CornellEngineering

Fracture Surface Transition for Notched Bars in Torsion

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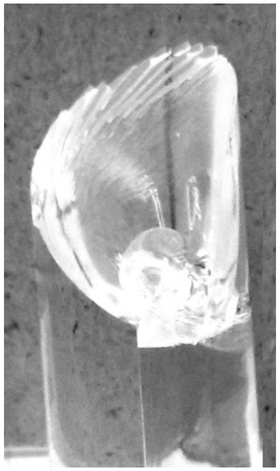
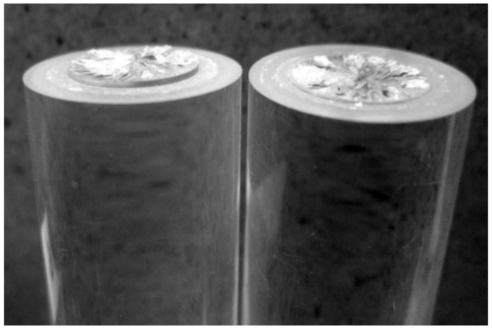
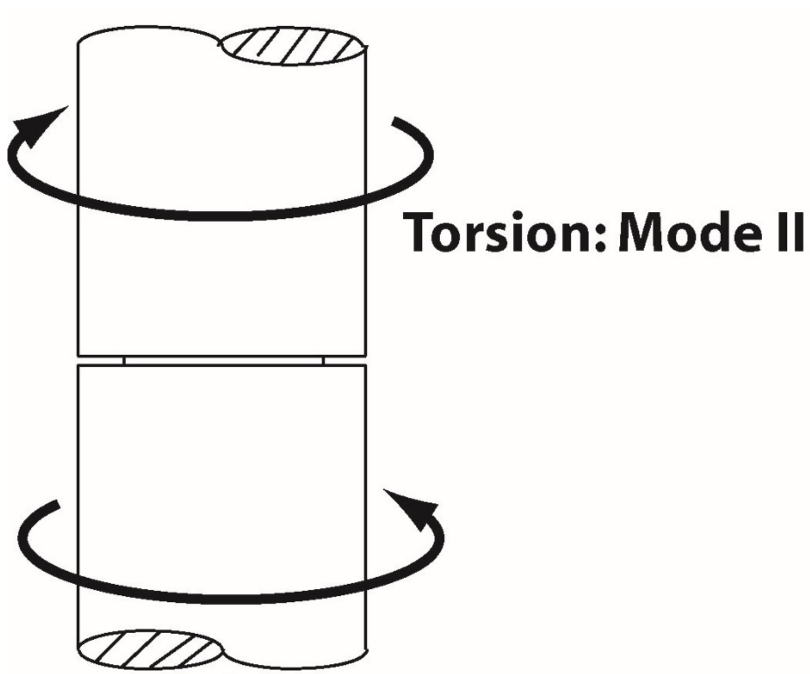
Overview



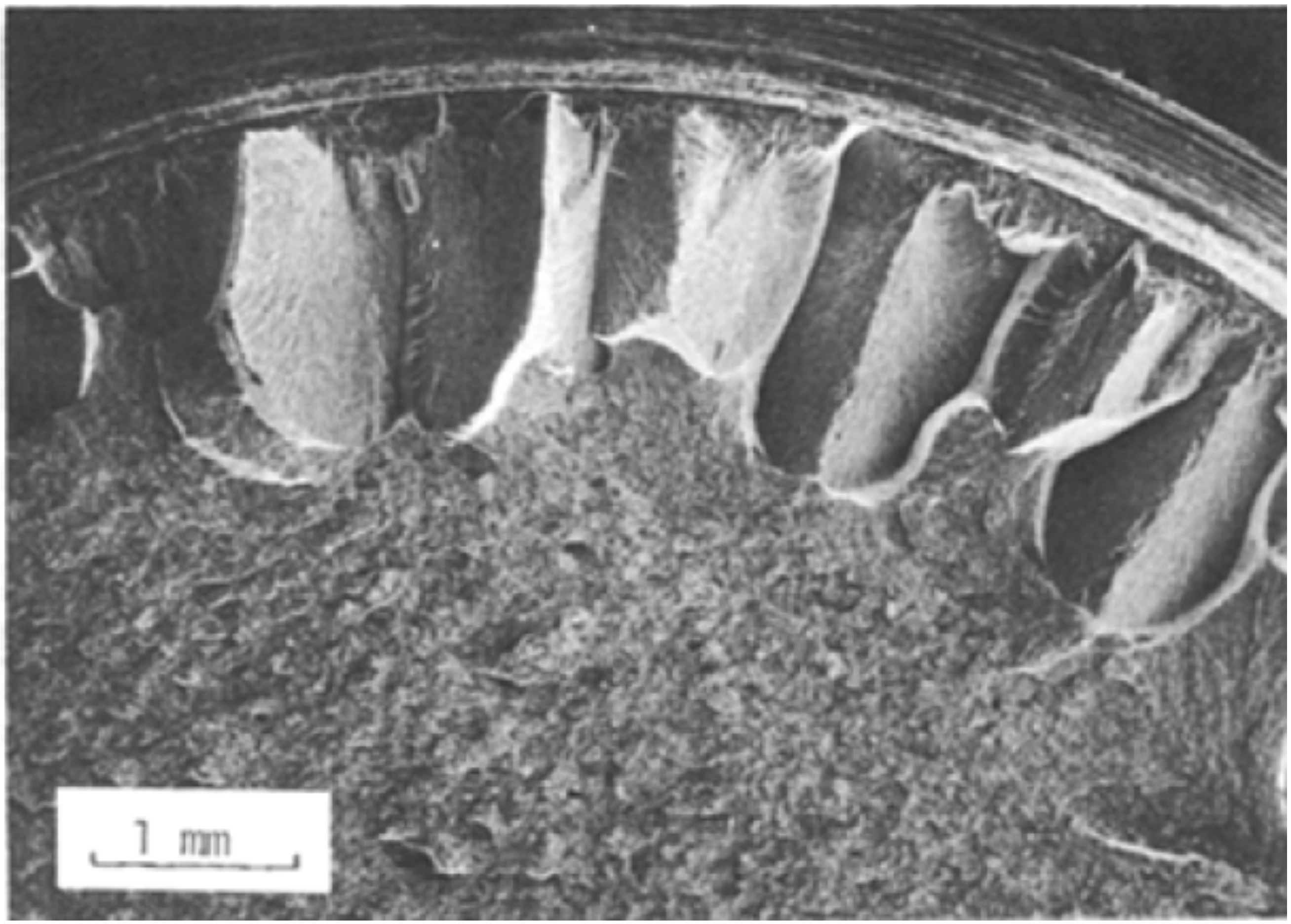
- Notched rods of a brittle material under torsional loading
  - Uniform rods break in a spiral and often fragment
  - Deeply notched rod will fail on a to flat (on macro-scale, rough on micro-scale) surface
- Hypothesis:
  - There is a notch depth for which surface transitions from:
    - spiral fracture surface
    - to flat (on macro-scale, rough on micro-scale) surface
- What is this depth?
- Does it depend on material or on notch geometry details?
- Can the transition be predicted?
- Challenges for theoretical and computational fracture mechanics:
  - Correct prediction of load for onset of failure with and without pre-cracks
  - Capturing crack path in 3D
  - Capturing formation, growth and linking of multiple fractures
  - Material behavior – in a nominally brittle material must inelastic deformation and failure modes be considered?



Mode III Loading of Notched Rod



Torsional fracture surface of a notched rod – high strength steel



E. Tschegg, “Mode III and mode I fatigue crack propagation behaviour under torsional loading,” **J. Mat. Sci, 18** (1983).

Transition: varying notch radius

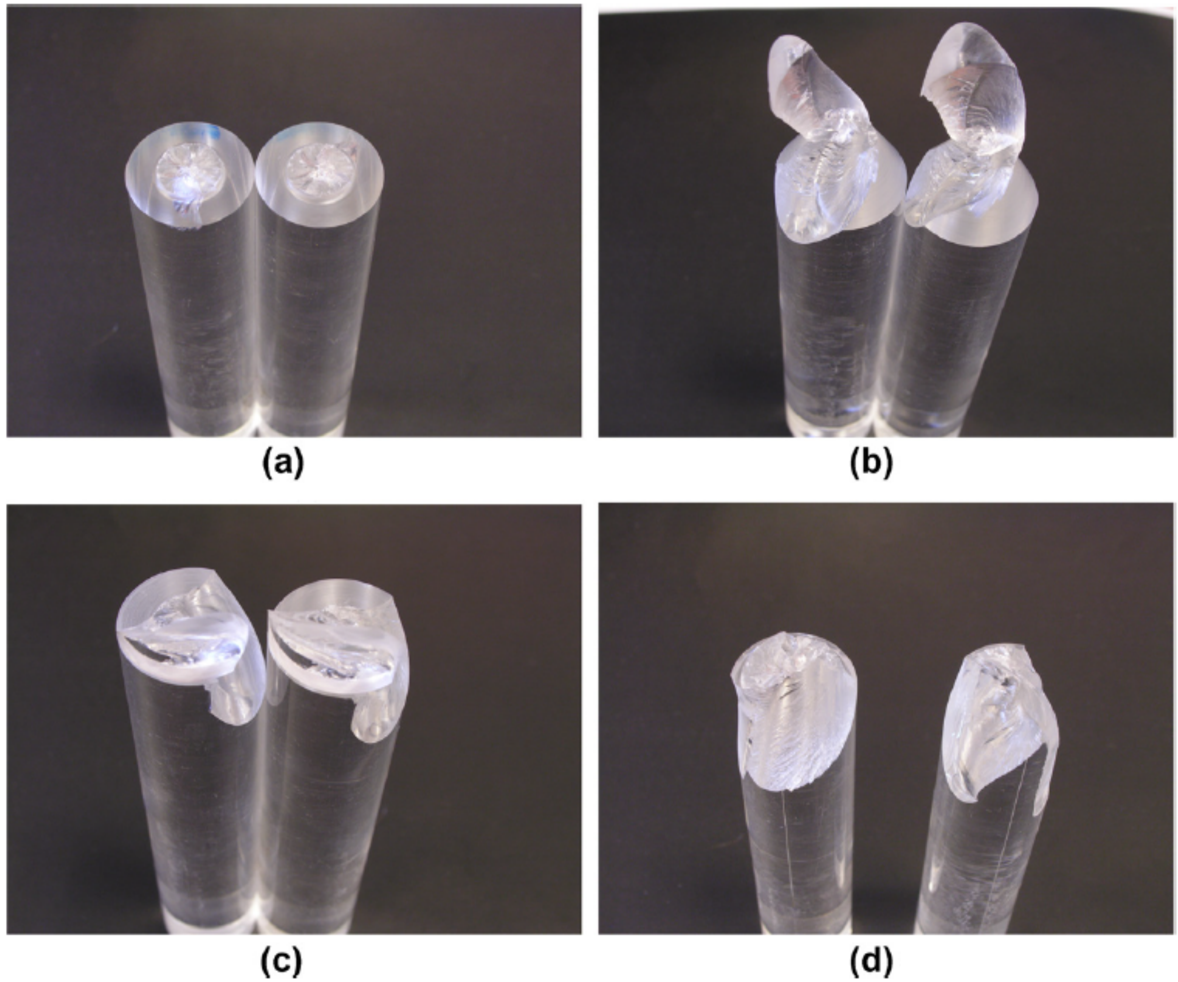


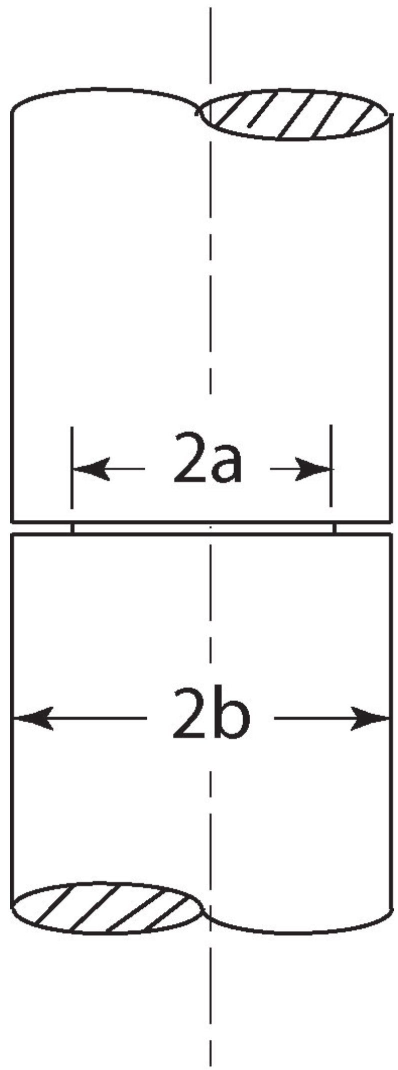
Fig. 6. Failure modes in some specimens with $d = 5$ mm: U-notch, $R = 0.5$ mm (a), V-notch, $R = 2$ mm, (b). Failure modes in some specimens with $d = 2$ mm: U-notch, $R = 0.5$ (c), V-notch, $R = 1$ mm (d).

* Berto et al., "Fracture behaviour of notched round bars made of PMMA subjected to torsion at room temperature," **EFM, 90** (2012), 143-160

Our Experiments

- 25.4 mm and 19.05 dia notched PMMA rods
- Two types of circumferential pre-cracks, or notches were cut :
  - 0.7 mm wide, square notch
  - 0.5 mm wide, V-notch using utility knife blade as a cutting tool, notch root radius less than 0.04 mm.
- Notch depth/radius ratio from 0.05 to 0.25
- Classify fracture surfaces
- Image cracks with micro-CT scan
- Analysis of CT-scans

Experimental Setup



Nominal PMMA Properties

$E \approx 2.95$ GPa,

$\nu \approx 0.34$,

Yield strength ≈ 50 MPa

Ultimate strength ≈ 80 MPa

Strain to failure ≈ 0.05

Toughness,

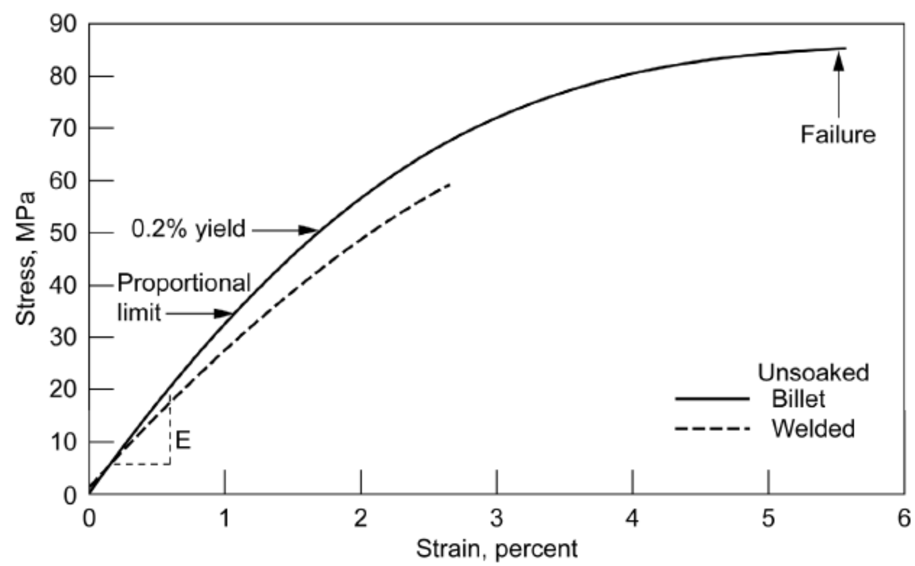
$K_{IC} = 1$ MPa $m^{1/2}$,

$G = 338$ J/m^2,

$\rho = 1152$ kg/m^3

p-wave speed = 1990 m/s

s-wave speed = 980 m/s

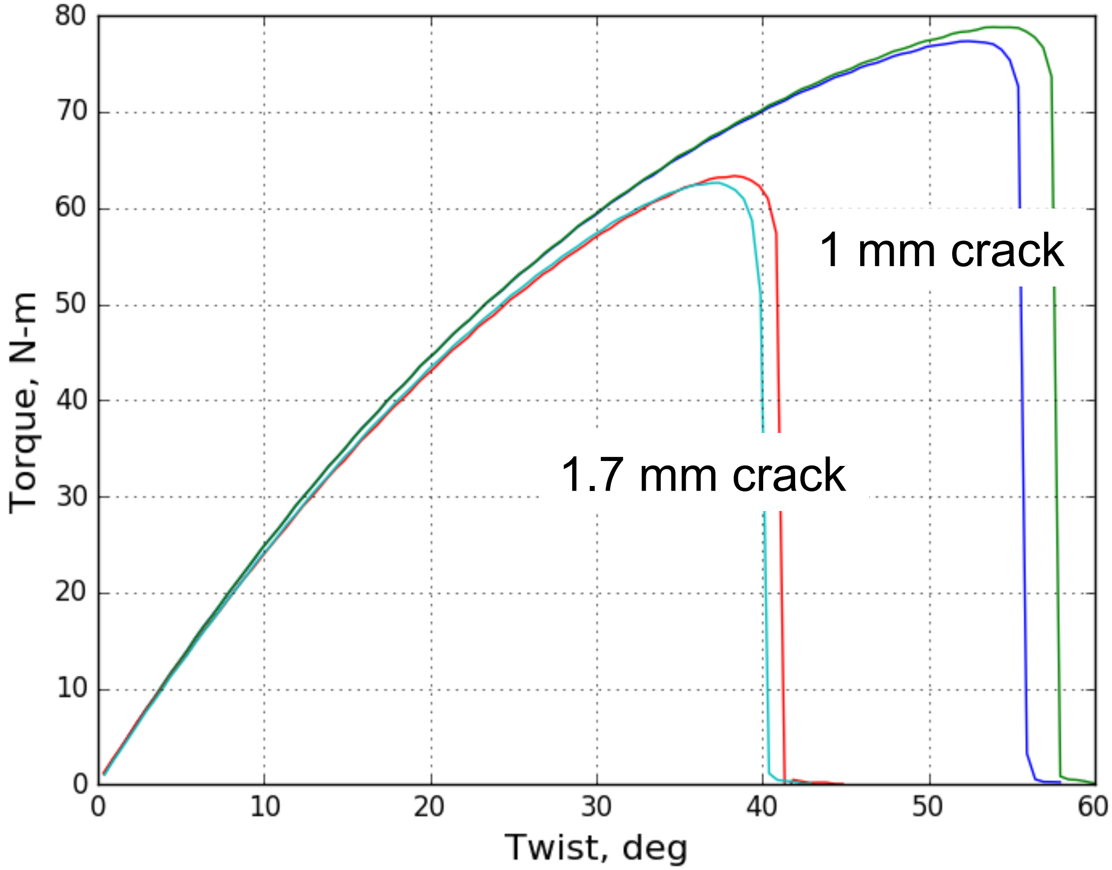


From NASA/TM—2007-214835 *Polymethylmethacrylate (PMMA) Material Test Results for the Capillary Flow Experiments (CFE)* and Shu Liu, Yuh J. Chao *, Xiankui Zhu, *Tensile-shear transition in mixed mode I/III fracture,* **International Journal of Solids and Structures 41** (2004) 6147–6172

Length scales of this problem

- Notch depth to rod radius
  - .05 to .25
- Notch width
  - 0.7 and 0.5 mm
- Notch root radius
  - Less than about 0.04 mm
- Plastic zone at onset of fracture
  - $r_p = \frac{1}{\pi}\left(K/\tau_y\right)^2 \approx 2\ mm$
- Rod diameter
  - 25 and 19 mm
- Rod length
  - 100 and 75 mm

Example torque-twist curves



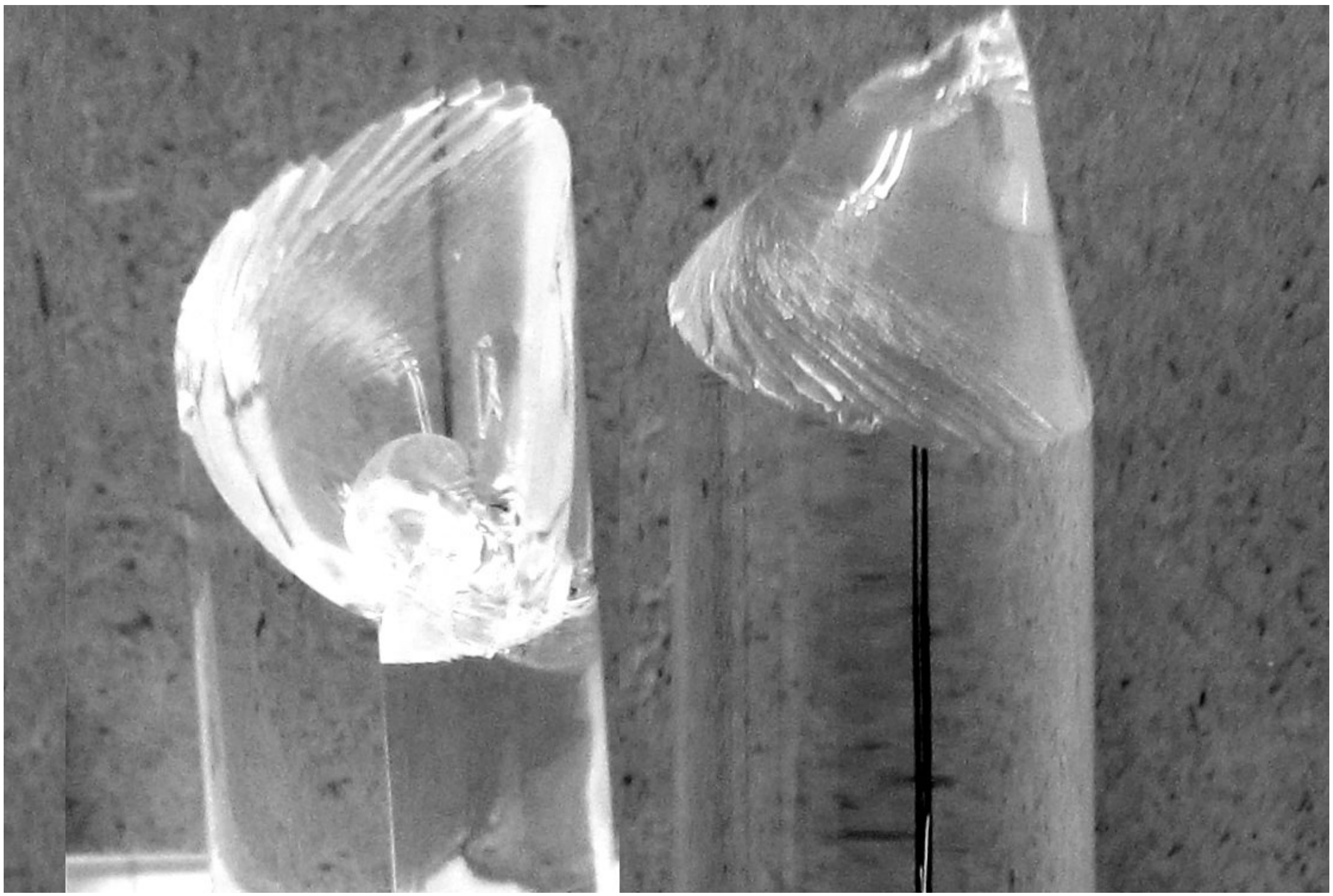
19.05 mm dia samples, cut with utility knife

- Fracture of PMMA is not purely elastic under torsional loading

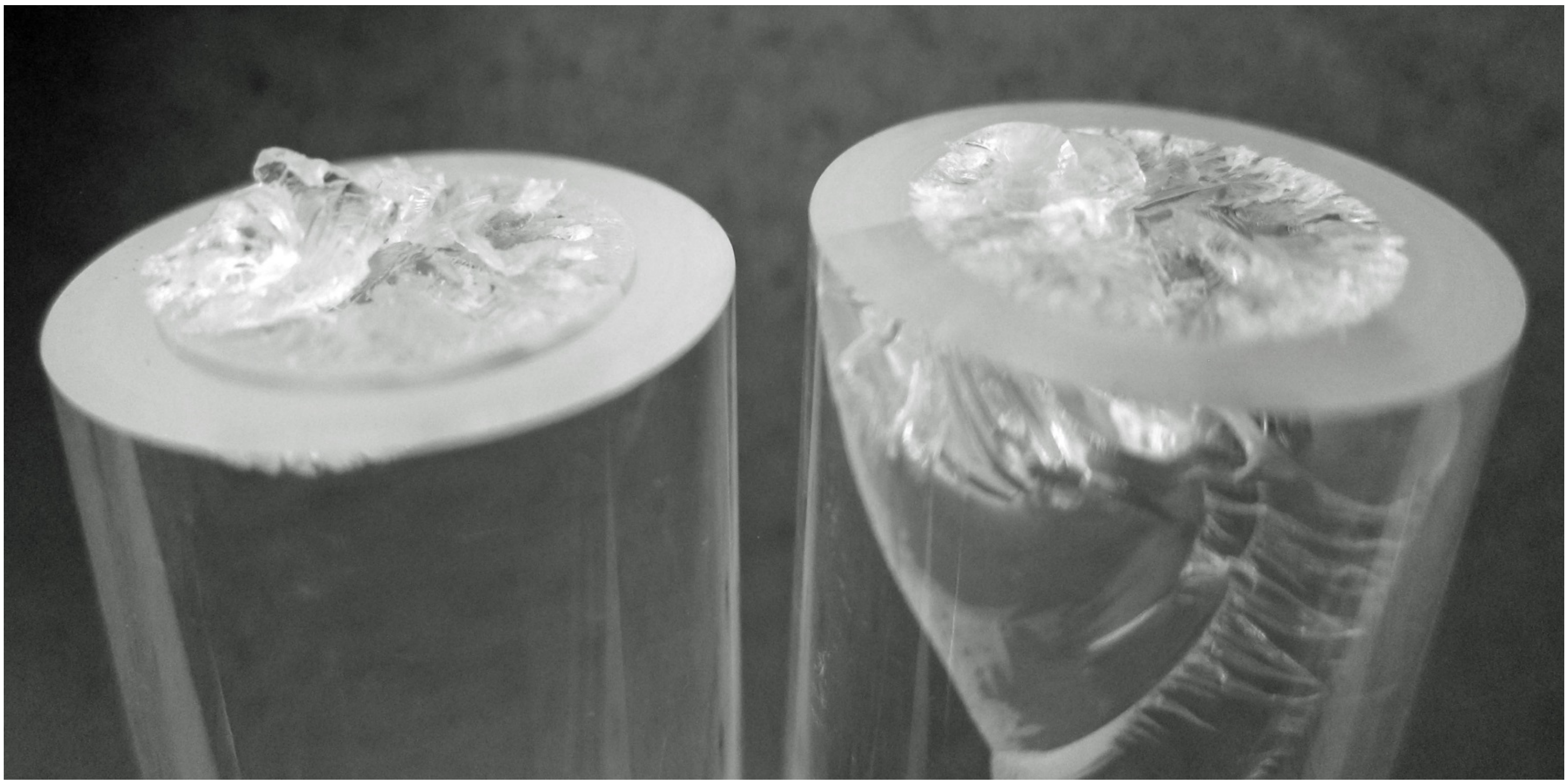
Surface Classification

- We classify surfaces at macro-scale as
  - Spiral
  - Flat
  - Spiral/flat
- Note, that at micro-scale, surfaces are rough and have multiple microcracks

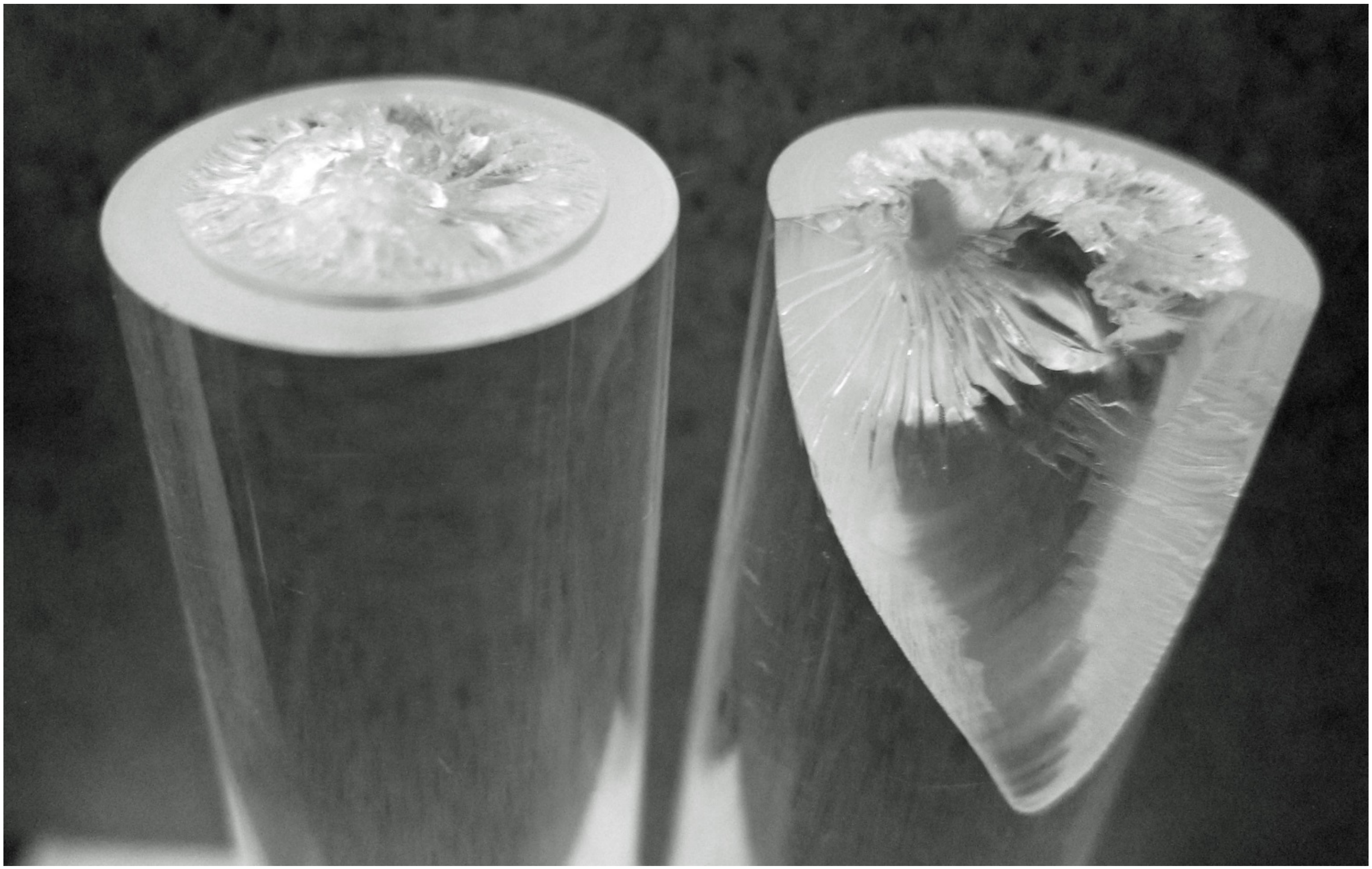
Spiral Fracture Surface



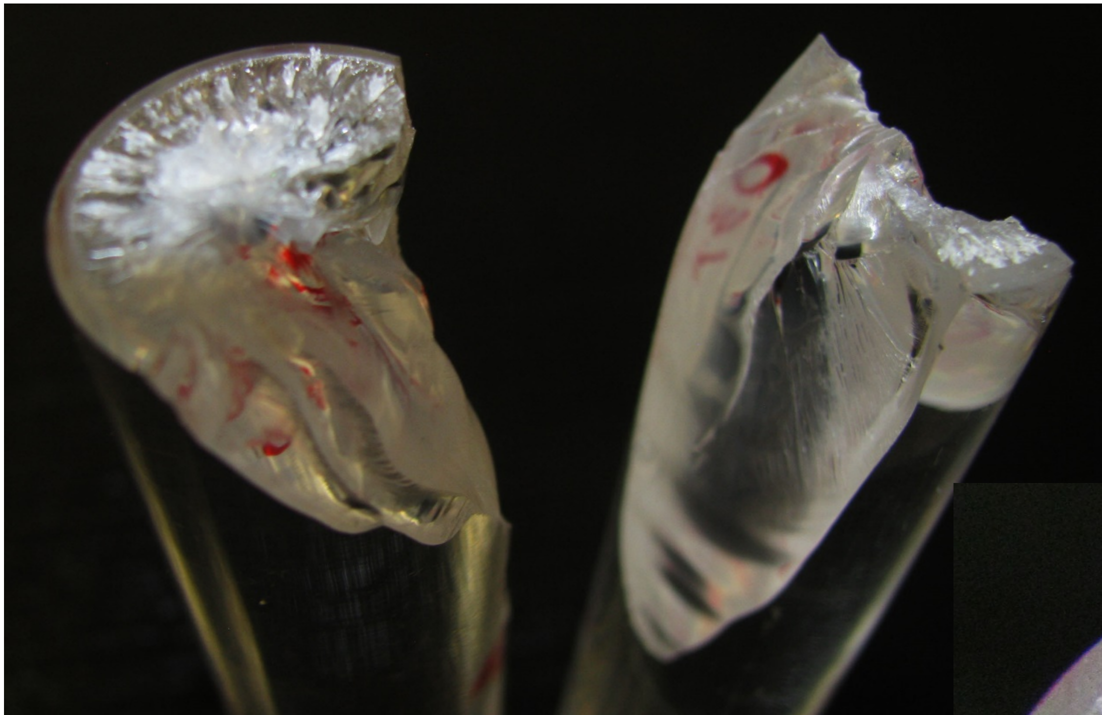
Flat Fracture Surface – notched sample



Spiral/flat Fracture Surface - notched sample

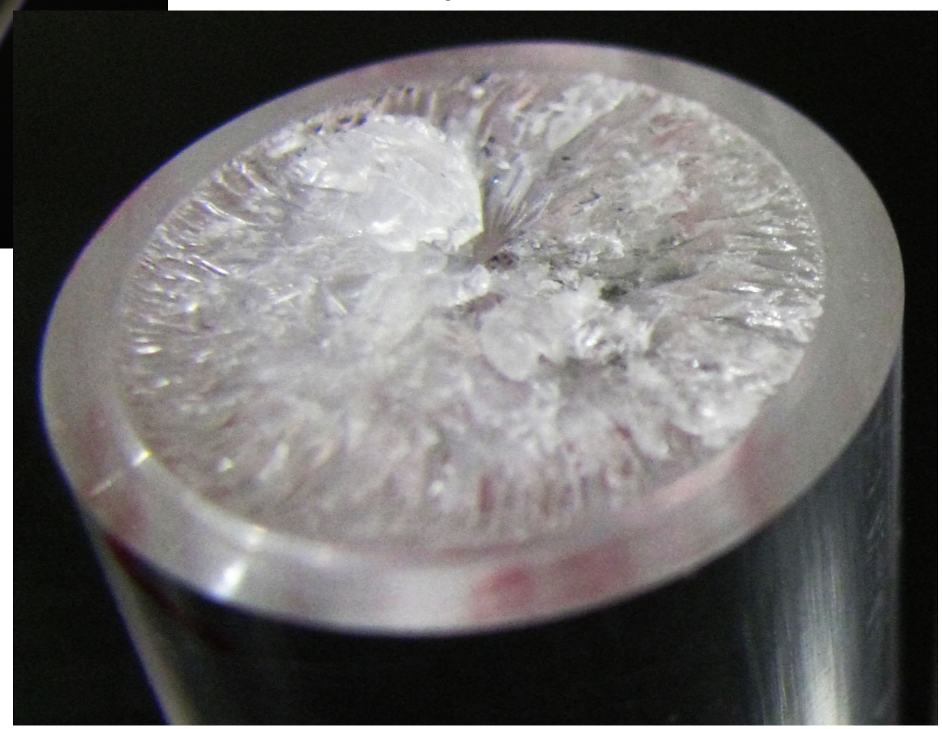


Surfaces of knife cut samples

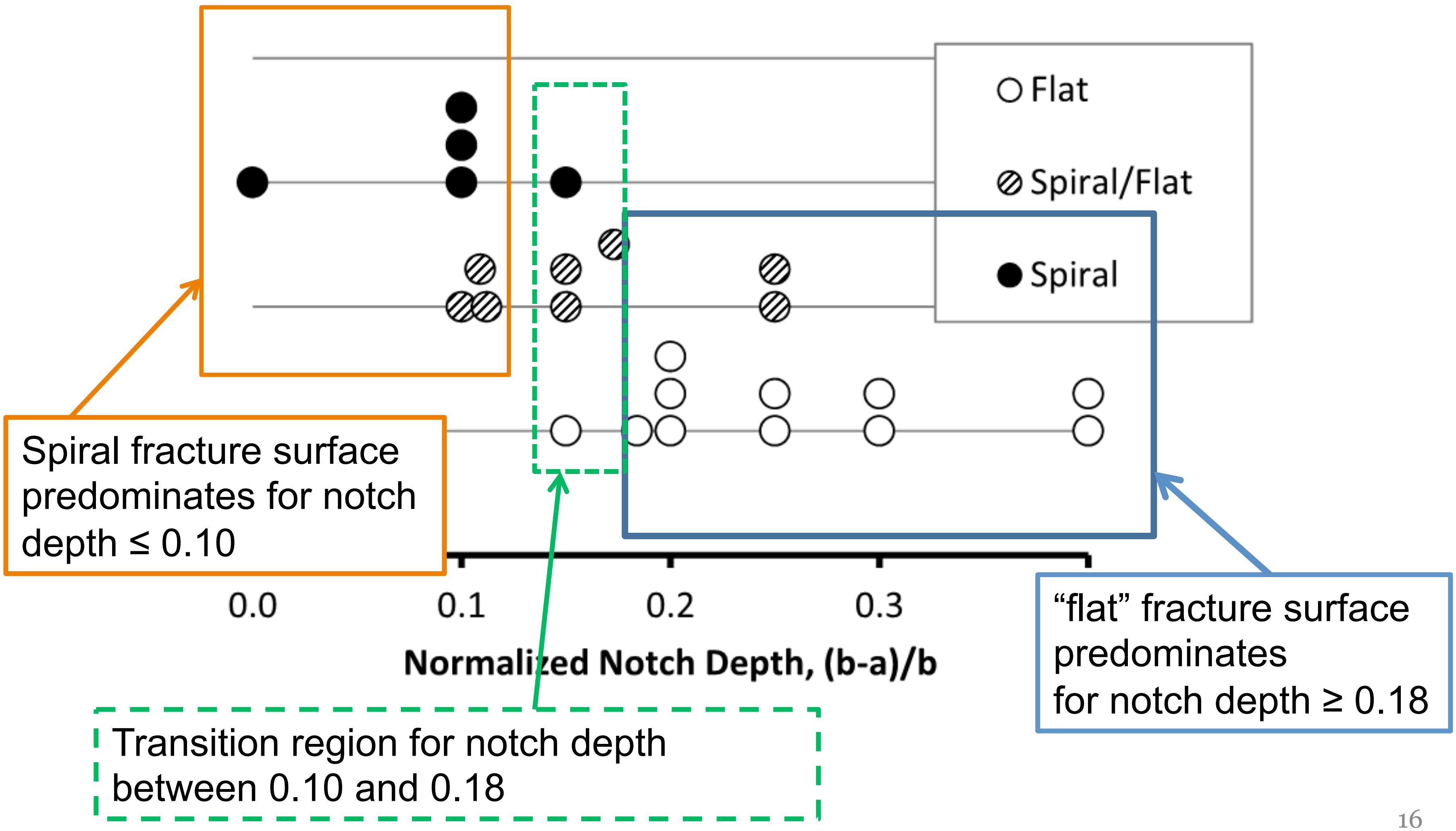


Notch depth/radius = 0.10

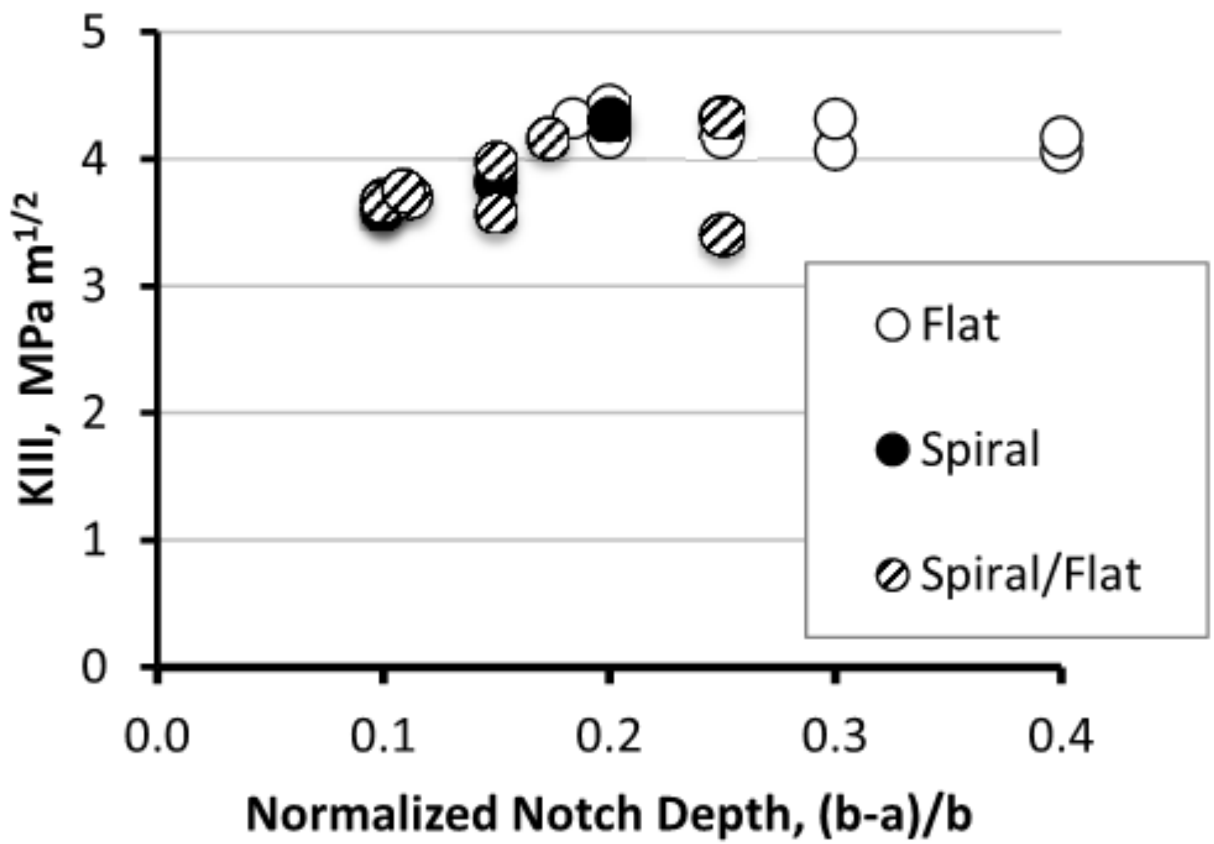
Notch depth/radius = 0.18



Fracture surface depends on notch depth



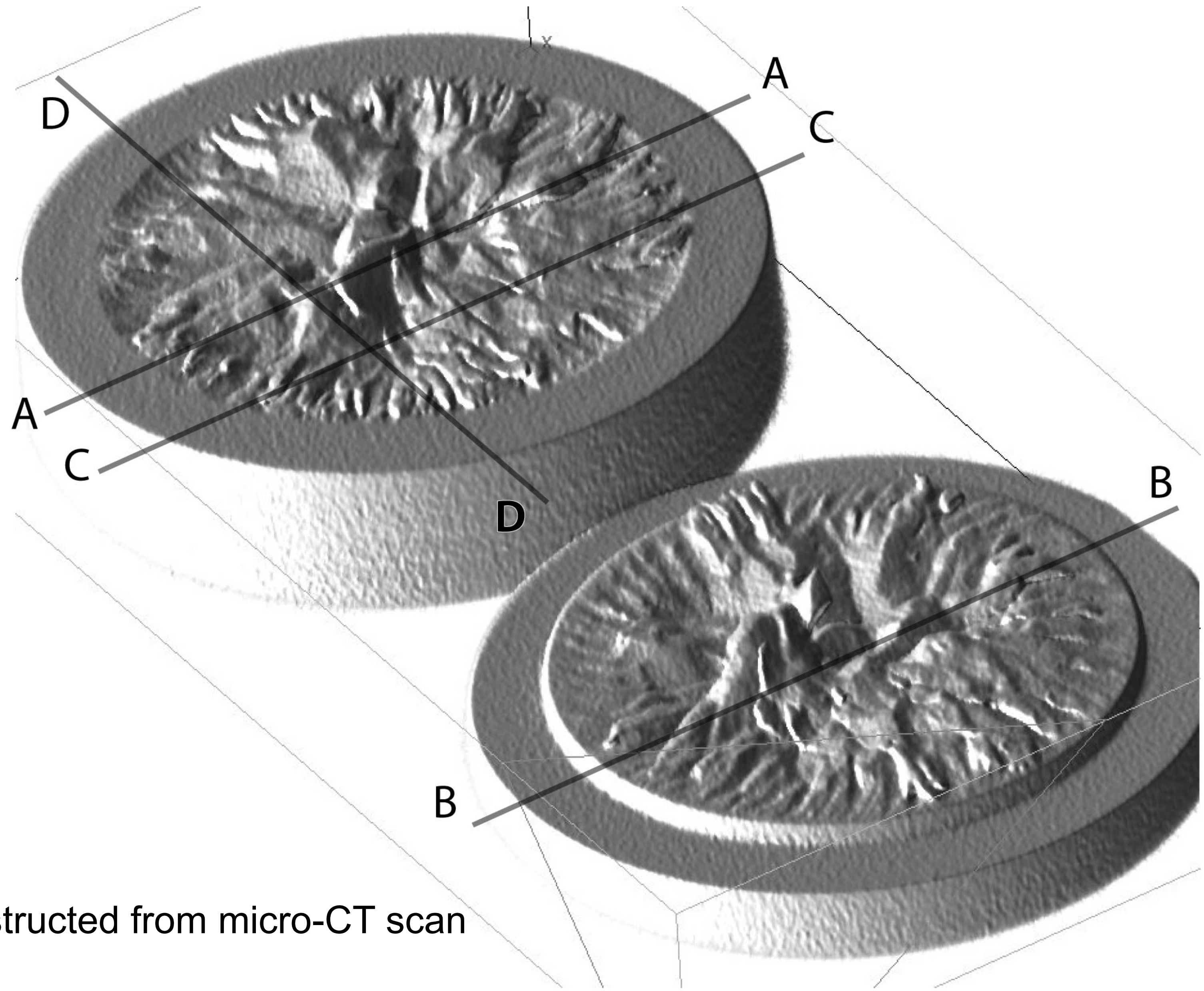
Nominal fracture toughness



Reported values of critical K_{III} :

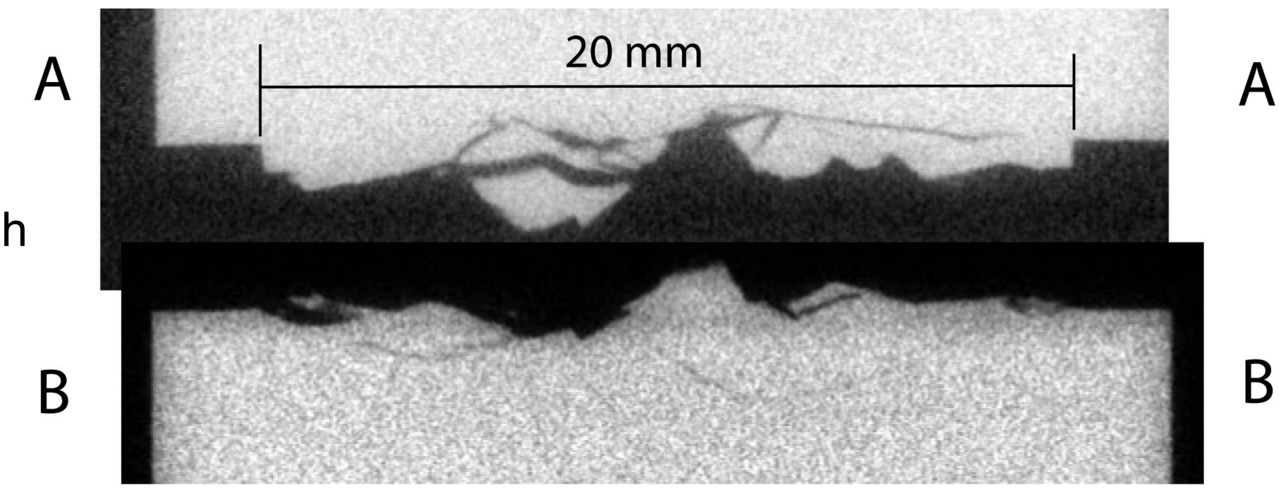
- 1.4 – 1.7 MPa $m^{1/2}$ Liu (1994) fatigue crack,
- 1.5 MPa $m^{1/2}$ Aliha (2015), razor cut crack
- 3.5 MPa $m^{1/2}$ Berto et al. (2013), .025 mm radius diamond wire saw cut

Example “flat” fracture surface

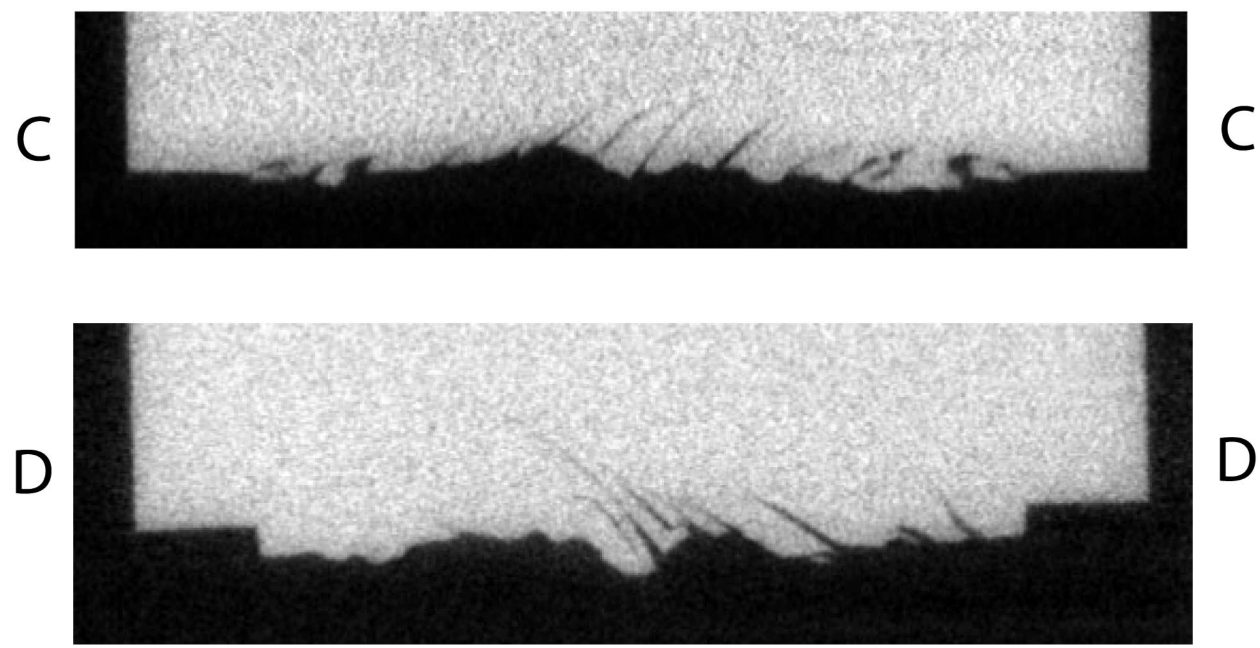


Reconstructed from micro-CT scan

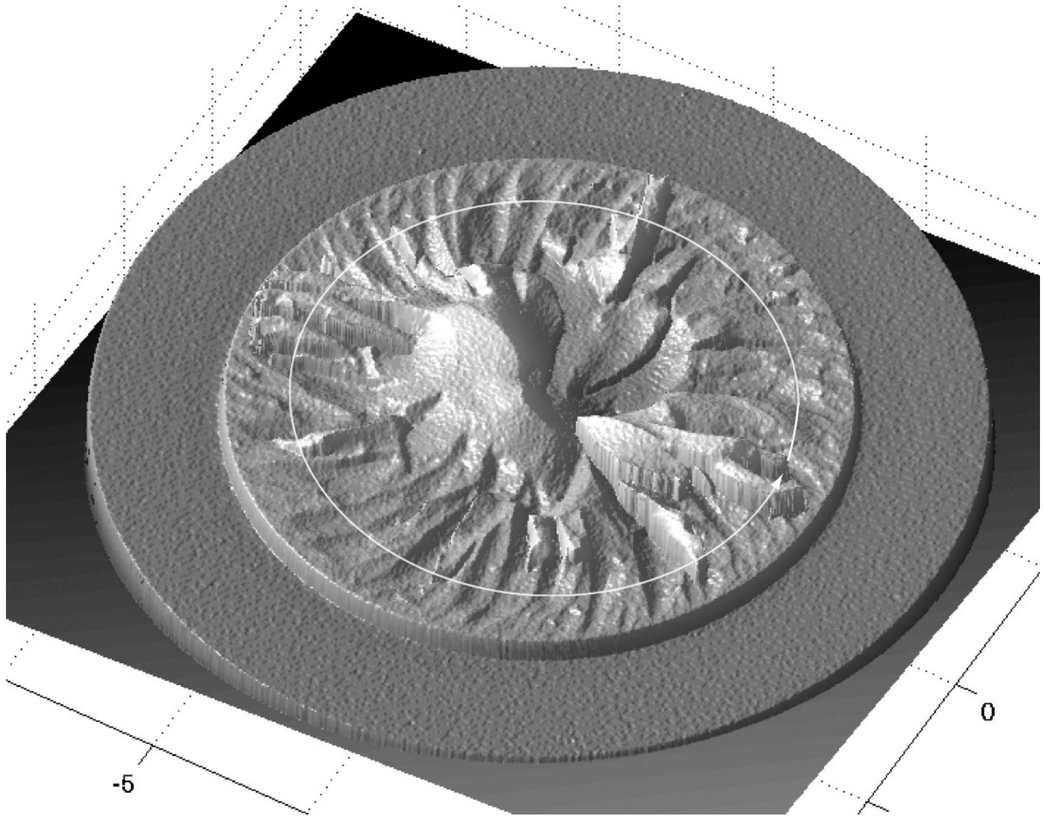
Mating fracture surfaces – cut through center



Cuts at ¼ diameter: Majority of cracks at angles of 30-25 deg.

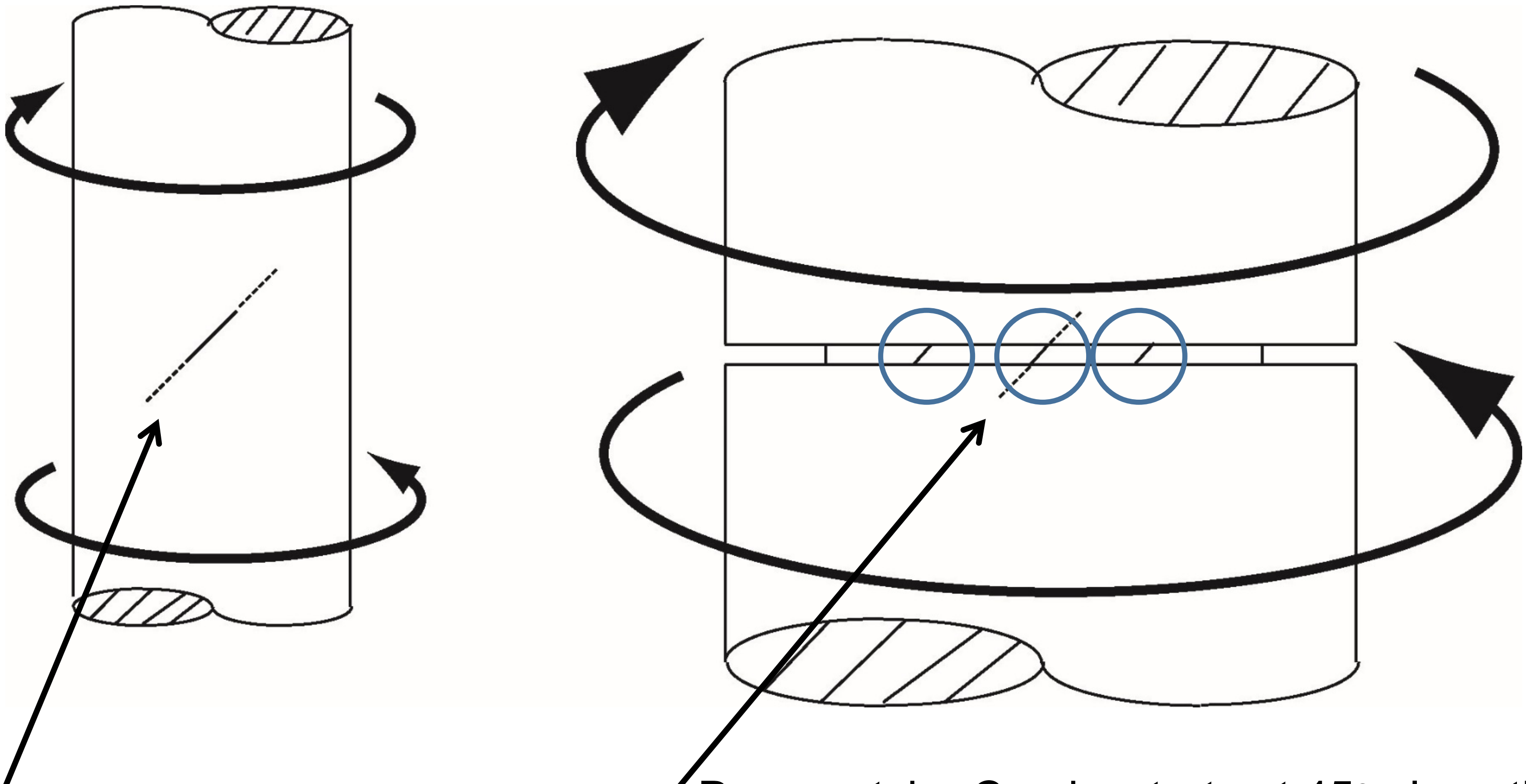


Analysis of fracture surface: on circumferential paths



Typical spacing of facets along initial crack line is .07 mm
On r= 8 mm, rms roughness = 0.22 mm, rms angle = 22 deg
On r = 5 mm, rms roughness = 0.33 mm, rms angle = 33 deg.

Rough ideas on stability of single vs. multiple cracks



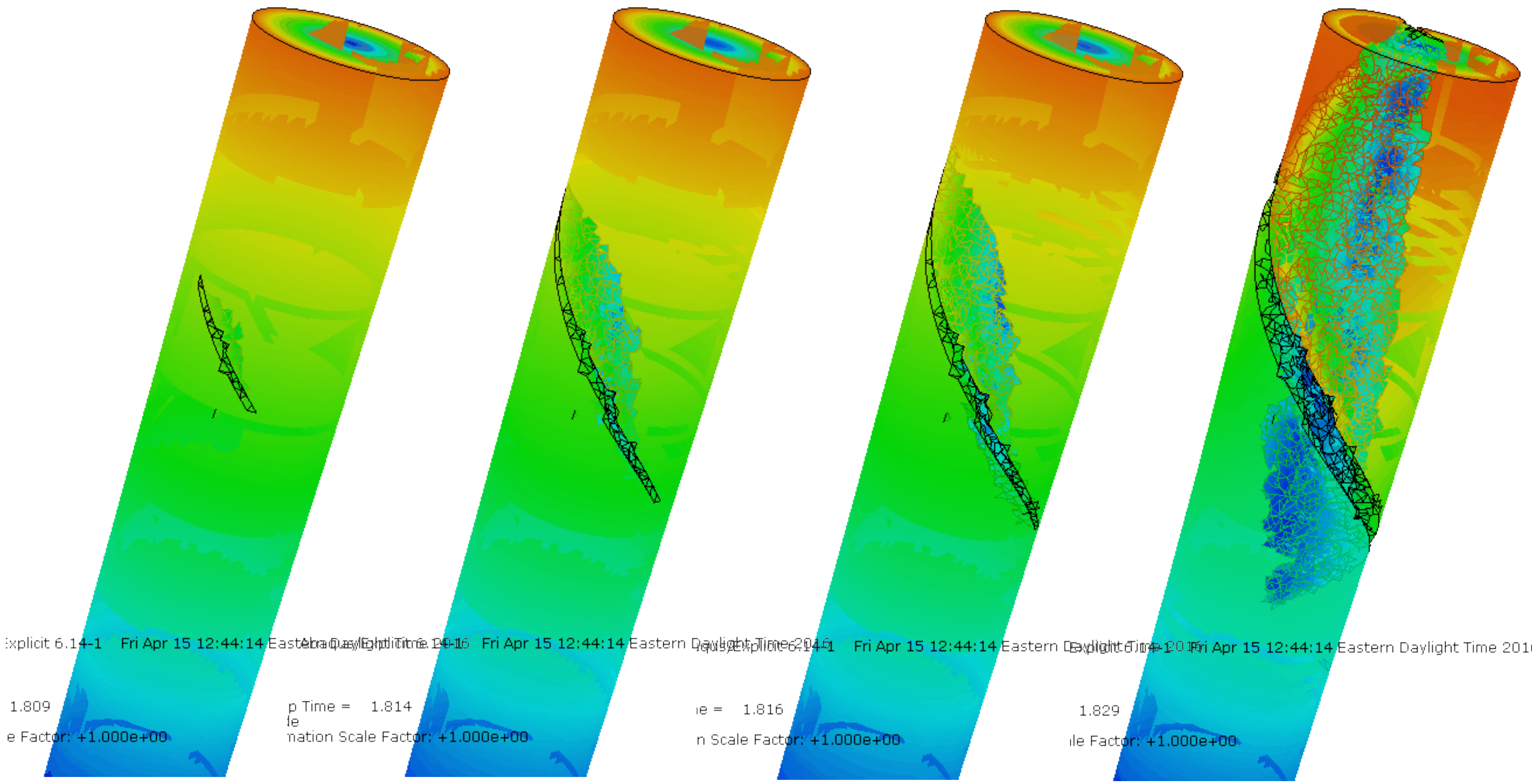
No or shallow notch, crack starts at 45^o grows in vertical direction into uniform stress field. Spiral crack forms

Deep notch. Cracks starts at 45^o along the crack front. If these grow in vertical direction they run into region of larger net diameter and lower stress

FEM Simulations of Crack Initiation and Growth

- Finite element models of notched and un-notched rods in torsion and tension
- Goal is to illustrate crack propagation and determine if transition can be predicted with such a simple model.
- Key model parameters:
  - Sharp crack
  - Rod length = 100 mm, radius = 10 mm, notch depth: [0, 1, 2, 3] mm
  - E=2.95 GPa, ν=0.34, ultimate strength = 80 MPa, toughness, K_{IC} = 1 MPa $m^{1/2}$, (G = 338 J/m^2), ρ = 1152 kg/m^3
  - Linear tet elements, 1.0, 0.5 and 0.25 mm size
  - Quasi-static loading, dynamic crack growth
  - Abaqus brittle cracking model with element deletion. Linear elastic behavior up to failure onset. Linear tension softening, critical displacement is 8.5 μm.
  - Mass scaling used to increase stable time step
  - Rayleigh stiffness and mass damping at about 1% damping ratio

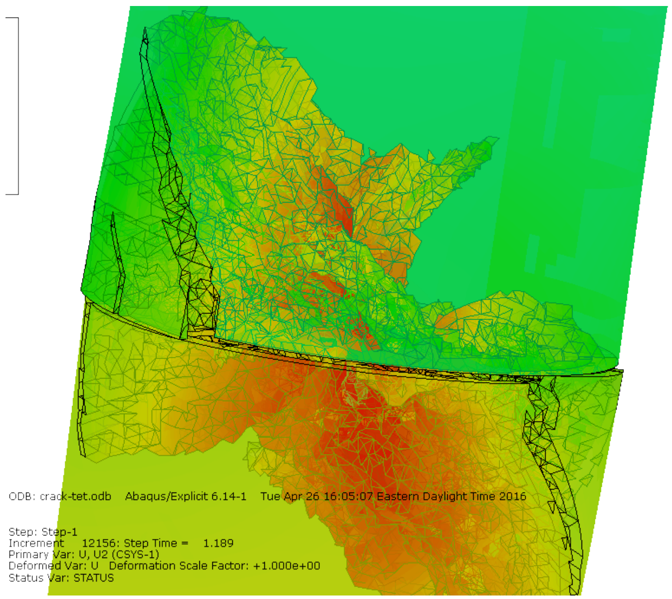
Uncracked rod in torsion



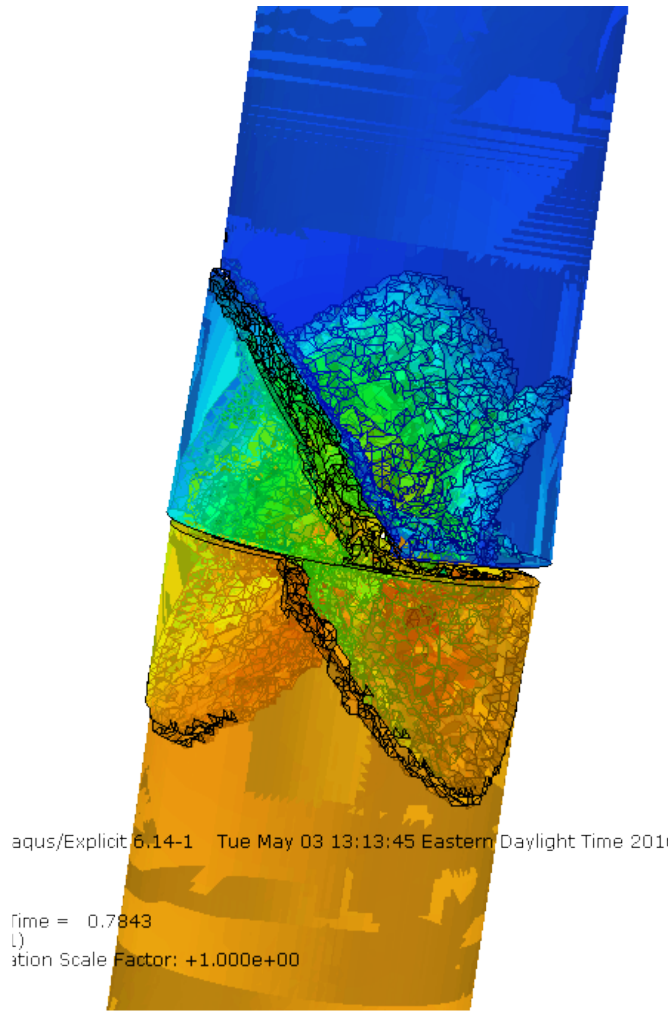
Progression of fracture in 4 time steps.
Color scale is theta displacement

Torsional fracture surfaces for notched rods

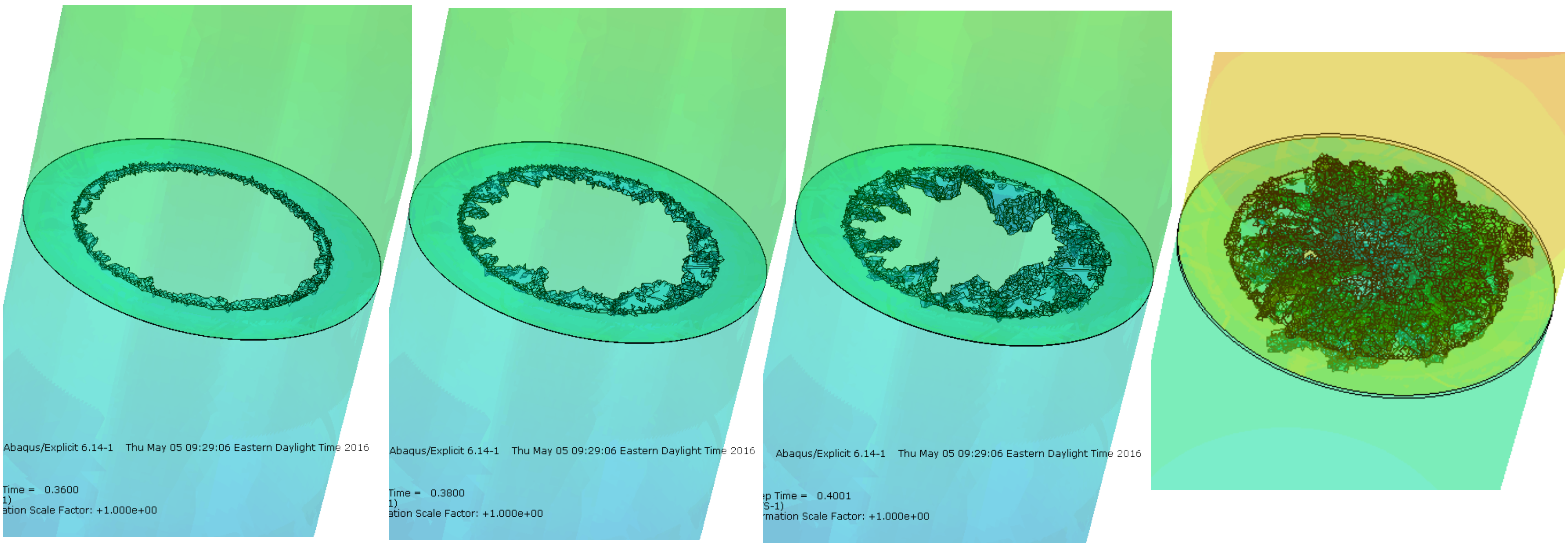
0.1 notch depth/radius



0.2 notch depth/radius

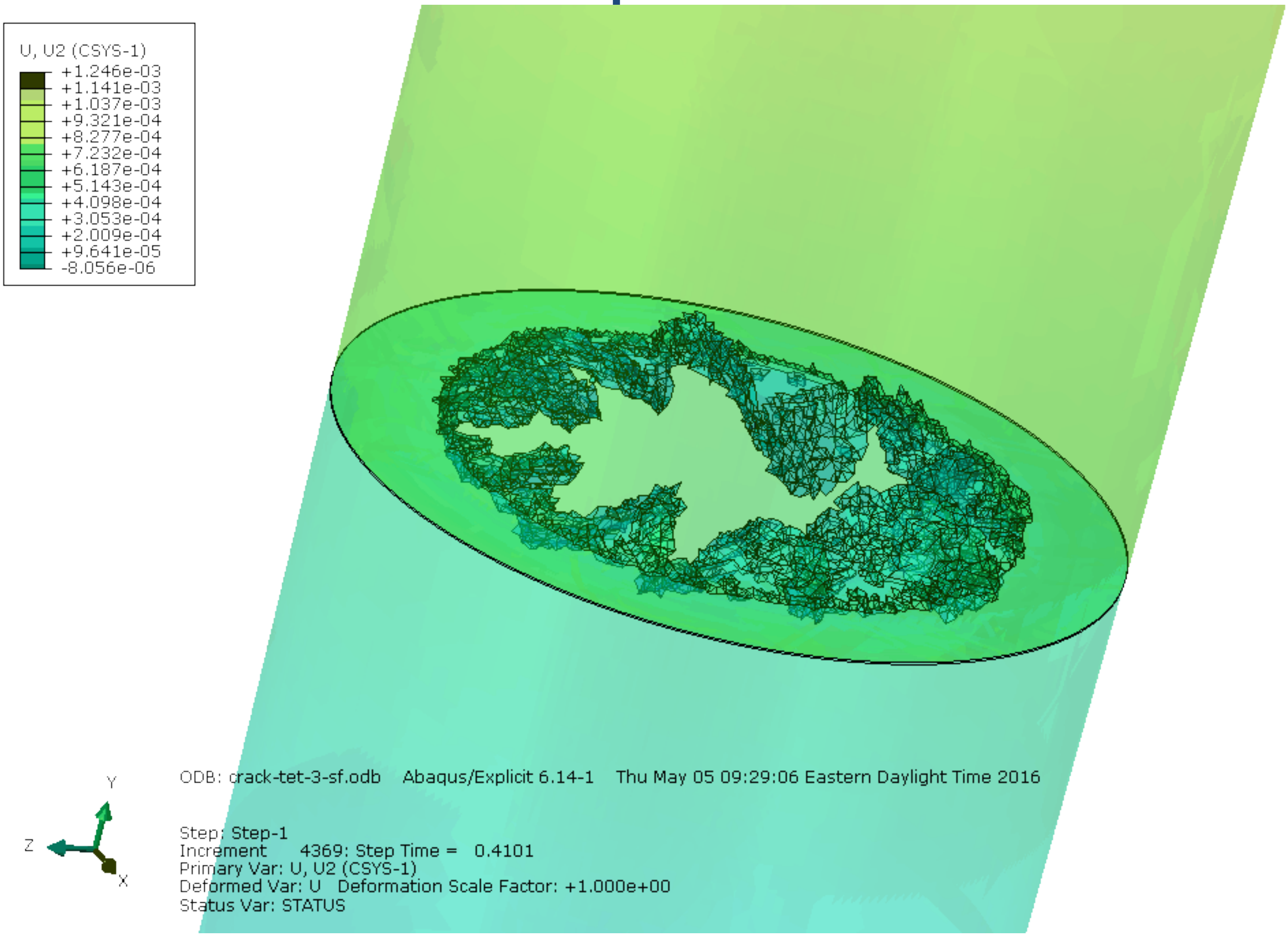


Torsional Fracture Surface: notch depth/radius = 0.3

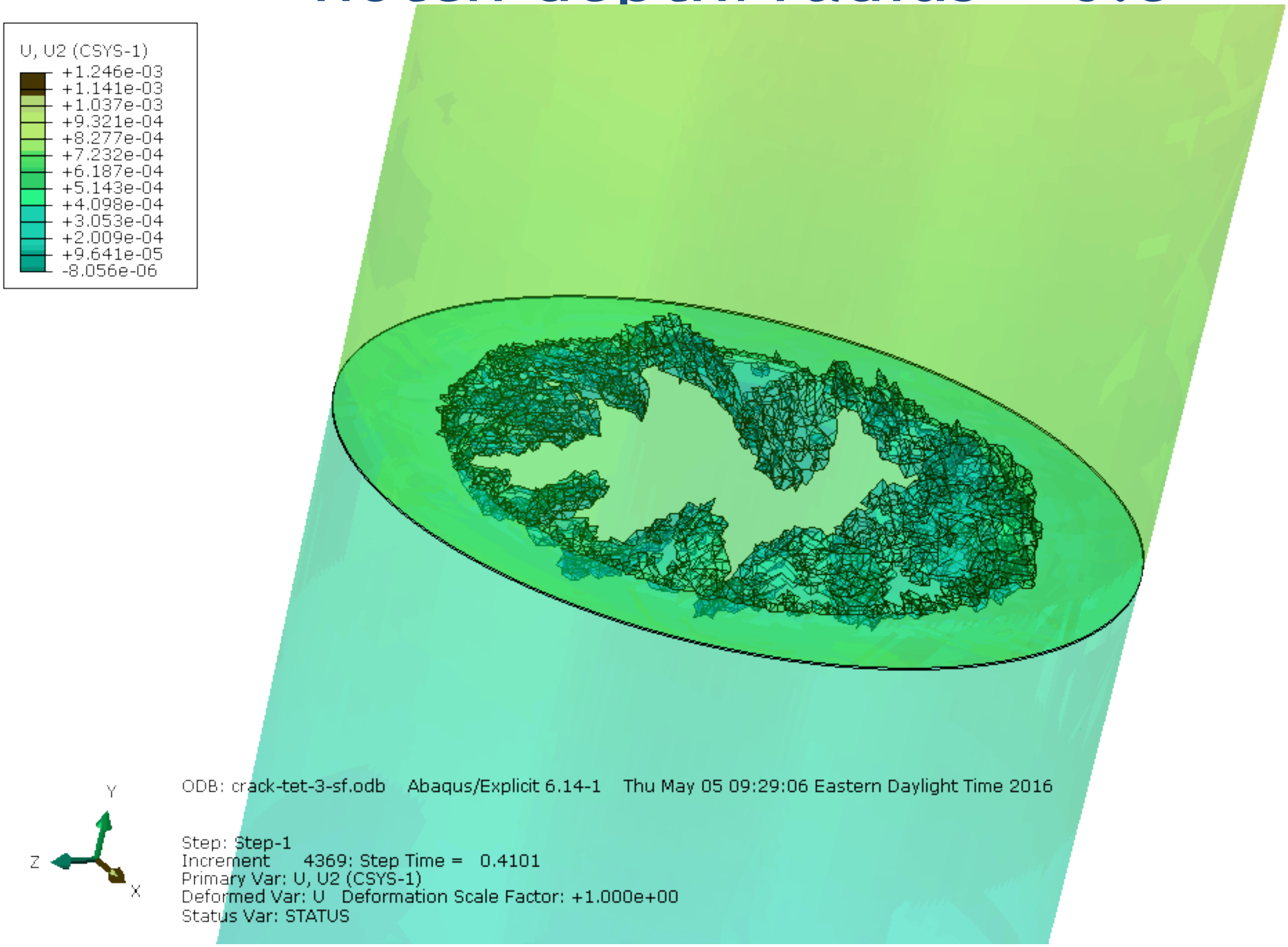


Progression of fracture in 4 time steps.
Color scale is theta displacement

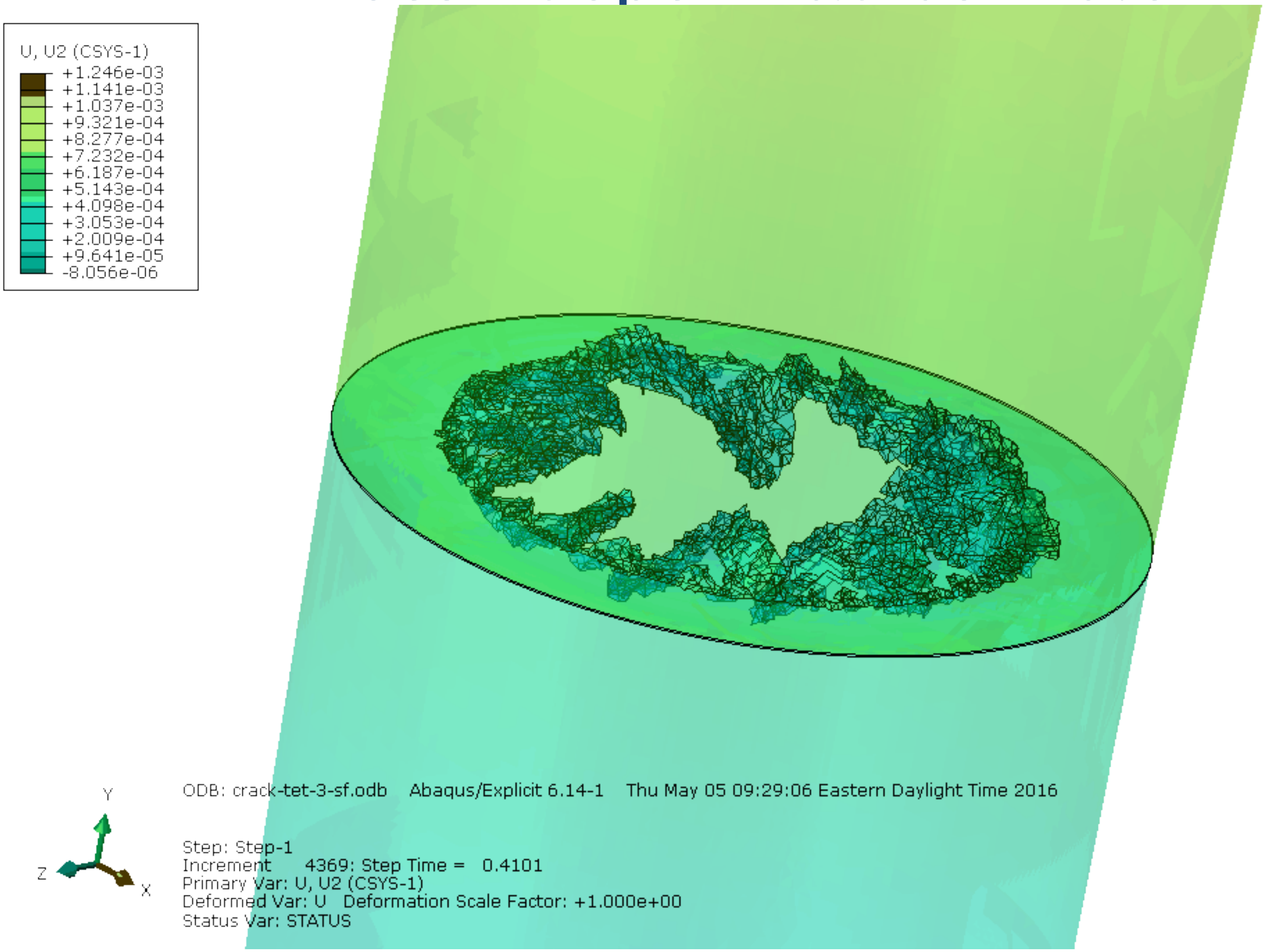
Helicoidal crack surface notch depth/radius = 0.3



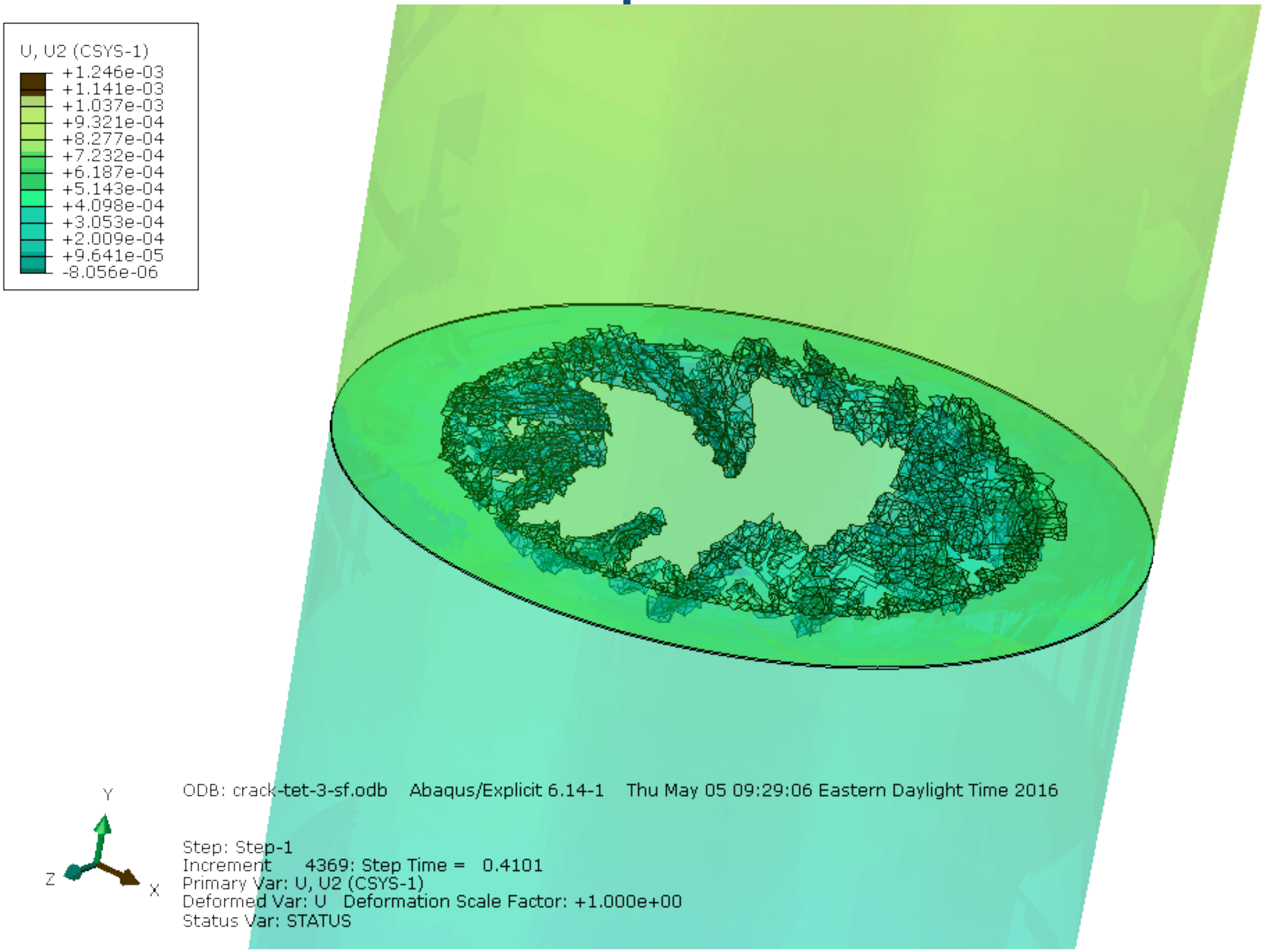
Helicoidal crack surface notch depth/radius = 0.3



Helicoidal crack surface notch depth/radius = 0.3



Helicoidal crack surface notch depth/radius = 0.3



Notes on simulations

- Details of crack patterns are mesh dependent. Overall behavior not.
- In un-notched rod simulations crack speeds are unrealistic – can run above shear wave speed
- Transition from spiral to flat but faceted is evident – but not strongly supported by simulation results
- Actual material behavior is elastic-plastic while model is elastic-brittle
- Models over predict failure load and torque.
  - Input $K_{IC} = 1.0$ MPa $m^{1/2}$
  - Models fail with $K_I \approx 2.1$ MPa $m^{1/2}$ and $K_{III} \approx 2.2\text{-}2.5$ MPa $m^{1/2}$

Summary and Questions

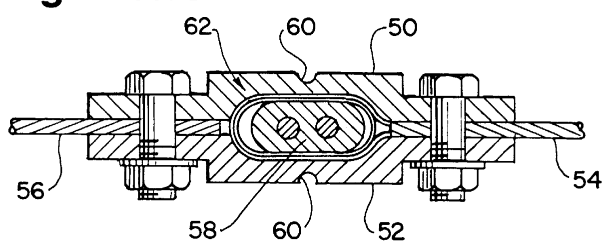
- Under torsion loading, as notch depth increases to about 0.18 of radius, fracture surface transitions
  - from spiral or spiral/flat
  - to macroscale flat "factory roof" surface
  - Facet angles are less than 45^{o} .
- Is transition sensitive
  - to notch sharpness?
  - to brittleness of material?
- What are the conditions that govern the stability of the fracture surface ?
- What computational approaches could predict the transitions and capture sufficient detail of the fracture?
- Note: PMMA used here (and in many other studies) as a "model" brittle material – but it does have plastic deformation prior to fracture


Questions ?

Some general comments

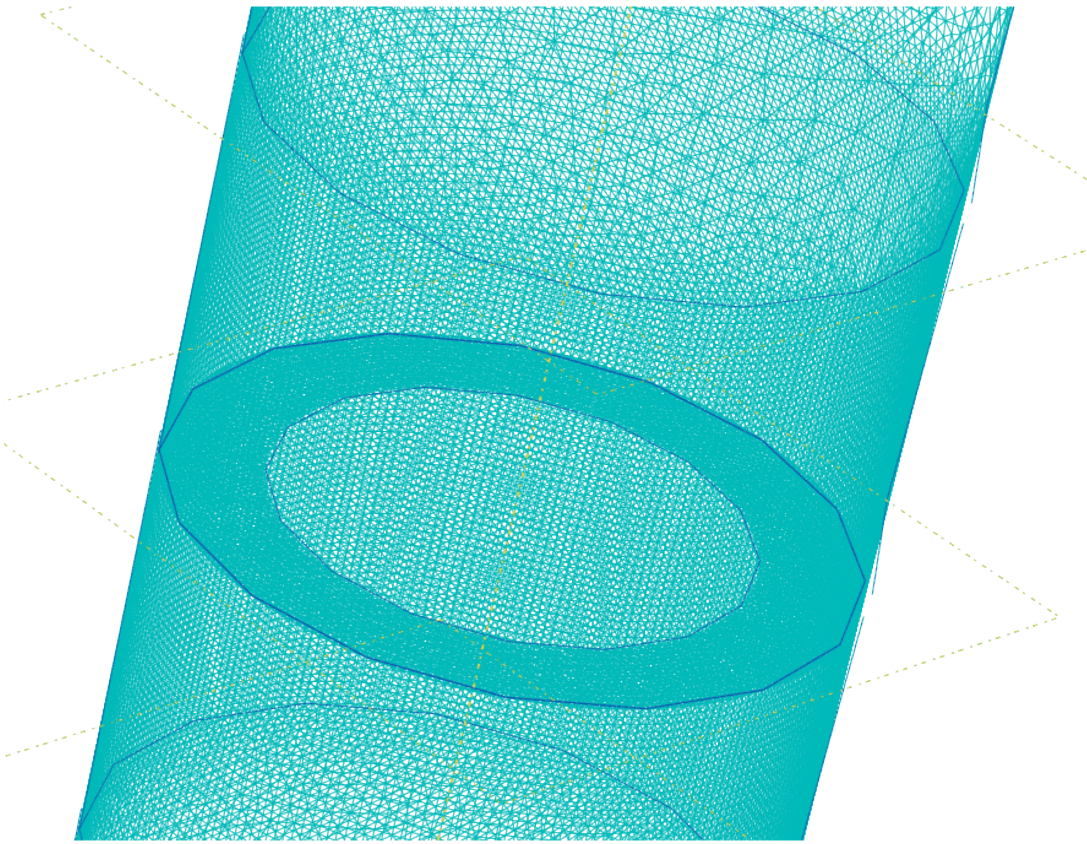
- Fracture is among the hardest problems in mechanics
  - Materials are taken to their limits
  - You don't know the geometry ahead of time
  - Fracture is dynamic
  - Inherently multi-scale in the sense that failure involves separation of atoms but the application is to a structure
- It matters
  - An example is frangible joints used for rocket stage separation. They must break – not early – not late – but when needed
  - Getting the failure load right matters and getting the crack path right matters – does the joint generate fragments that might cause damage?

Fig. 3 PRIOR ART

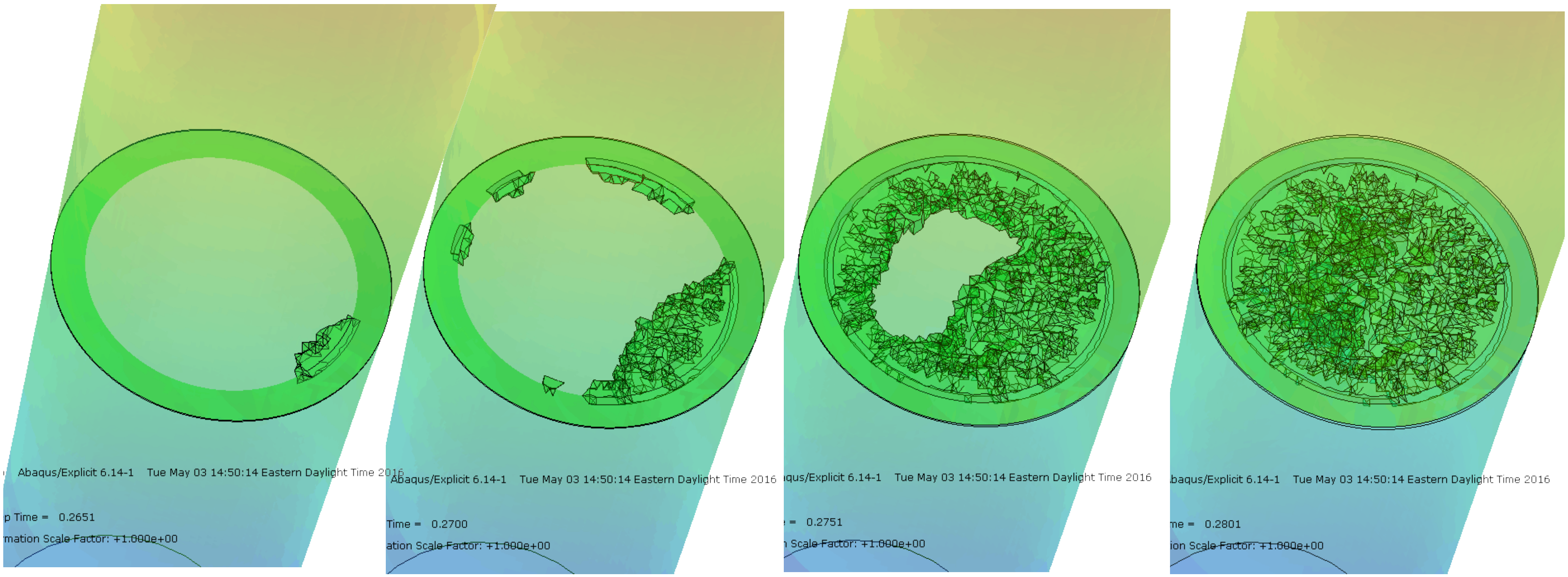


Typical model: crack depth/radius =0.3

Mesh near crack surface

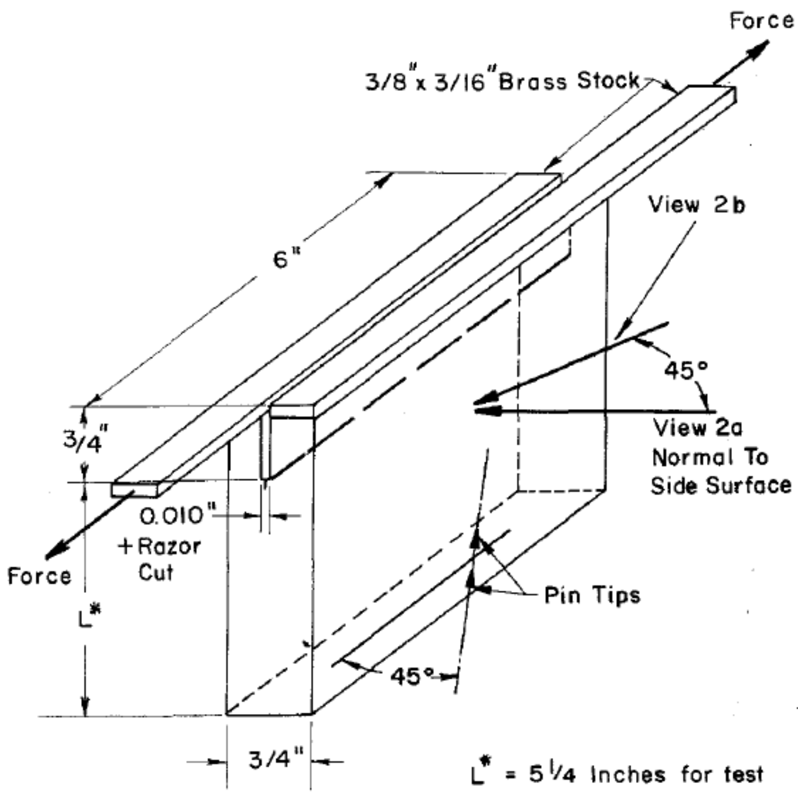


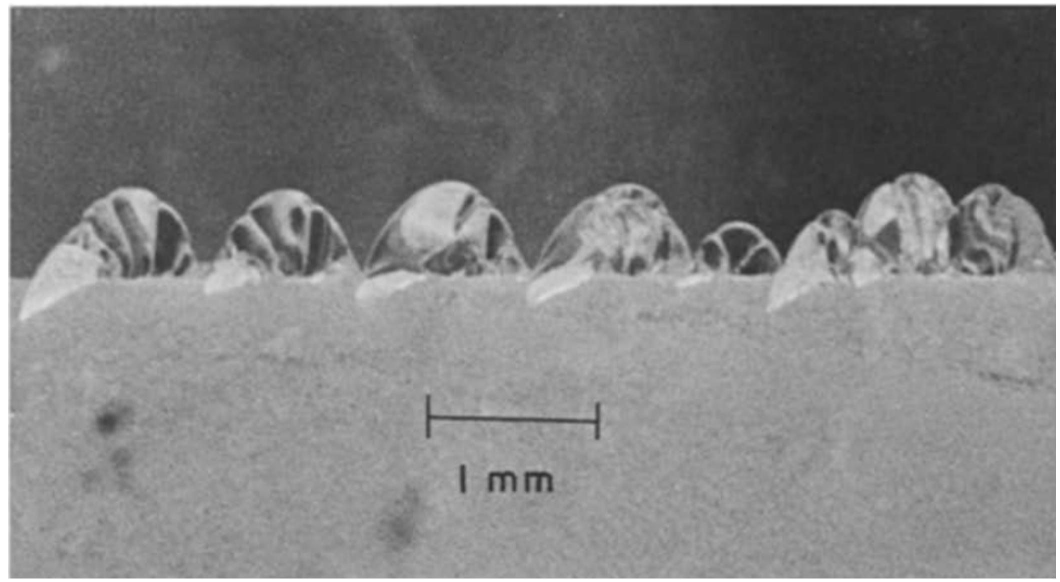
Cracked rod in tension fails along flat surface



Progression of fracture in 4 consecutive time steps.
Color scale is axial displacement

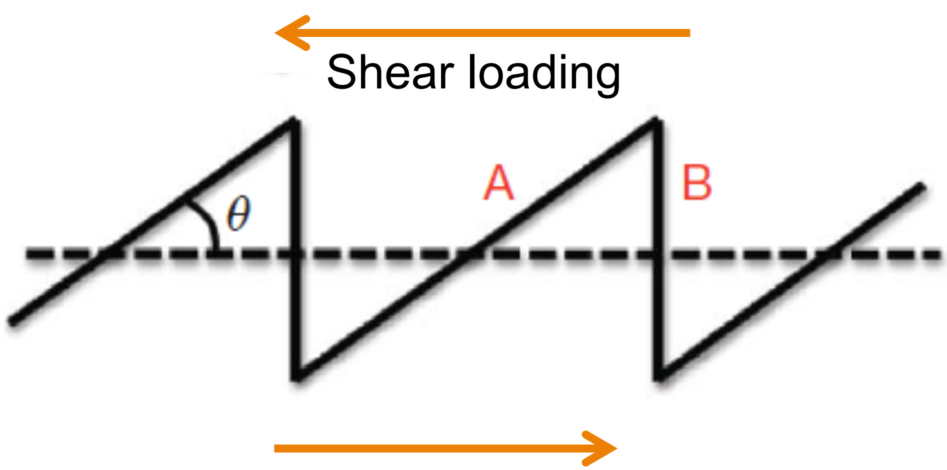
Under Mode III fracture starts with microcracks at 45° to crack front



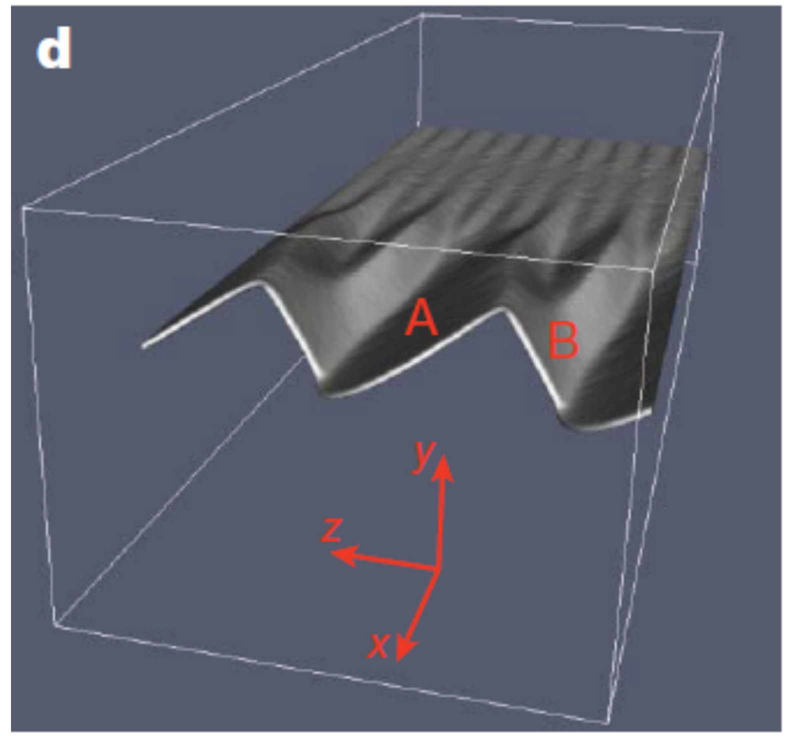


W.G. Knauss, "An observation of crack propagation in anti-plane shear," **IJF 6**, 1970.

45° microcracks link to form "Factory Roof" surface



View looking orthogonal to crack front



Pons and Karma, "Helical crack front instability in mixed-mode fracture," **Nature, 464**, March 2010.