MSFC - 744 - ABSTRACT

ABSTRACT

Assessment of Crack Path Prediction in Non-Proportional Mixed-Mode Fatigue

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P-SAR
20 March 2008
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Non-proportional mixed-mode loading is present in many systems and a growing crack can experience any manner of mixed-mode loading. Prediction of the resulting crack path is important when assessing potential failure modes or when performing a failure investigation. Current crack path selection criteria are presented along with data for Inconel 718 under non-proportional mixed-mode loading. Mixed-mode crack growth can transition between path deflection mechanisms with very different orientations. Non-proportional fatigue loadings lack a single parameter for input to current crack path criteria. Crack growth transitions were observed in proportional and non-proportional FCG tests. Different paths displayed distinct fracture surface morphologies. New crack path drivers & transition criteria must be developed.

MSFC-744 - PRESENTATION

Georgia Institute of Technology

NASA

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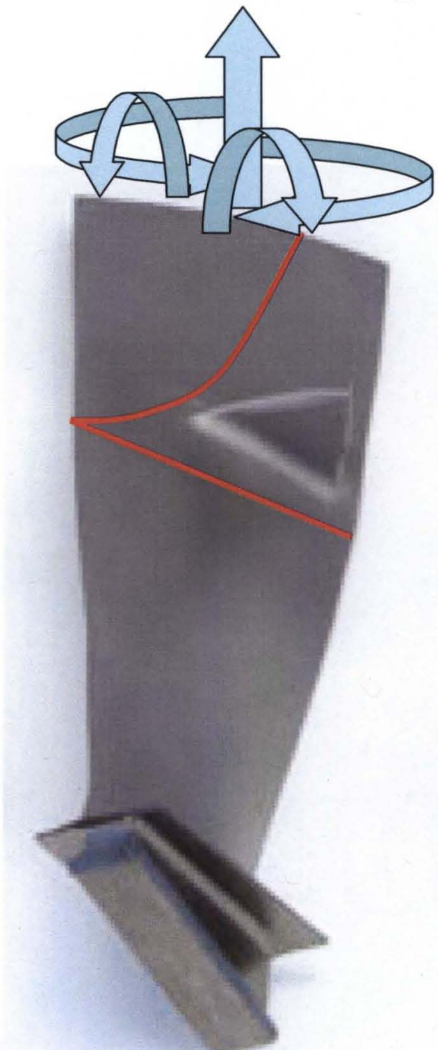
Outline

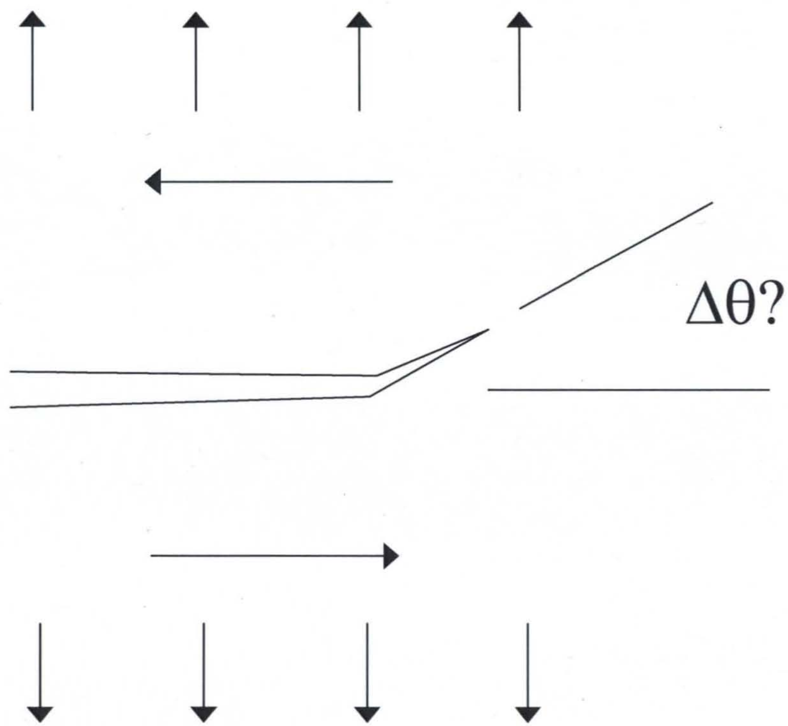
- Project motivation
  - Mixed-mode crack loading
- Background
  - Crack path selection criteria
- Problem
  - Criteria insufficient for non-proportional loading
- Testing & analysis
- Results & fractography
- Summary

Motivation: Non-proportional loading



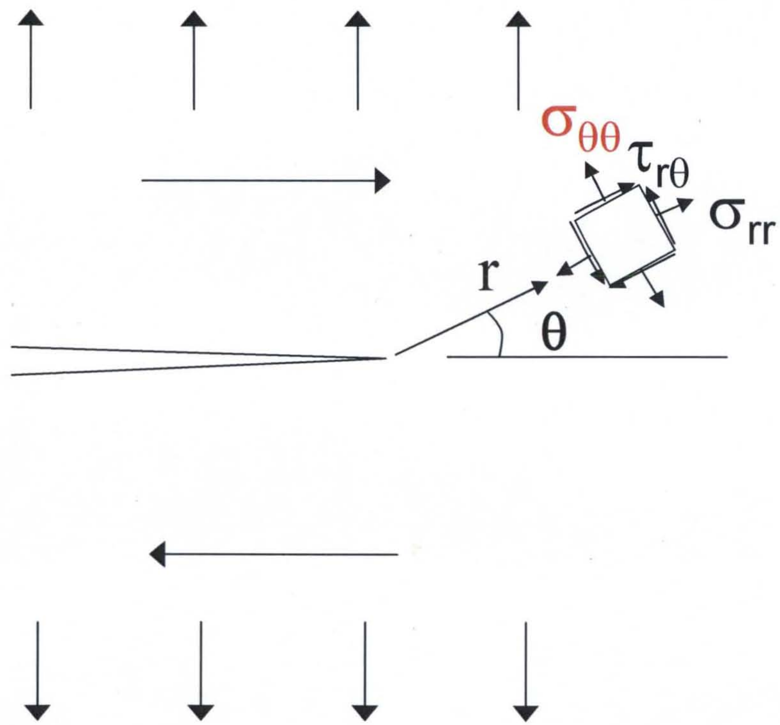
- Rotational & aerodynamic loads impose normal, bending & twisting loads
- Growing crack can experience any manner of mixed-mode loading
- **Objective**: Where will crack grow?
  - And how much mass/energy will it liberate?

Background - Mixed mode crack path



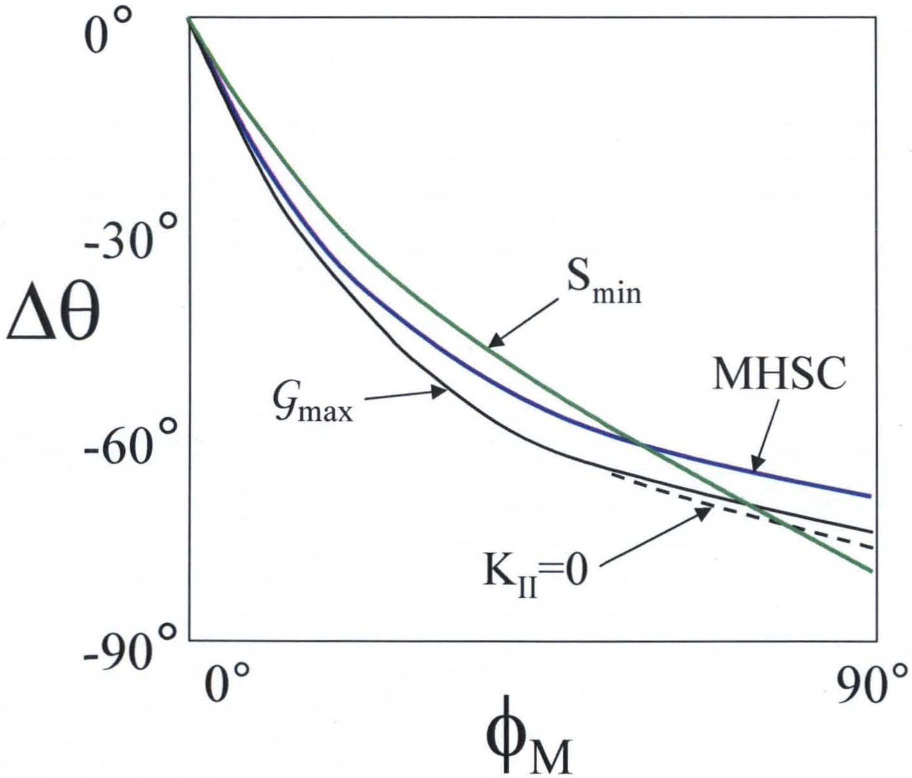
- Crack growth predominantly considered in terms of Mode I
- Microstructure, geometry, load transients can perturb crack angle or applied load
  - Addition of Mode II
- What is expected behavior of crack trajectory?

Background - Mixed mode crack path models



- Erdogan & Sih (1963) - max hoop stress criterion (MHSC)
- Hussain et al (1974) - max strain energy release rate $\mathcal{G}$ ("Griffith" theory)
- Sih (1974) - min strain energy density *S*
- He & Hutchinson (1989) - K_{II}=0

Background - Mixed mode crack path models



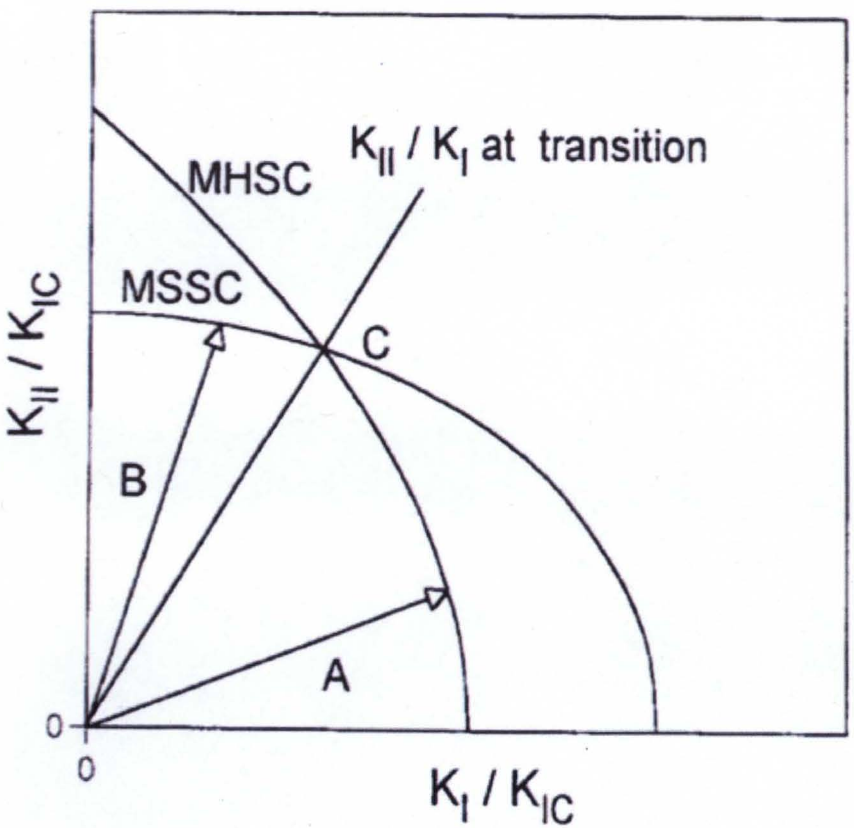
- All generally predict same crack deflection as function of mixity

$$\phi_M = \tan^{-1}\left(\frac{K_{II}}{K_I}\right)$$

Background - Fracture mode transition

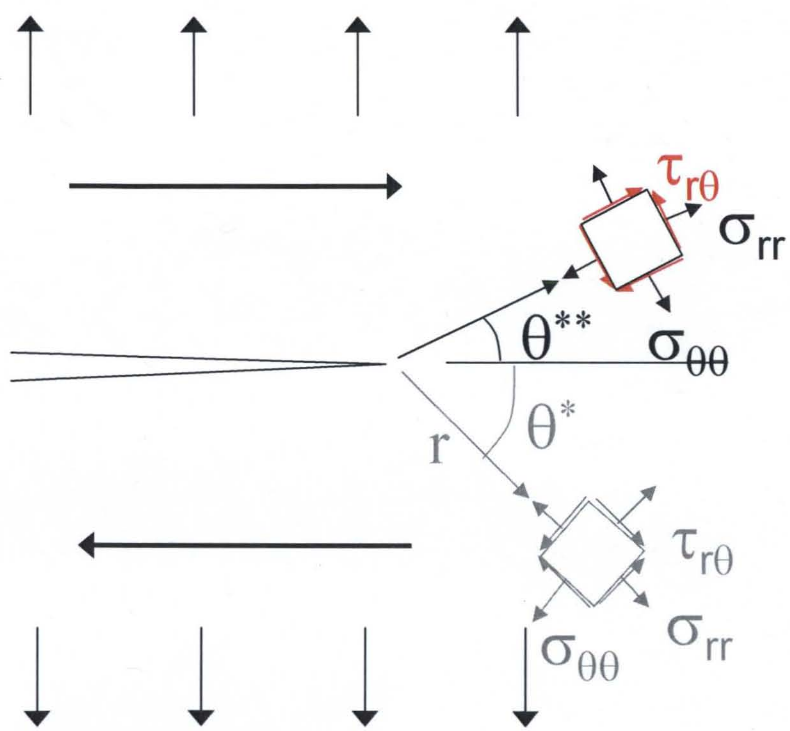
- Hallback & Nilsson (1994) observe Mode I to Mode II-dominated transition (to max shear plane) around $\phi = 40°$ in 7075-T6
  - Initial crack trajectory predicted by MHSC at lower mixities, by max shear stress criterion (MSSC) at higher mixities
- Amstutz et al (1995) also observe transition to shear crack growth in range of $68° < \phi < 75°$ in 2024-T3

Background - Fracture mode transition



- Chao & Liu (1997) argue that crack propagation occurs along most critical mode
- Competition b/w MHSC and MSSC based on loading path (mixity)
  - Transition based on ratio of $\tau_{crit}/\sigma_{crit}$

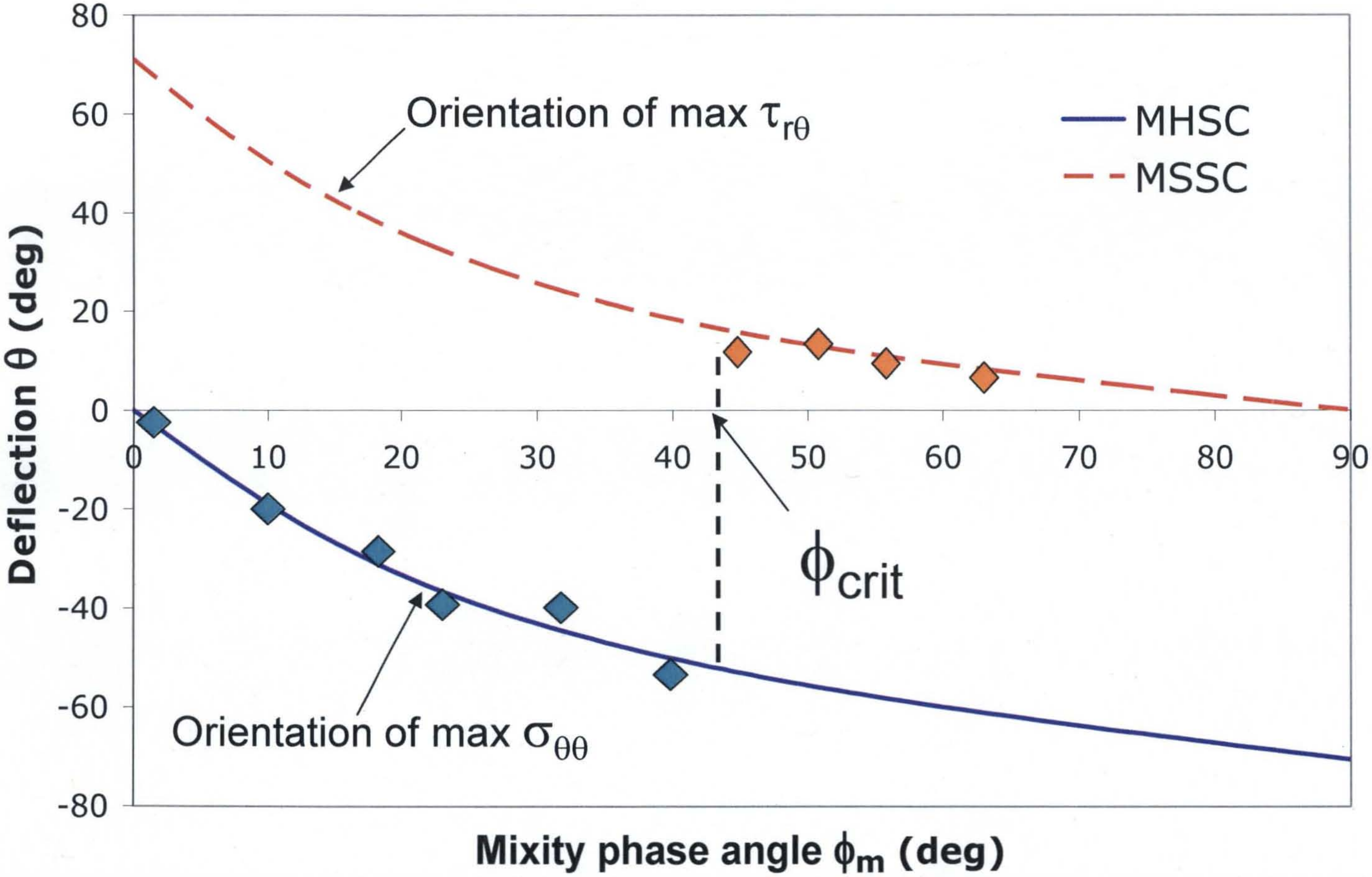
Background - Fracture mode transition



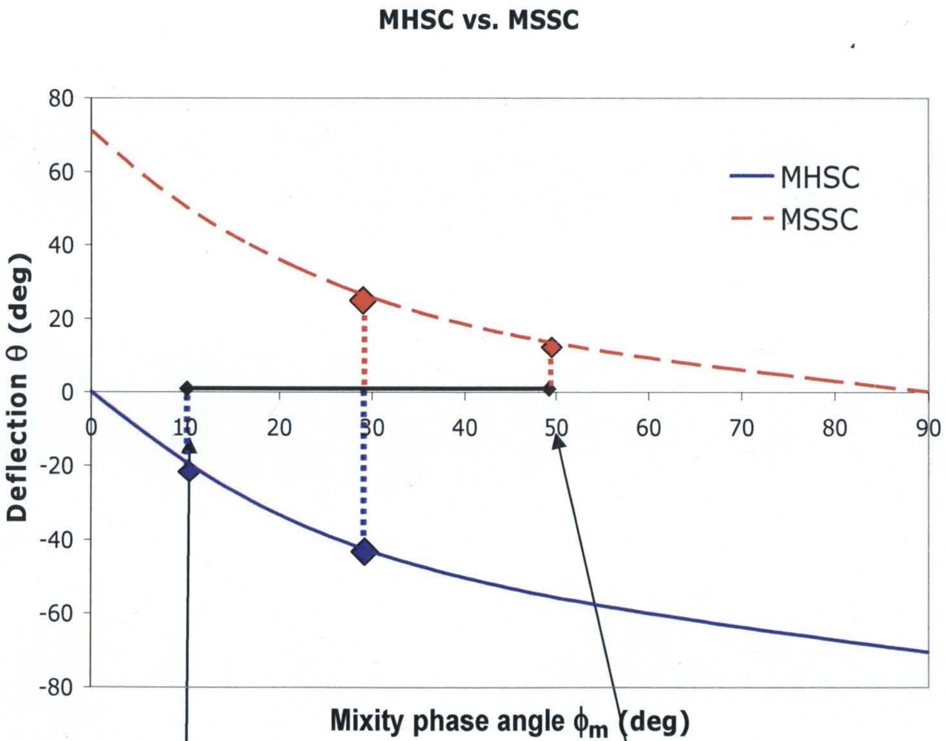
- Normal crack deflection dictated by max $\sigma_{\theta\theta}$
- As K_{II} increases relative to K_I the angle θ^* of max normal stress $\sigma_{\theta\theta}$ deflects downward
- Simultaneously the shear stress $\tau_{r\theta}$ is increasing on a positive deflected plane θ^{**}
- At a material-dependent K_{II}/K_I ratio, the critical shear stress is reached (at some characteristic distance) before critical normal stress and crack deflection shifts to shear

Background - Fracture mode transition

MHSC vs. MSSC



Problem - Non-proportional mixed mode loads

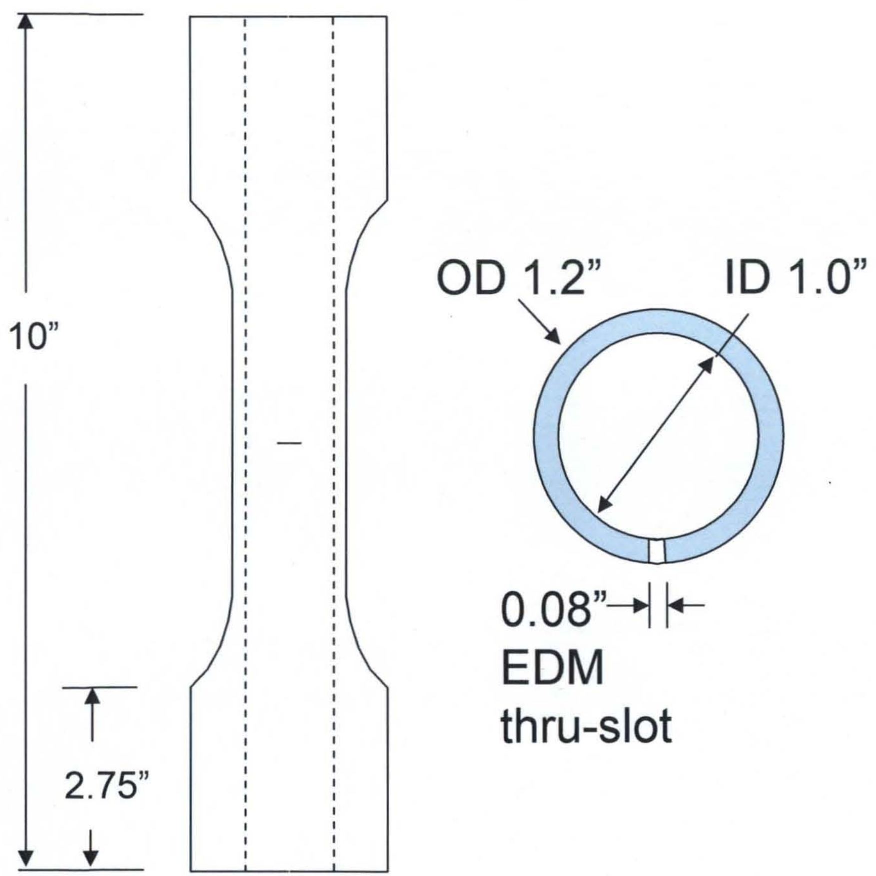


Max tension of constant torque or OOP test

Max torque of constant tension or OOP test

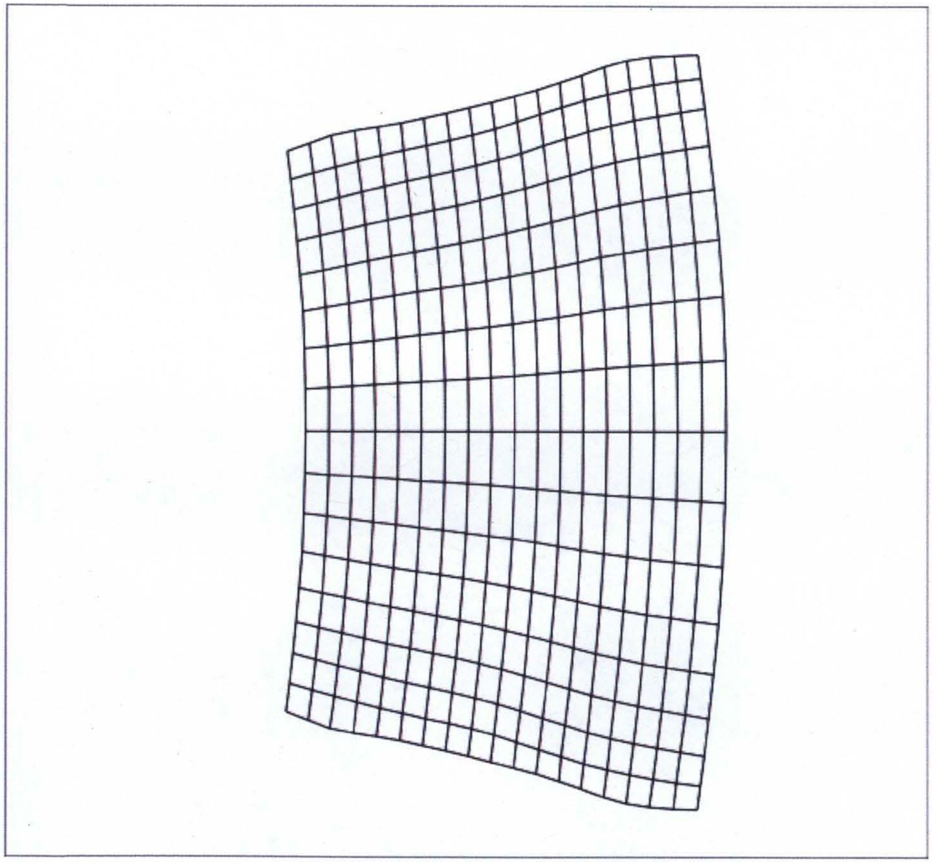
- Different points of waveform have different mixities
- Which parameters can be used to predict θ?
- Can we do so using only LEFM / K?

Testing - Tension-torsion tubular FCG



- Inconel 718
- 17 specimens tested at NASA Marshall
- Compression then tension pre-cracking
- Measure initial deflection angle from pre-crack upon mixed-mode loading
- Examine fracture surface morphology

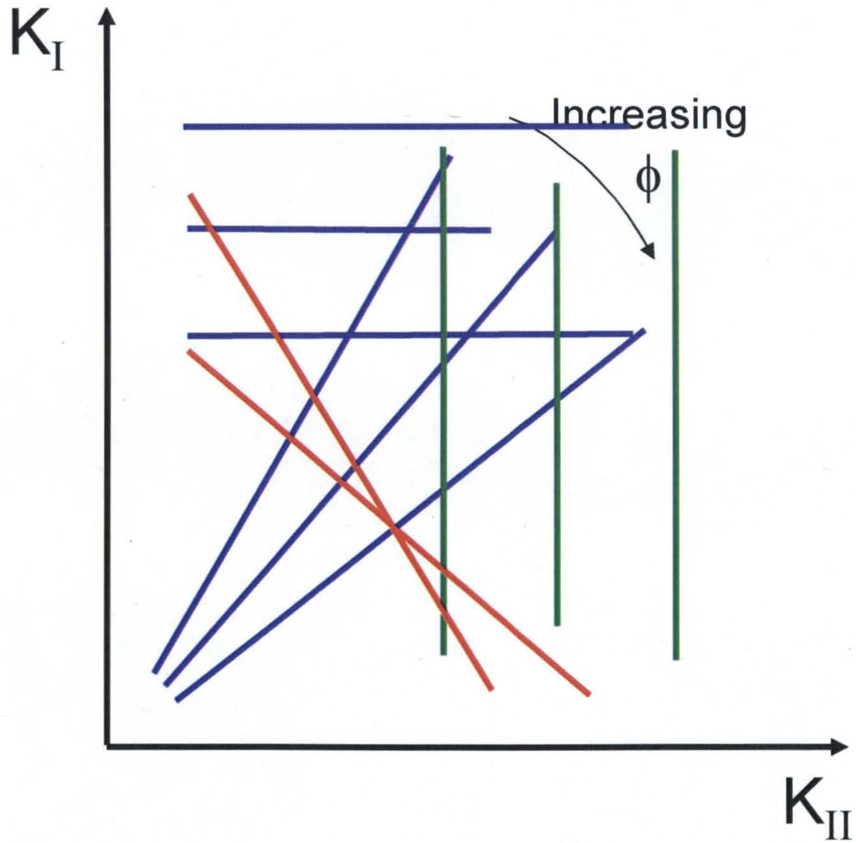
Modeling - SIFs for tubular T-T specimen



Plan view of precrack

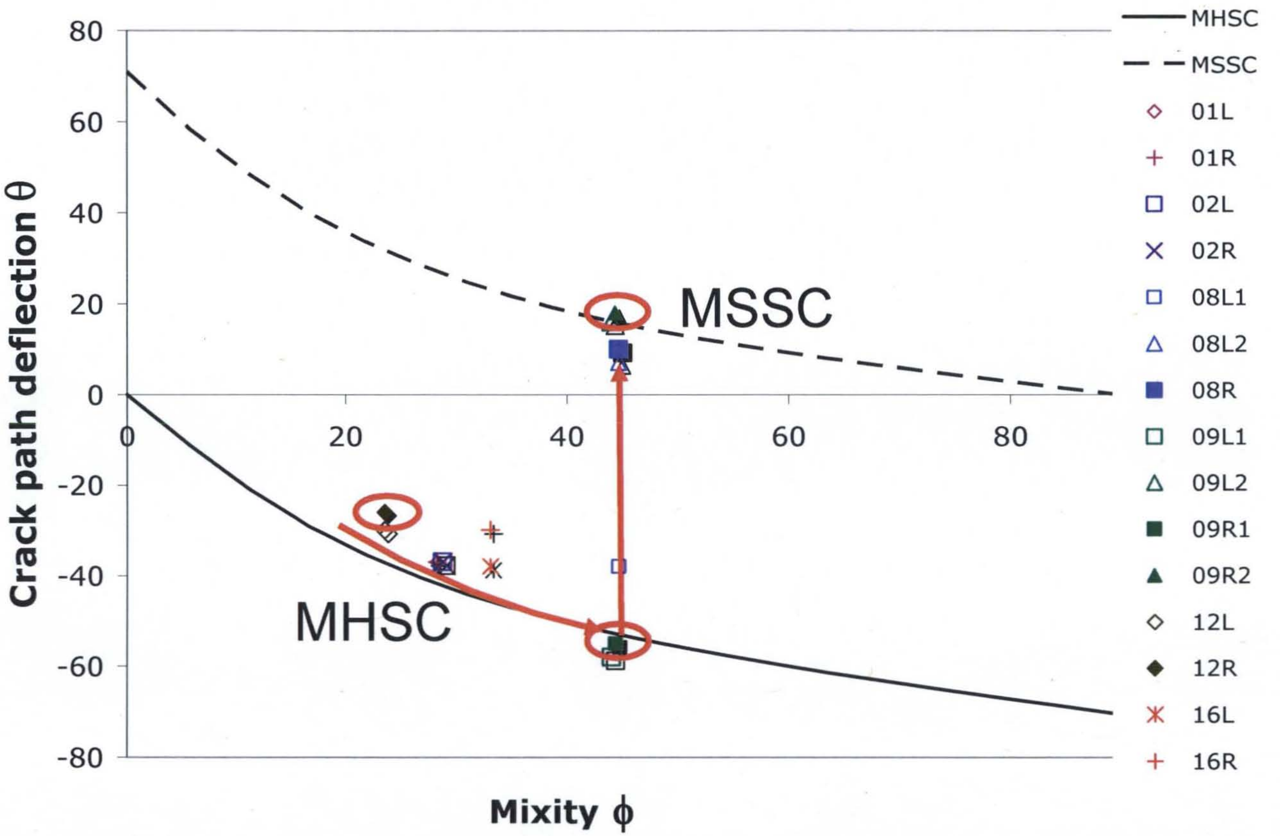
- FRANC3D linear elastic boundary element model
- Local mesh refinement around precrack
- Each specimen precrack geometry modeled using fracture surface measurements
- Tension & torsion applied individually and together

Testing - Mixed mode test matrix



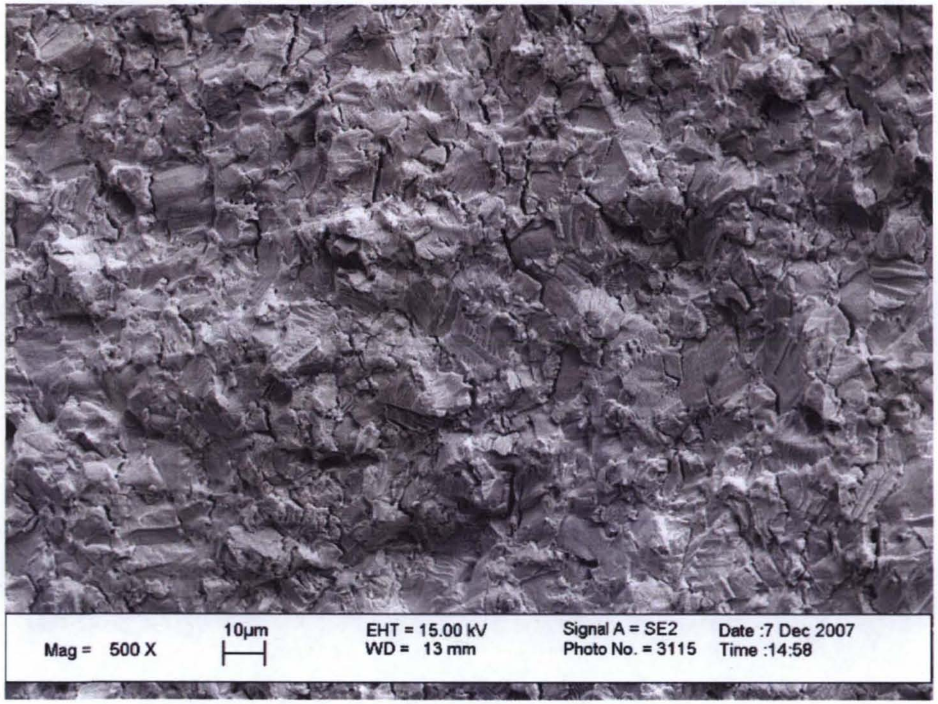
- Baseline in-phase tests over range of mixity
- Contant tension (K_I) / cyclic torsion (K_{II})
- Contant torsion (K_{II}) / cyclic tension (K_I)
- 90° out-of-phase

Results - In Phase

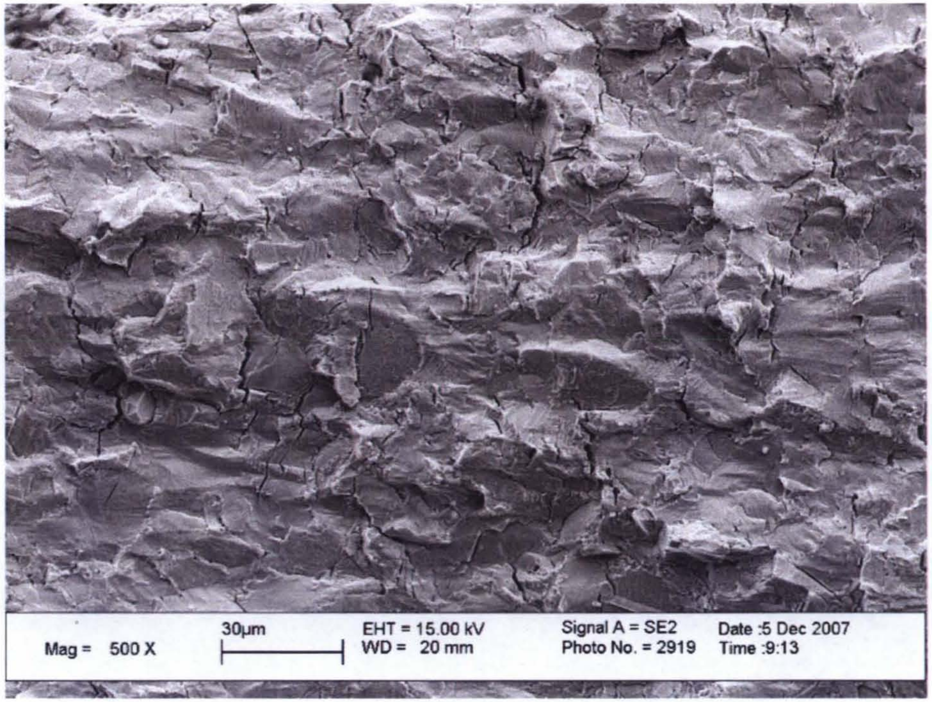


- In-phase deflections follow Max Hoop Stress criterion as expected up to critical ϕ value, then see transition to Max Shear Stress
- Torque limitations prevented further MSS testing

In-phase fractography - 500x



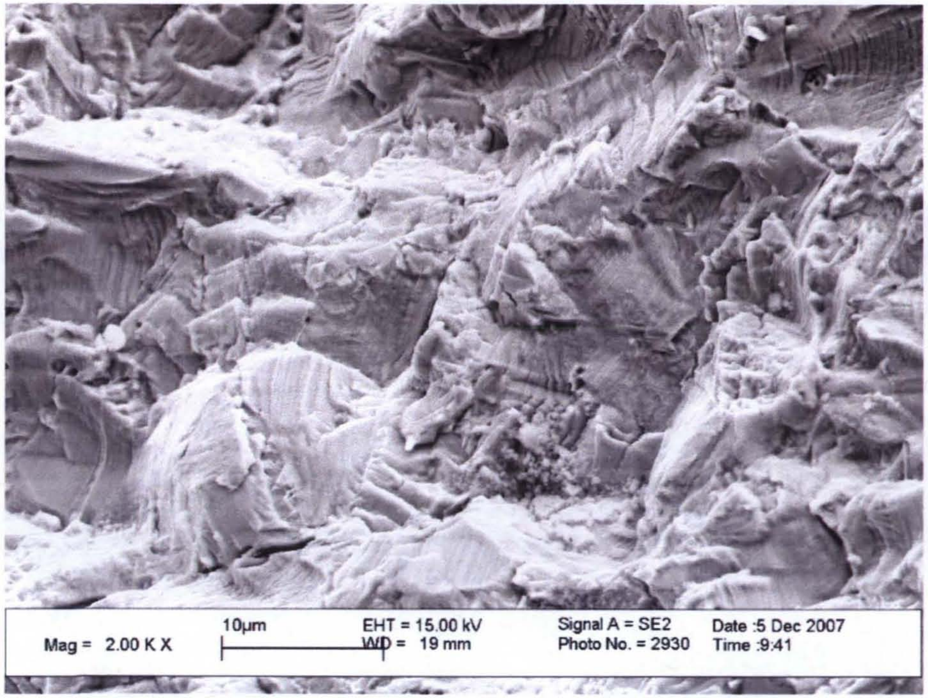
Tensile crack (MHS) deflection
$\theta = -27°$



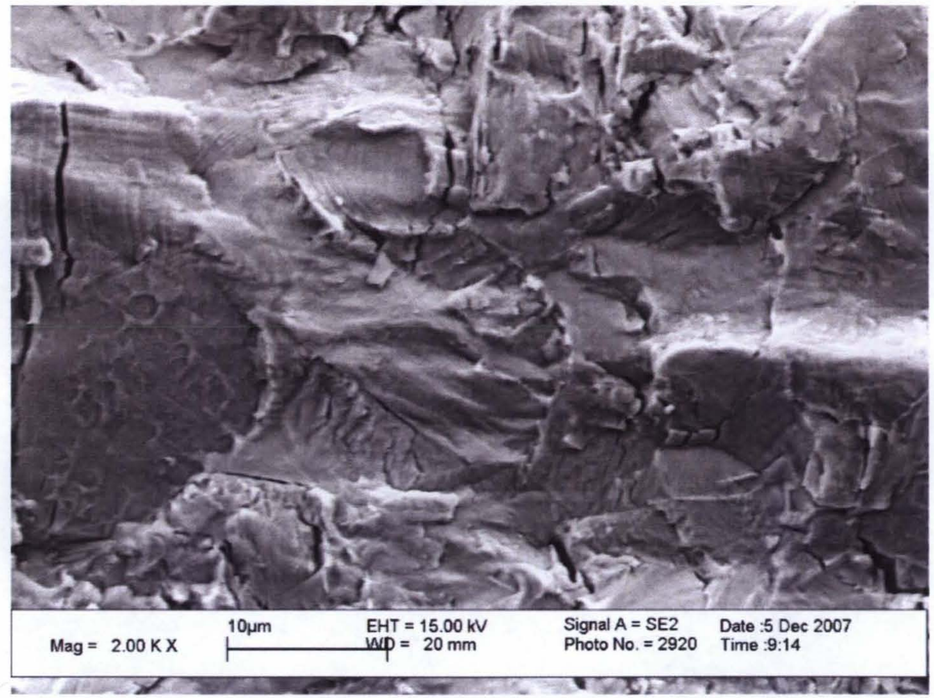
Shear crack (MSS) deflection
$\theta = 18°$

- Clear morphology difference reinforces transition in crack path deflection mechanism

In-phase fractography - 2000x



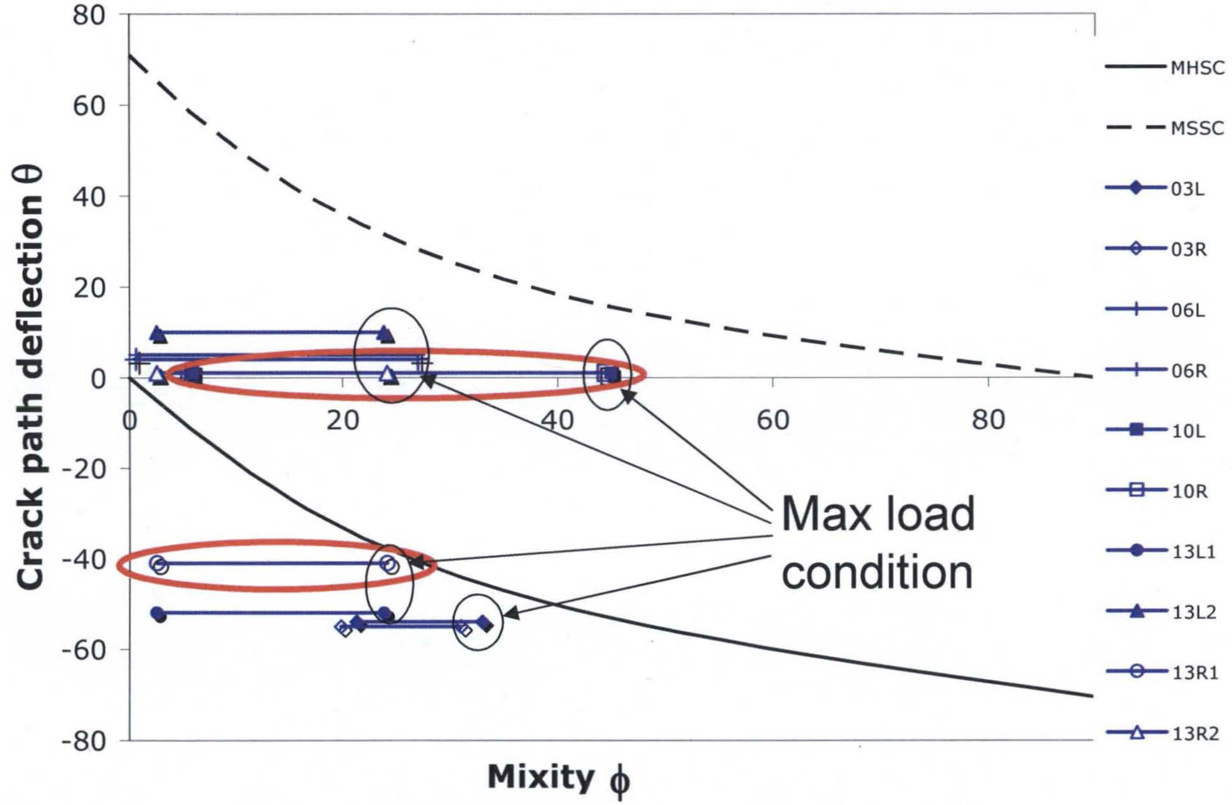
Tensile crack (MHS) deflection
$\theta = -55°$



Shear crack (MSS) deflection
$\theta = 18°$

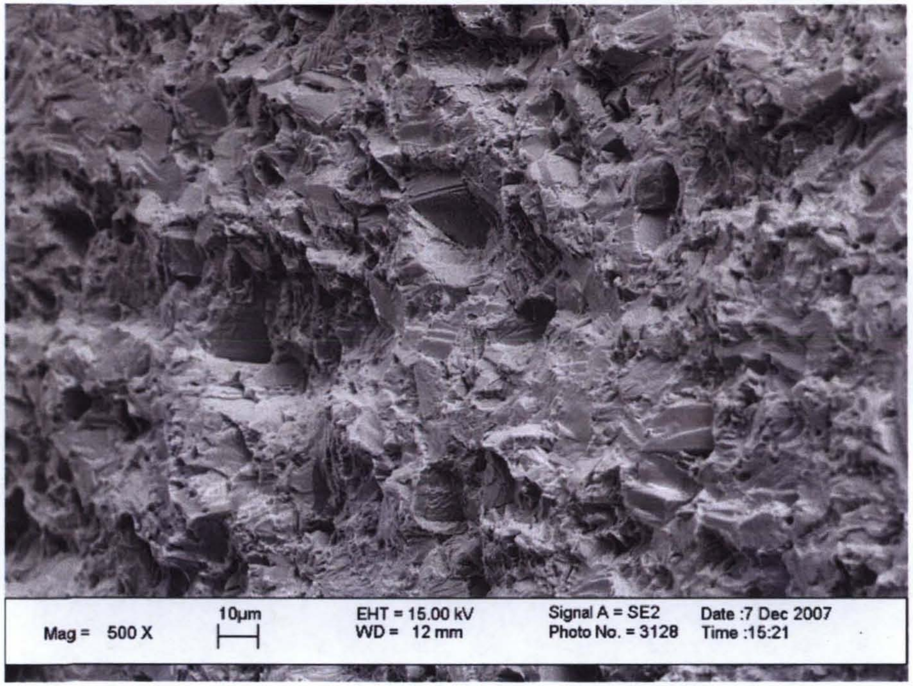
- Fine microstructural features on shear crack flats suggest they are not the product of crack face contact

Results – Constant Tension / Cyclic Torsion

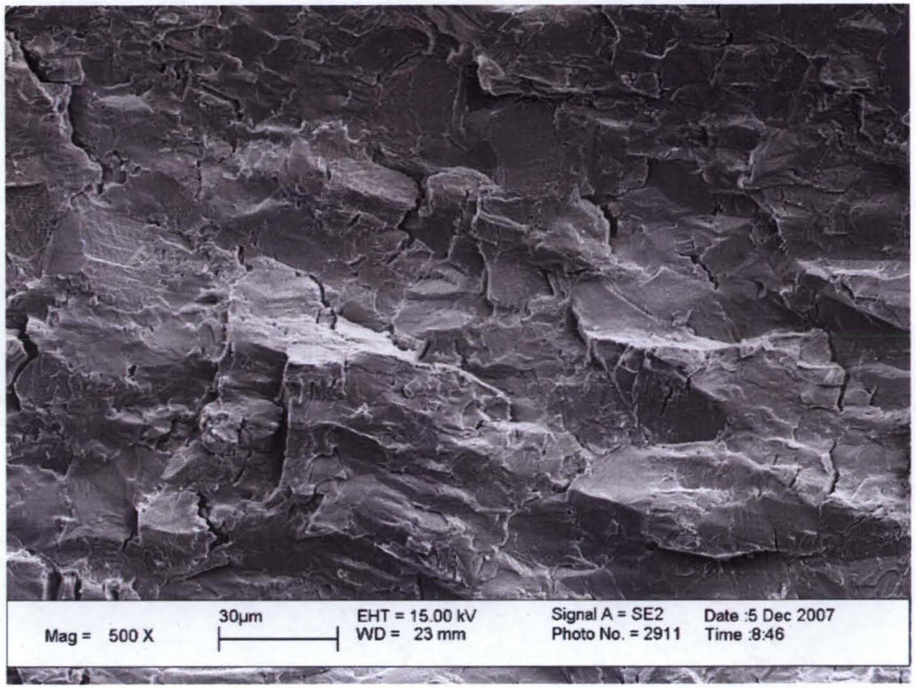


- Two distinct groups of crack path deflection
- No clear indicator of transition criterion

Fractography - Constant Tension / Cyclic Torsion 500x



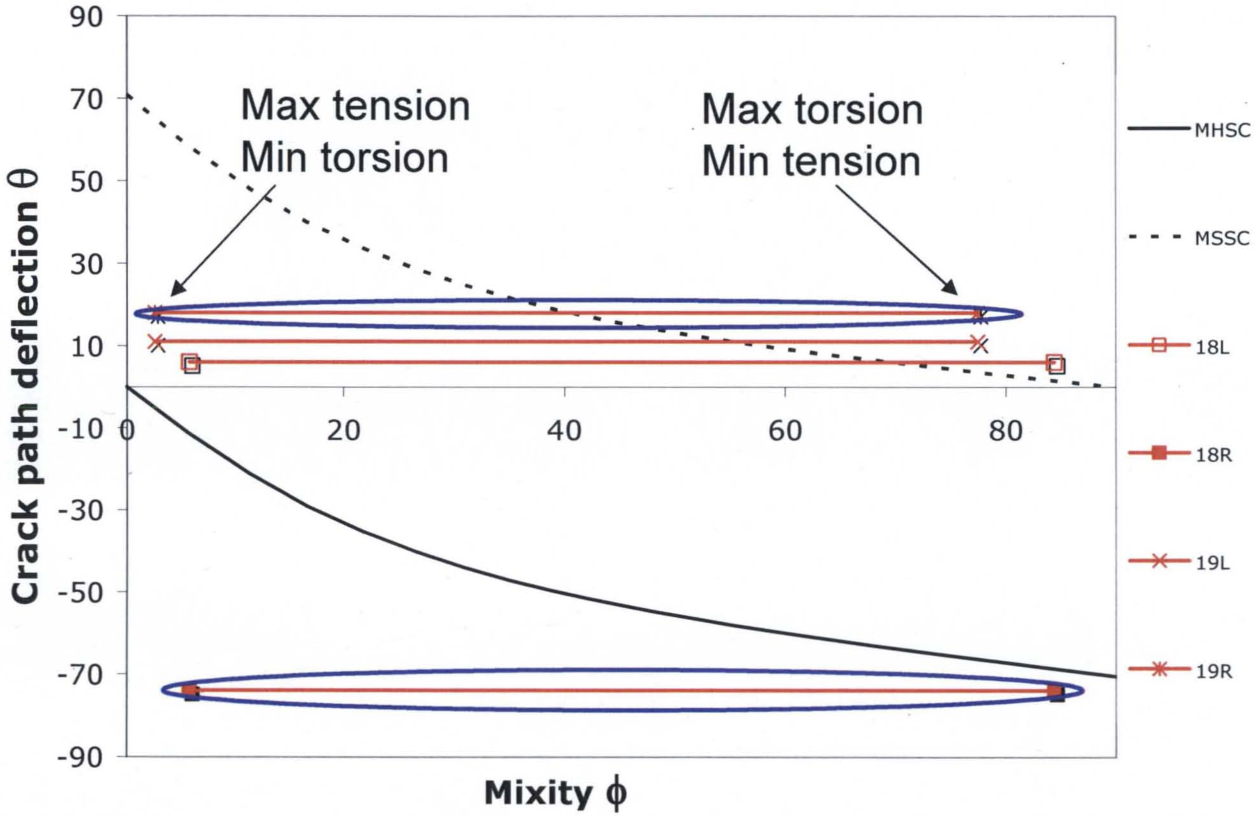
Tensile crack (MHS) deflection
$\theta = -41°$



Shear crack (MSS) deflection
$\theta = +2°$

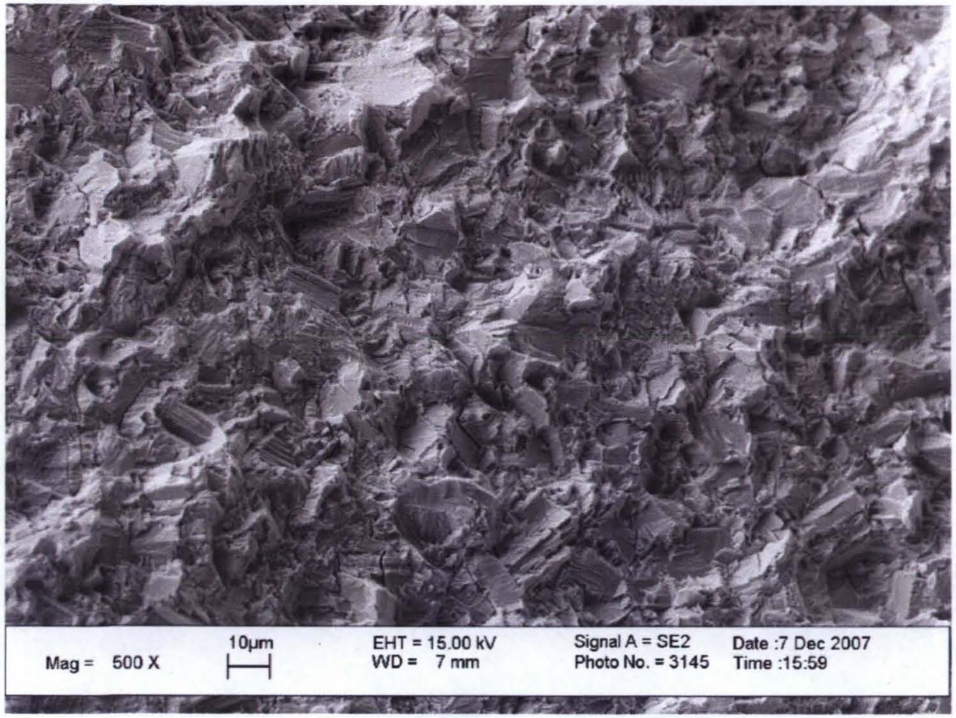
- Even more pronounced morphological difference but similar in nature to in-phase

Results - 90° Out of Phase

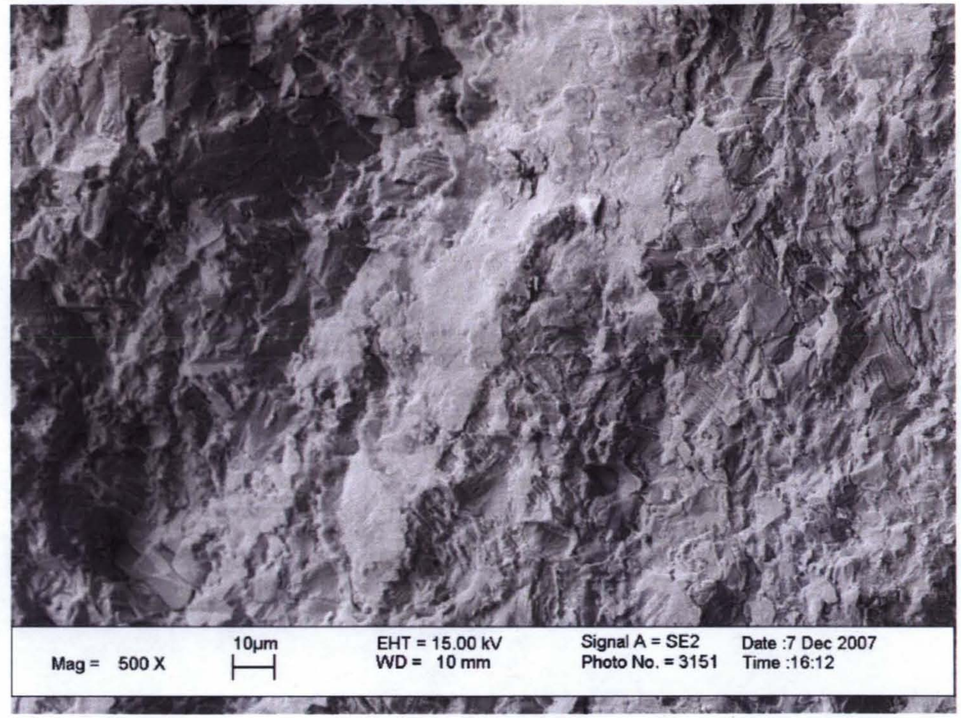


- Two distinct crack path deflections, but fractography not as clear

Fractography - Out of Phase 500x



Tensile crack (MHS) deflection
$\theta = -74°$

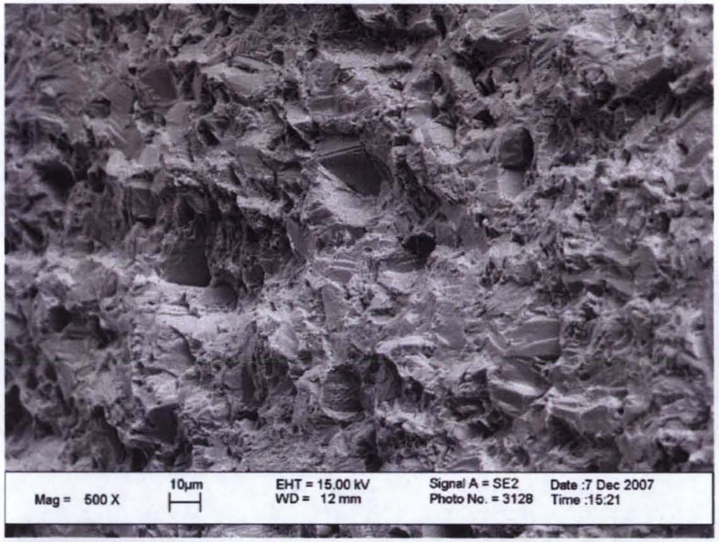


~~Shear crack?~~
$\theta = 18°$

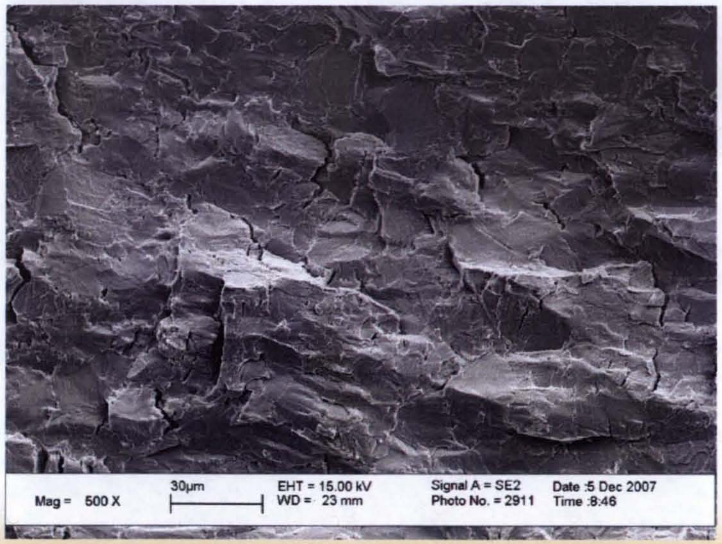
- Positive deflected crack looks more like a crushed tensile crack than like previous shear cracks

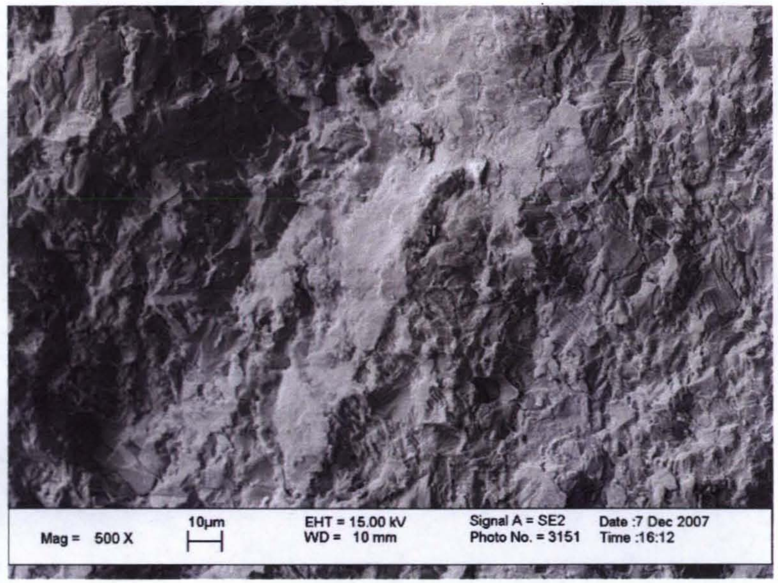
Fractography - Comparison to Tensile & Shear 500x

Constant tension/
cyclic torsion
Tensile (MHS)
crack
$\theta = -41°$



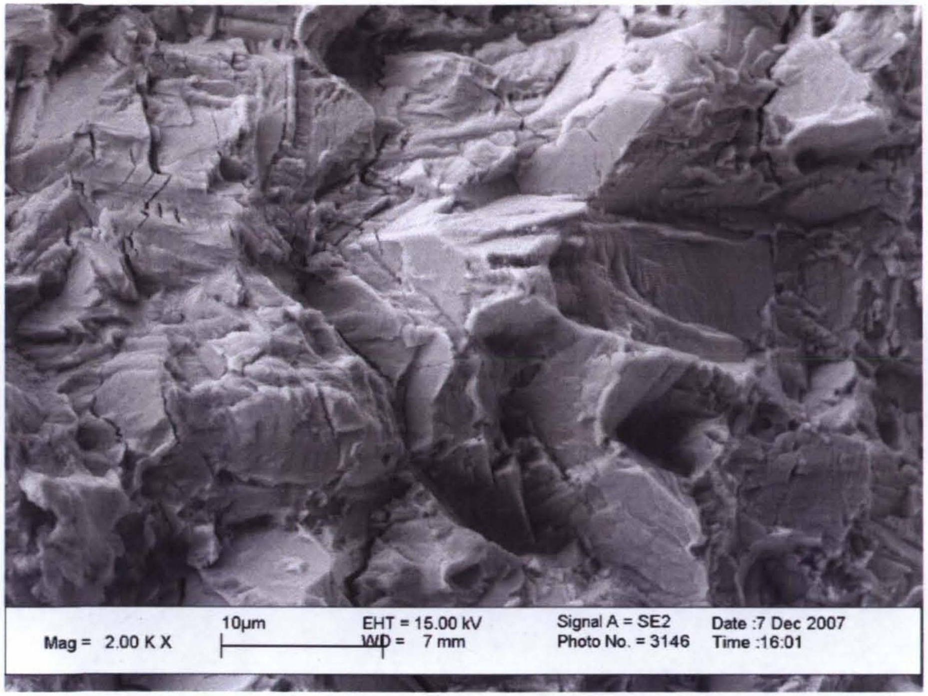
Constant tension/
cyclic torsion
Shear (MSS)
crack
$\theta = 2°$



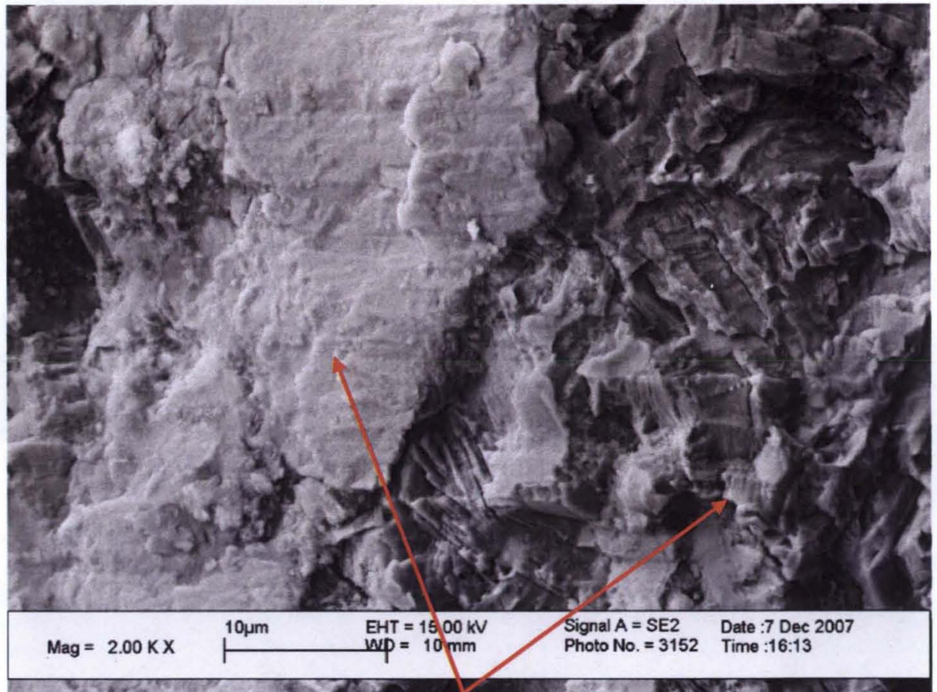


Out-of-phase
$\theta = 18°$

Fractography - Out of Phase 2000x



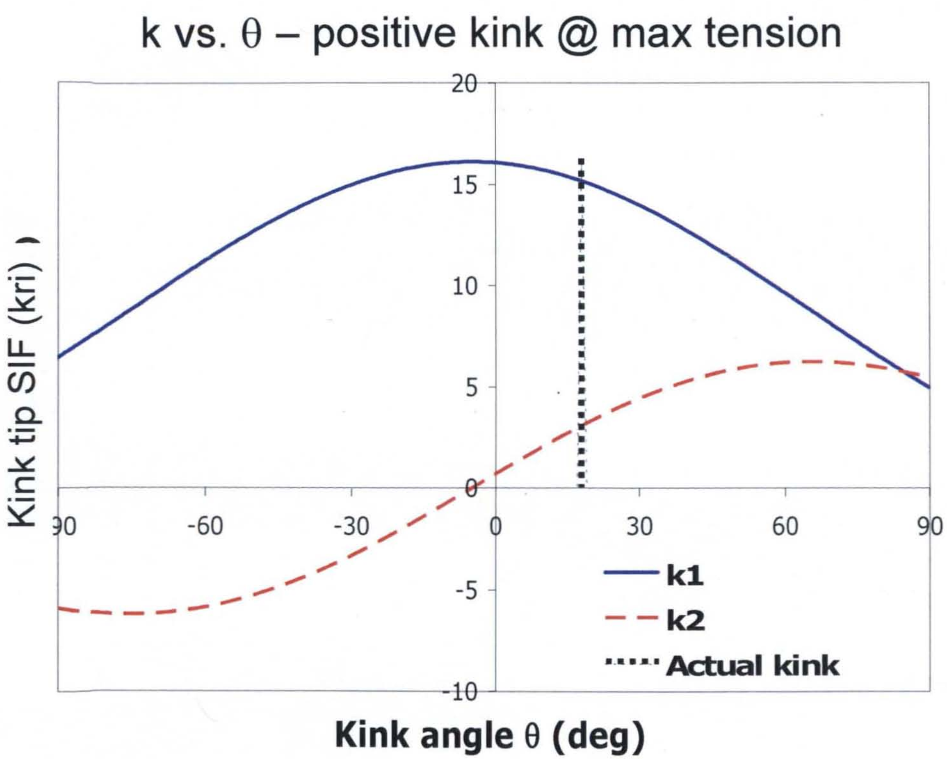
Tensile crack (MHS) deflection
θ = -74°



Unknown mechanism
θ = 18°

- θ=18° crack shows MHS-like faceting at right; flat region appears crushed
- If both are tensile cracking, what is the driver?

Example: Kink SIF for Out-of-Phase crack deflections



- Crack tip SIFs k_1 & k_2 for putative kink
- Positive-kinked OOP test (mechanism unclear) tracks well to Δk_1
- Negative-kinked OOP test (likely tensile) does not
  - *Does* track toward max k_1 of cycle (at max torque)
  - But positive-kinked OOP test not as likely

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Summary

- Mixed-mode crack growth can transition between path deflection mechanisms with very different orientations
- Non-proportional fatigue loadings lack a single parameter for input to current crack path criteria
- Crack growth transitions were observed in proportional & non-proportional FCG tests
- Different paths displayed distinct fracture surface morphologies
- New crack path drivers & transition criteria must be developed

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Acknowledgments

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