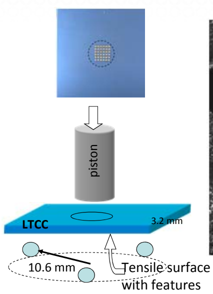
Cracks at/near Vias



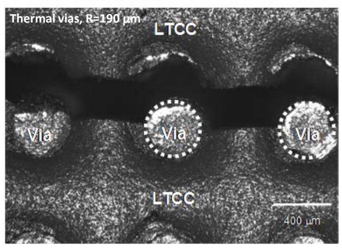
~60% Strength loss due to Vias



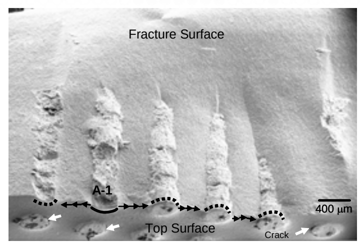
Test Structure



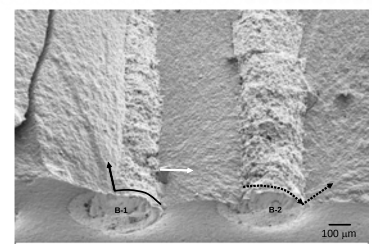
Fractured Structure: Top



Fracture Surface showing Crack Path

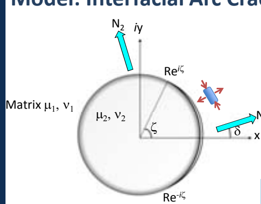


Higher Mag. View of Fracture



Crack initiates at the via-LTCC boundary at several vias. These cracks grow as arc cracks along the interface on ↑ stress. At some load, one of the arc cracks kinks out into the matrix, links up with other cracks, and causes failure.

Model: Interfacial Arc Crack



Driving Forces:

- σ_{rr}=tensile, as $\alpha_2>\alpha_1$
- Biaxial loads, N_1 and N_2
- $\sigma_{\theta\theta}$=compressive. In-plane stress for kinking analysis

Stress Intensity Factors

K due to thermal expansion mismatch

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

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

$$\sigma_{th} = -\frac{4\mu_2}{1+\kappa_2}(\Lambda'_1-\Lambda'_2)\Delta T \text{ where } \Lambda'_j=\Lambda_j \text{ [for plane stress]; or } =(1+\nu_j)\Lambda_j \text{ [for plane strain]}$$

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

K due to Biaxial Loading

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

$$b_1 = \frac{(1+\alpha)(N_1+N_2)-(1-\alpha^2)(N_1-N_2)(0.25+\gamma^2)\sin^2\zeta\cos2\delta}{(3+\alpha)(1-\beta)-(1-\alpha)(1+\beta)e^{-2\gamma\zeta}(\cos\zeta+2\gamma\sin\zeta)} + i\frac{(1+\alpha)(N_1-N_2)(0.25+\gamma^2)\sin^2\zeta\sin2\delta}{(1-\beta)+(1+\beta)e^{-2\gamma\zeta}(\cos\zeta+2\gamma\sin\zeta)}$$

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

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

Interface K, G expressions

$$\mathcal{K}_{Net} = K_1 + iK_2$$

$$K_1 = F_1\sqrt{\pi R\sin\zeta}\,(\cos\psi+2\gamma\sin\psi)e^{-\gamma\zeta}$$

$$K_2 = F_1\sqrt{\pi R\sin\zeta}\,(\sin\psi-2\gamma\cos\psi)e^{-\gamma\zeta}$$

$$F_1 = F_0\left(\sigma_{app}+\sigma_{th}+\alpha\left[\sigma_{app}-\sigma_{th}\right]\right);\psi=\frac{\zeta}{2}+\gamma\ln(2R\sin\zeta)$$

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

R. Tandon, in preparation

Elastic Properties

Material, #	E (GPa)	ν	μ (GPa)	Λ(ppm/°C)
LTCC, 1	116	0.24	47	7
Gold-Via fill, 2	78	0.44	27	15

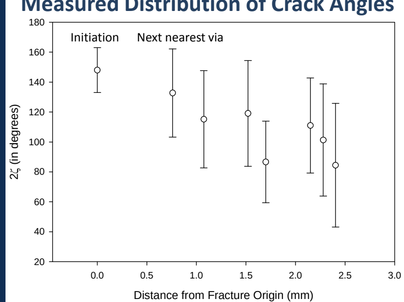
Calculated Values (Plane-Stress)

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

$$\alpha=\frac{\mu_2(\kappa_1+1)-\mu_1(\kappa_2+1)}{\mu_2(\kappa_1+1)+\mu_1(\kappa_2+1)};\ \beta=\frac{\mu_2(\kappa_1-1)-\mu_1(\kappa_2-1)}{\mu_2(\kappa_1+1)+\mu_1(\kappa_2+1)};\ \gamma=\frac{1}{2\pi}\ln\frac{1-\beta}{1+\beta}$$

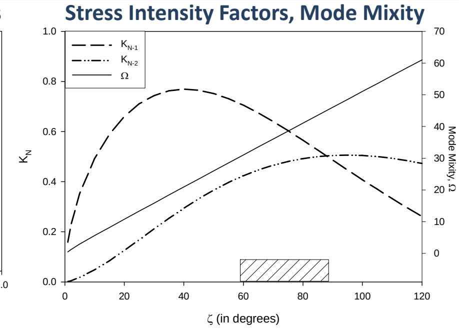
Note: γ is extremely small, ~0
K_1, K_2 ~ K_I, K_{II}

Measured Distribution of Crack Angles



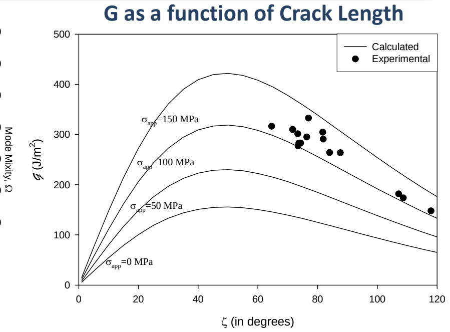
The via causing fracture was identified, and the crack angle at which kinking occurred was measured. 2ζ=148± 15°.

Stress Intensity Factors, Mode Mixity



Normalized K's: K_1 rises and decays more rapidly than K_2. Mode mix increases with ζ.

G as a function of Crack Length

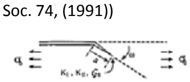


$\mathcal{G}$ has a maximum at ζ~50°. Kinking occurs on the decreasing portion of G-curve.

Crack kinking out of an interface

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

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



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

Non-dimensional length parameter which characterizes the stress parallel to the interface.

$$\eta = \frac{\sigma_0\sqrt{a}}{\sqrt{(E_*G_i)}}$$

η plays an important role in determining kink condition

For Arc Crack at LTCC-Au interface

- Crack kinking equality eq. satisfied due to decrease in $\mathcal{G}_{interface}$ with increasing ζ.
- For interface arc crack, mode mixity **Ω** at kinking~40°.
- Even though there is a compressive stress parallel to the interface, the contribution of the biaxial applied stress must exceed this value ⇒ stress parallel to the interface must be positive
- There does not appear to be any natural length parameter 'a' for calculation of η
- Taking η=0 will provide an upper bound for Γ_i

Therefore Γ_i/Γ_s ~ 0.6 (α=0), or ~0.8 (α=-0.5)
Γ_s ~9 J/m². Max. Γ_i ~5.5-7.2 J/m² – very brittle

Conclusions and Issue

Large amounts of stable crack growth followed by kinking lead to lower strength, and lower variability

As $\mathcal{G}_{interface}$ decreases with increasing ζ, kinking is expected even if Γ_i is not a strong function of **Ω**

Increasing Γ_i, and stiffness of matrix will lead to higher strength

Is the interface fracture toughness a function of geometry as well? Ω increases even though K_{II}↓

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