# FAILURE of Nd:$YVO_4$ AMPLIFIER CRYSTALS

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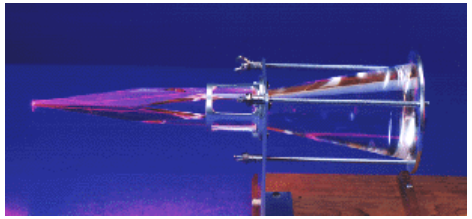
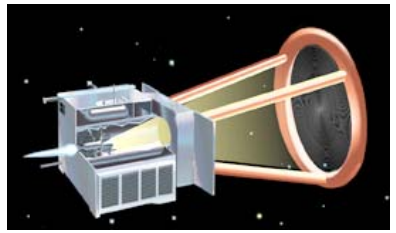
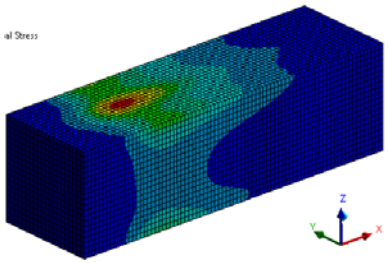
Fractography of Advanced Ceramics VI
September 9th, 2019
Smolenice, Slovakia

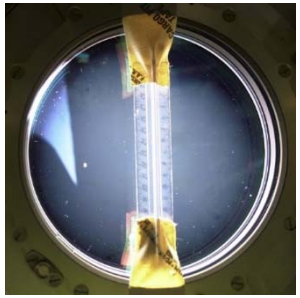
# Ceramics are used in Many NASA Applications

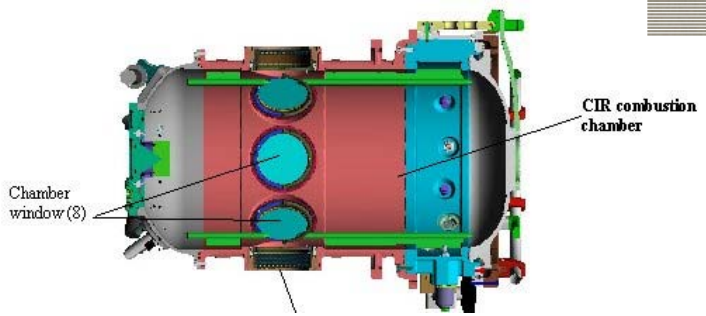
- Solar concentrators
- Specialty windows
- Lenses
- Spectrometer components
- Low expansion mounting plates
- Laser amplifiers







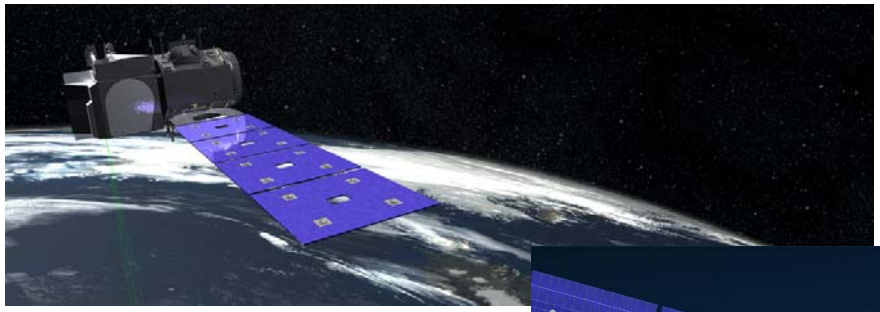


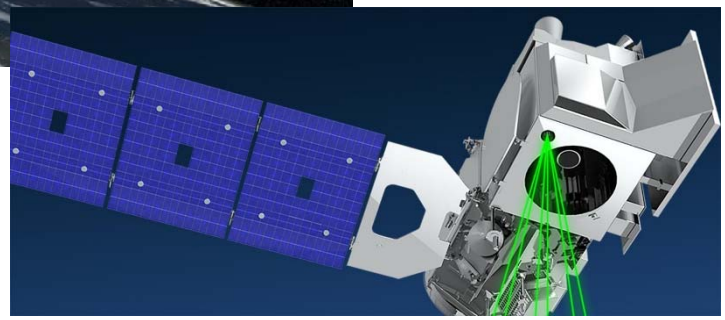


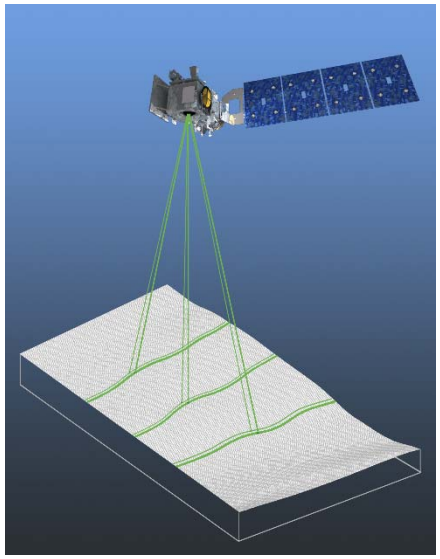
# ICESat-2

*Ice, Cloud, and Land Elevation Satellite*

- The four ICESat-2 science objectives are
  - Measure melting of ice sheets and sea level rise
  - Measure changes in the mass of ice sheets and glaciers
  - Estimate and study sea ice thickness
  - Measure the height of vegetation in forests worldwide





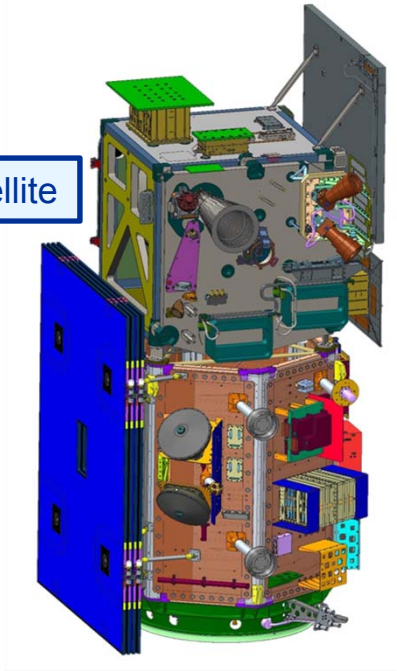


# ICESat-2

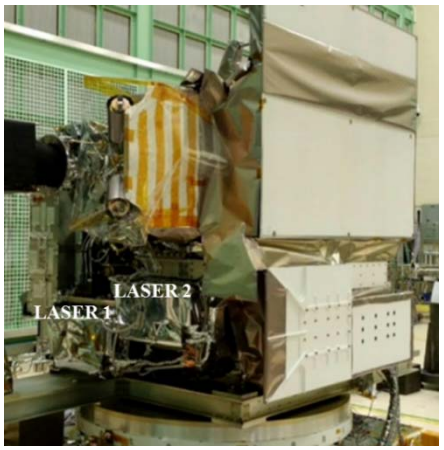
*Ice, Cloud, and Land Elevation Satellite*

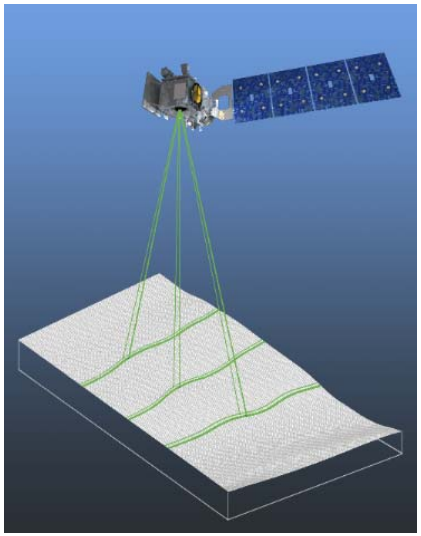
- ICESat-2 carries a single instrument – the Advanced Topographic Laser Altimeter System (ATLAS):
  - ATLAS measures the travel times of lasers pulses to calculate the distance between the spacecraft and Earth's surface.

ICSat-2 Satellite



ATLAS Instrument

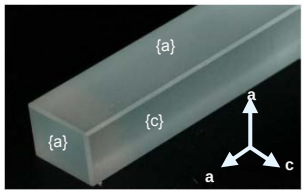


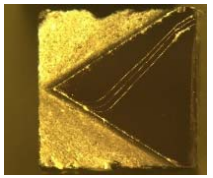
# Within the System are Nd:$YVO_4$ Crystals

- The $YVO_4$ single crystals are laser “slabs”
- Elastic modulus = 220 GPa <a> axis
- Fracture toughness = 0.48 MPa√m
- Fracture strength = 46 MPa (~7 ksi)
- Slow crack growth n = 17

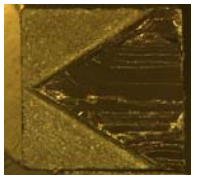
➢ Very brittle!!

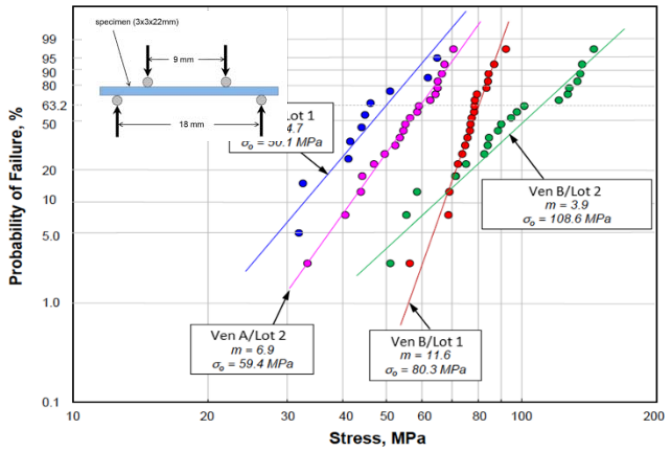



Air, a-a



Air, a-c





# Surfaces of the Crystals

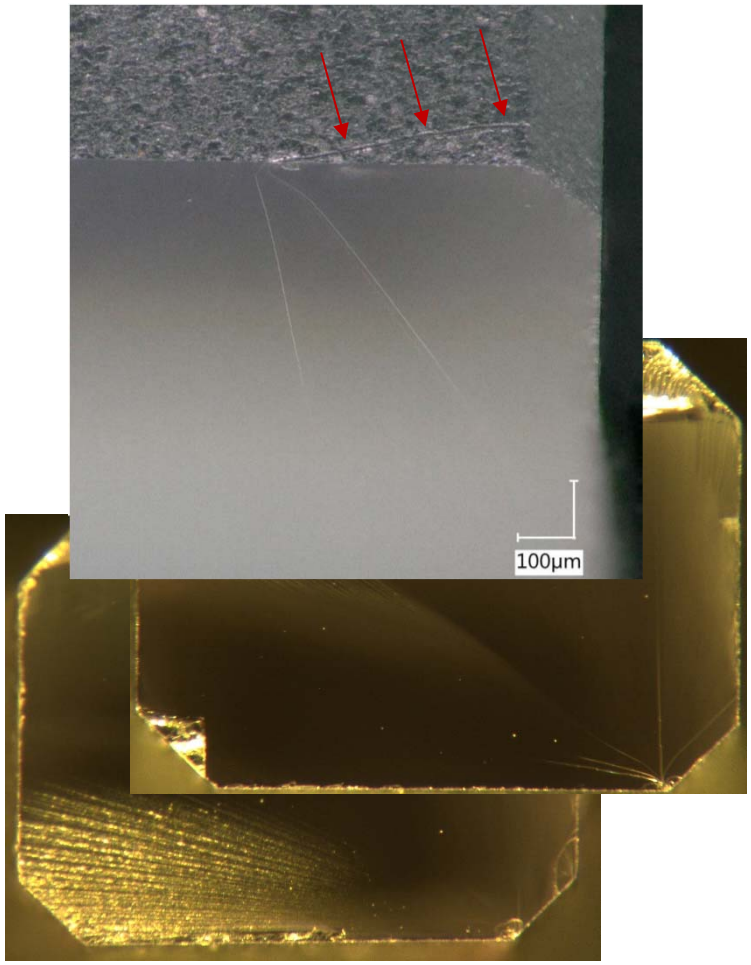
- Diamond ground, with surfaces that tend to be damaged (chips, scratches, etc.):




➢ One would expect surface failure.

# Failure of the Crystals

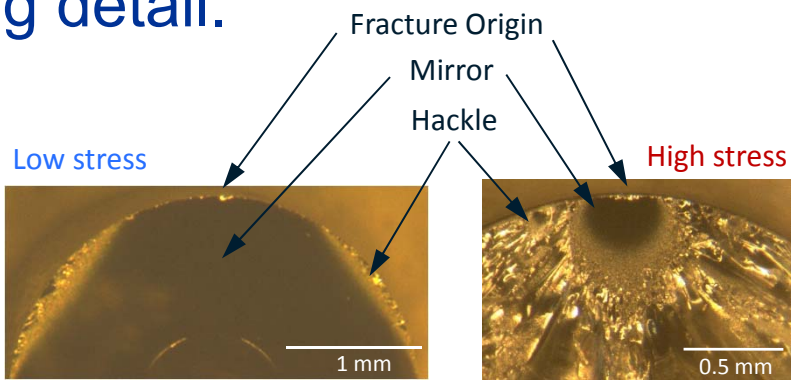
- Indeed, strength test specimens fail from surface flaws:





# Failed Crystals in Hardware

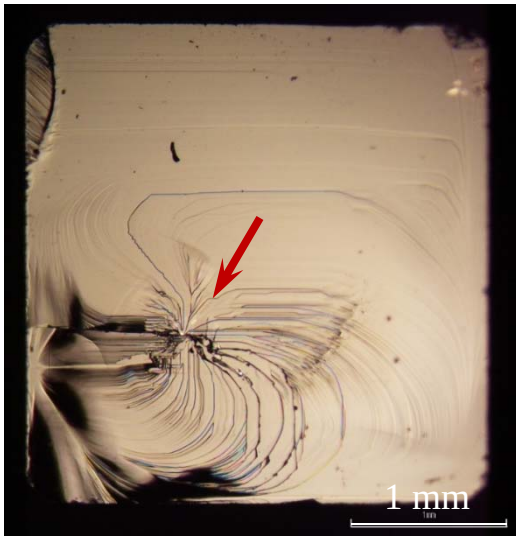
- Four failures are of particular interest:
  - Two that failed unexpectedly in flight hardware; these brought me into the project.
  - Two failed during bench testing while attempting to understand the prior failures; these created confusion about the nature of failure. These exhibited interesting patterns.
- I'll discuss these in varying detail.
  - ➢ Classic features to seek:

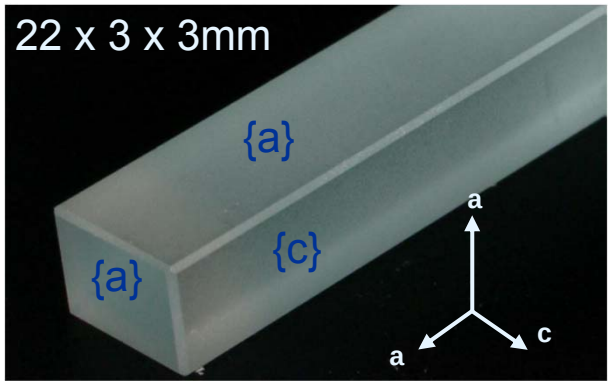


# First Pump-to-Failure Amplifier Crystal

*- Failed During Bench Testing -*

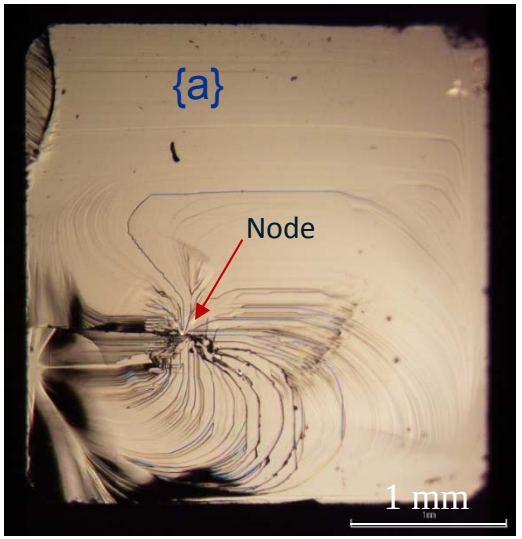
- During routine bench testing of a laser amplifier slab, the control loop was lost and the crystal over-pumped until fracture occurred.
- Disassembly revealed a fracture near one end, with the location of fracture thought to be near the center.



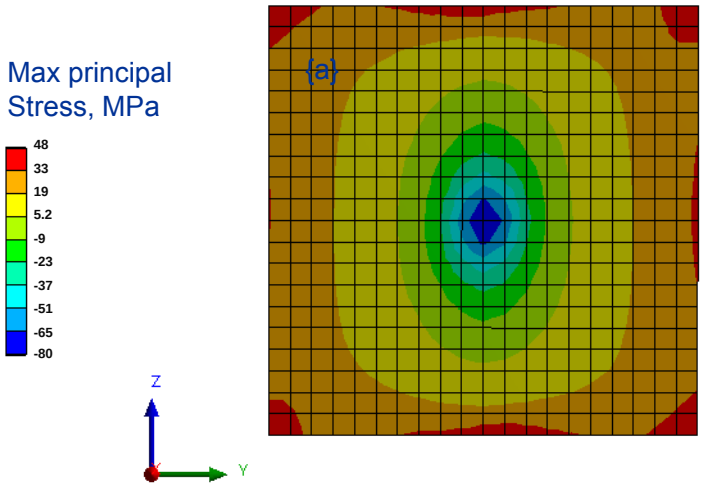
# Over-pumped Crystal:

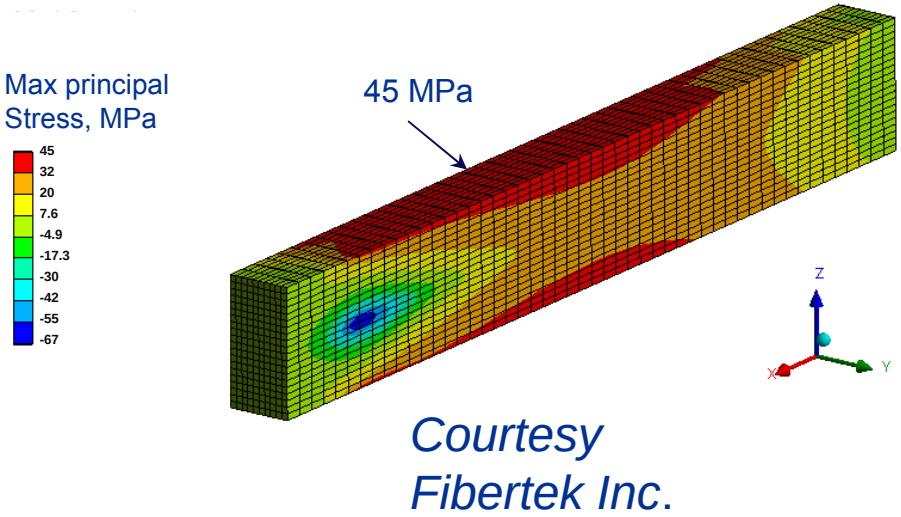

- Pronounced swirl at a central “node:”
- Failure located on the {a} crystal plane without macroscopic rotation from the {a} plane.
- Some felt that failure occurred from the center “node”…..



# Stress State at High Power

- X-axis, <a>, principal stresses:



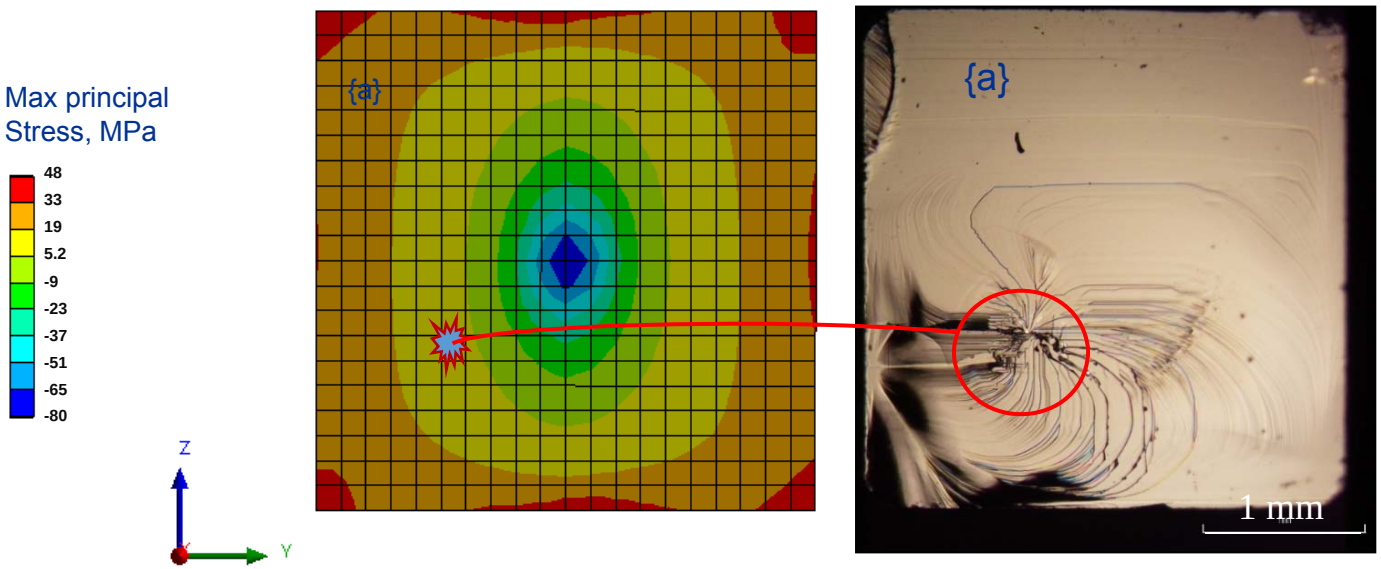




*Courtesy Fibertek Inc.*

- Center compression with edge tension, where the worst flaws are often located.
- Compressive strength is >> tensile strength.

# Location of Speculated Origin

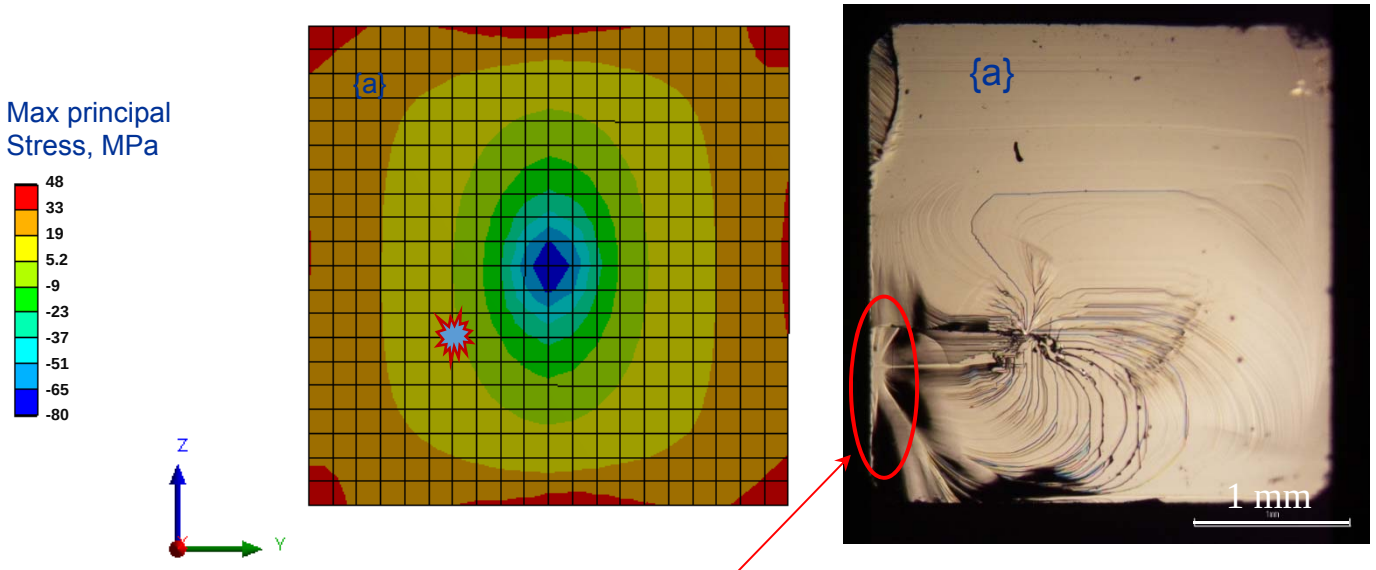
- Speculated origin is on the border of compression and tension, with low tensile stresses (~5 MPa):




- Could the origin be elsewhere? The surface?

# Other Fracture Features

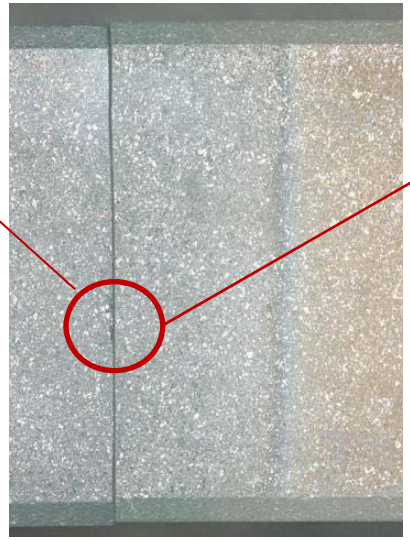
- Let's consider surfaces where stresses and damage are high:

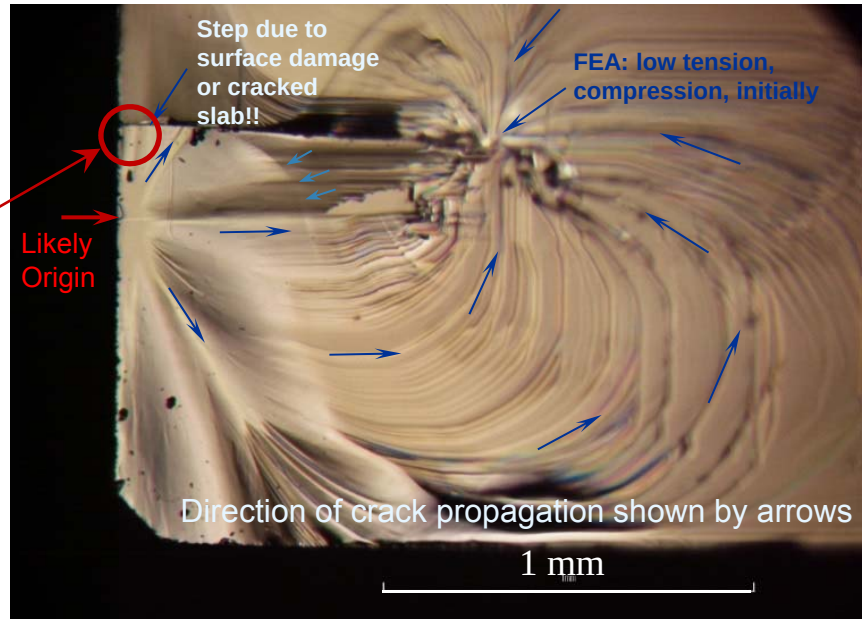



- At the surface a star-like feature is apparent – single crystal mirror?

# Surface Damage and Classic Mirror

Surface damage or post fracture edge chipping

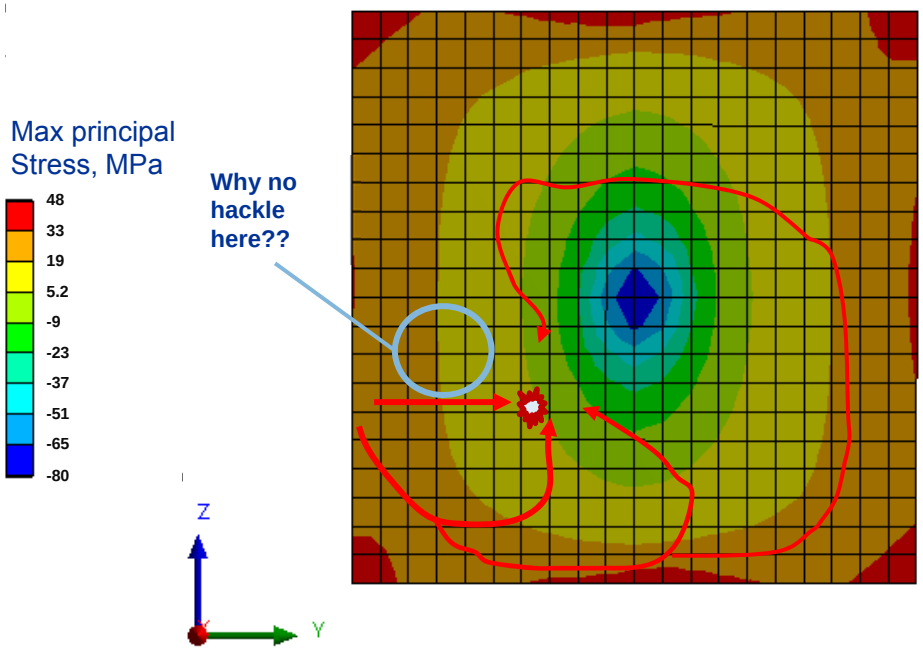


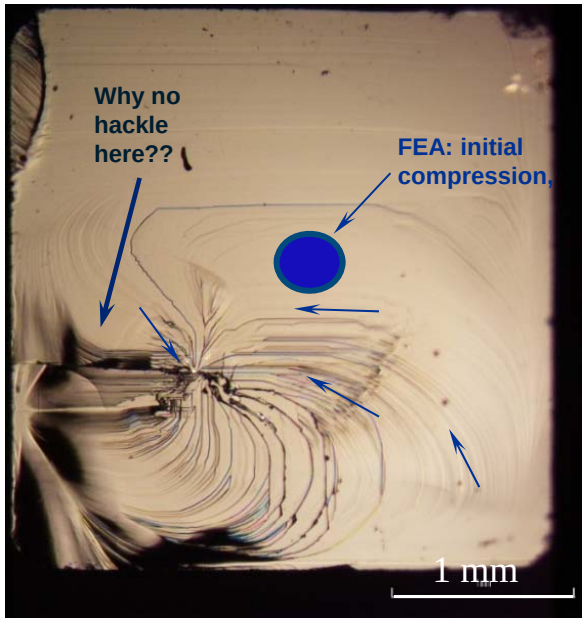



- But why the coalescence of river marks to a central region of initial compression??

# River Marks Follow Tensile Stress Pattern…

- As the crack grows, it spirals, avoiding the center compression, changing the center to tension until the cracks paths converge (?).
- The crack remains on the cleavage plane rather than tracking along the beam long axis:

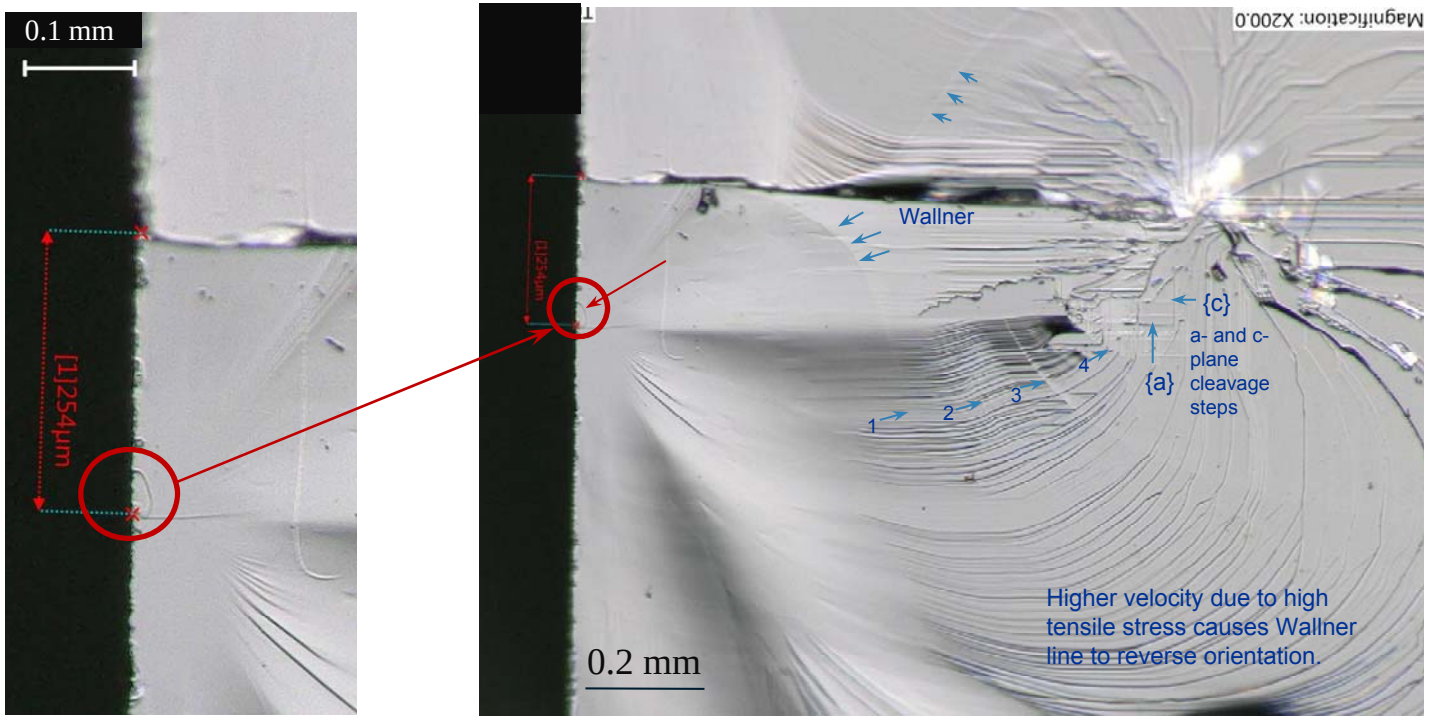



- No mirror or hackle markings on one side of the origin!!??…….

# "All Roads Lead to Rome" (or away!)

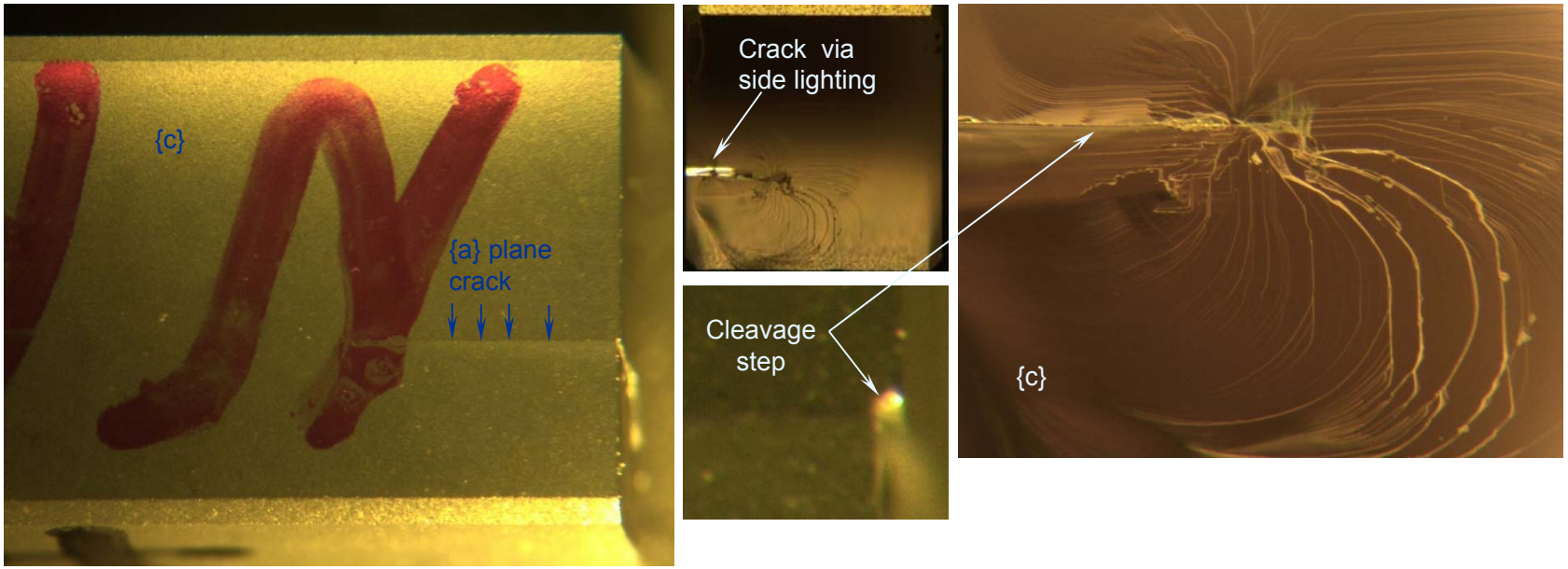
- Origin appears to be the corner of a small, semi-circular surface crack.
- Growing crack wraps around one side of the step…..Unusual pattern:




- "Rome" is the interface between tension and compression where the crack front stalls? But that hackle……..

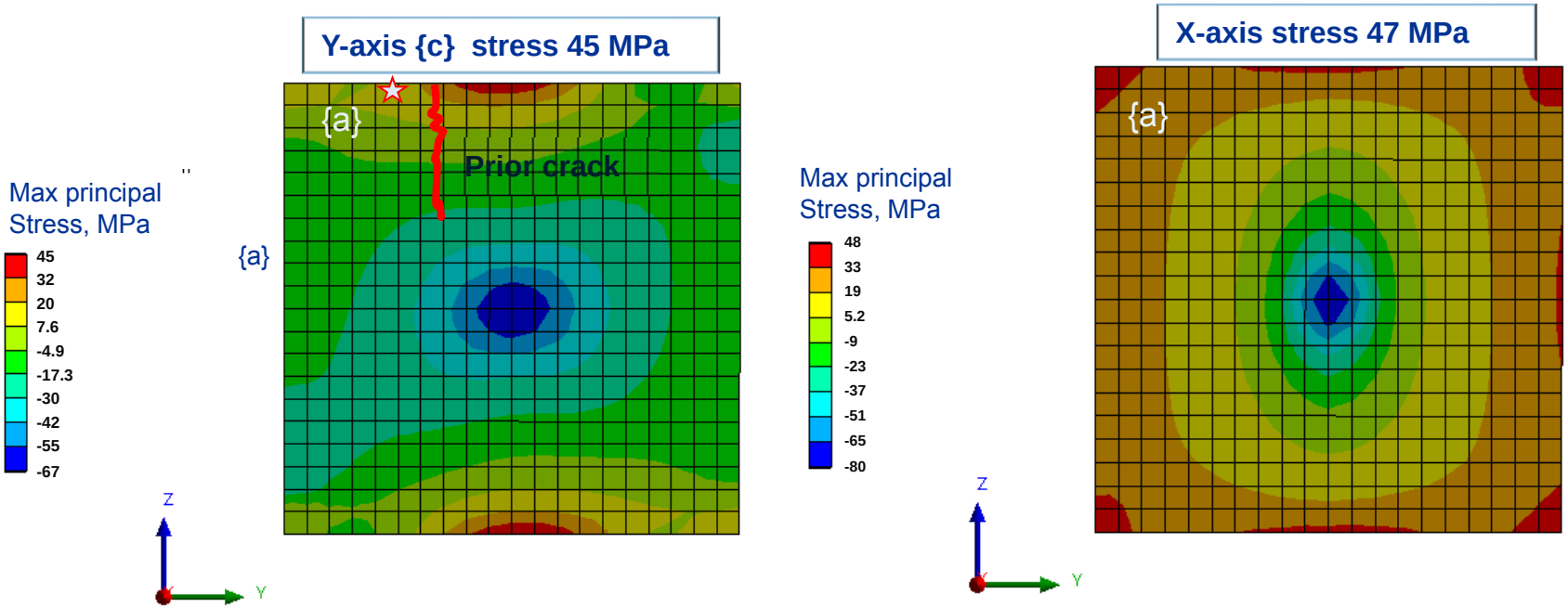
# Why No Hackle on one Side of the Origin?

- By side lighting, we see that the slab was cracked, likely prior to the fracture:



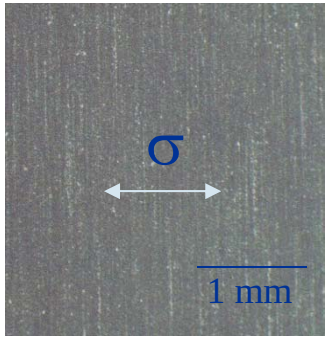

➢ Crack wrapped around the prior, longitudinal crack plane like a screw, creating the cleavage step and “node.”

# X and Y Direction Stresses are Similar:

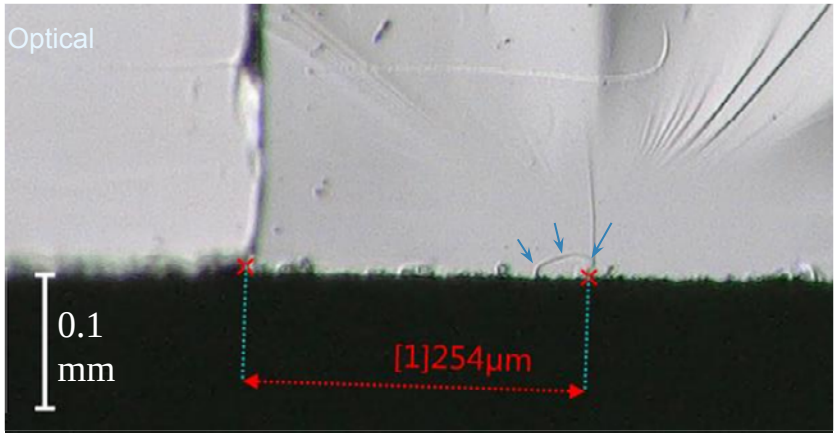


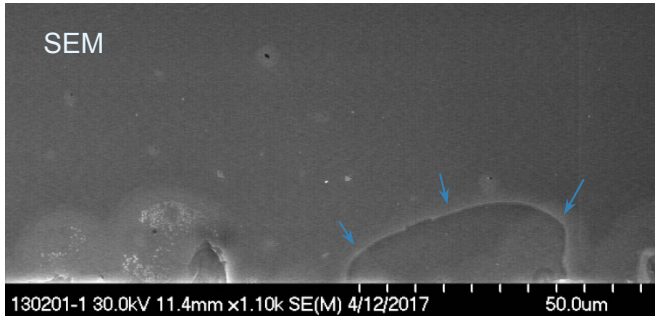

- Grinding is usually in the x-direction, and the stresses are similar on both the x- and y-directions, so longitudinal cracking is likely.

➢ Longitudinal crack was in tension, creating a stress concentration and drawing in the propagating crack.....creating the “node.”



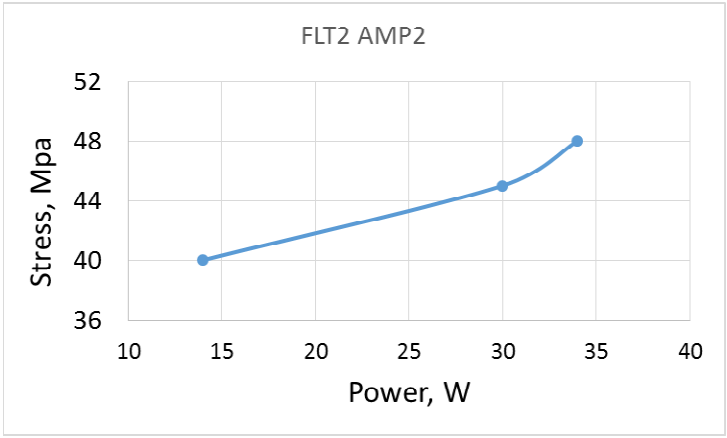
# Estimated Stress (Fractographic and FEA)




$$S_f = \frac{K_{Ic}}{Y\sqrt{a}}$$

| Stress (MPa) | Meas. Type | a (mm) | 2c (mm) | Y surface | Y depth | KIc MPa√m |
|---|---|---|---|---|---|---|
| 70.0 | OPT | 0.021 | 0.052 | **1.30** | 1.30 | **0.42** |

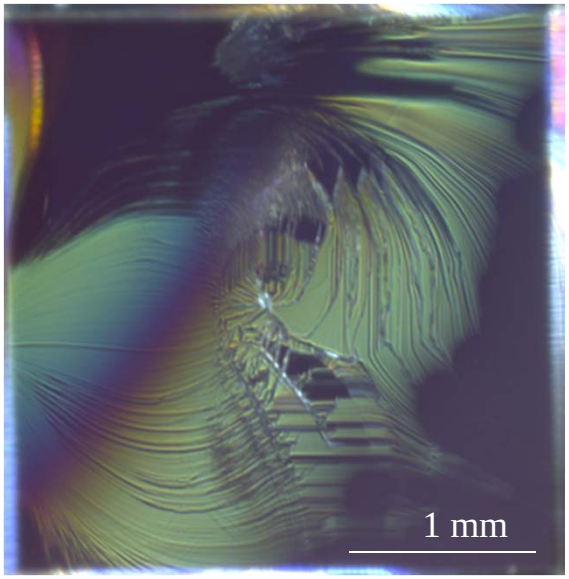


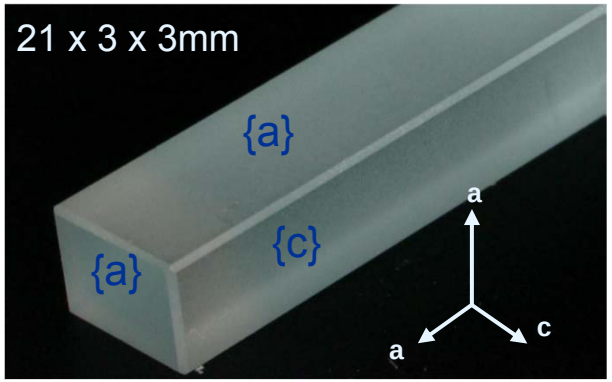

- High stresses are estimated, implying that the stresses were higher due to the prior longitudinal crack or that the pump level, which was unknown, was very large.

# Second Pump-to-Failure Amplifier Crystal

*- Failed During Bench Testing -*

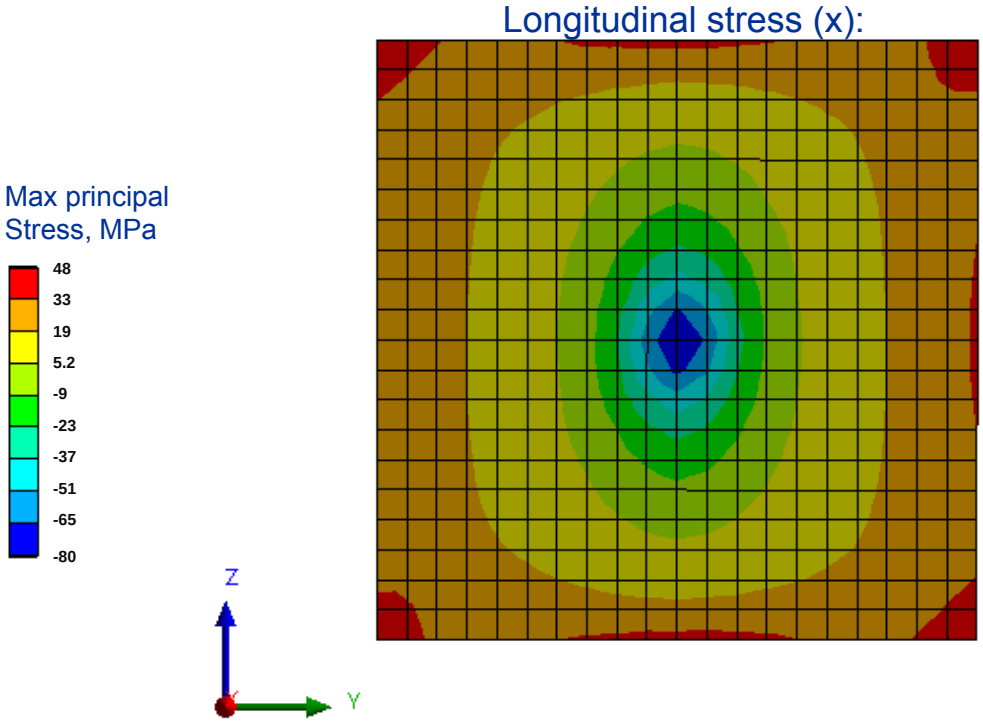
- Controlled bench test of  a laser amplifier slab (single crystal) to induce crystal failure via over-pumping.
- Disassembly revealed a fracture near one end, with the location of fracture thought to be near the center.

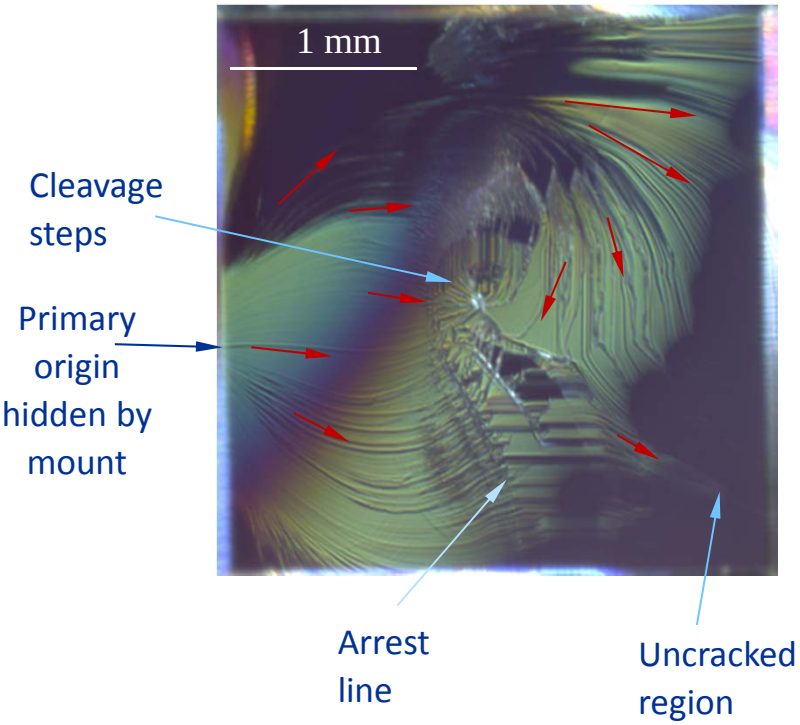


# Slab: Pump-to-Failure Fracture

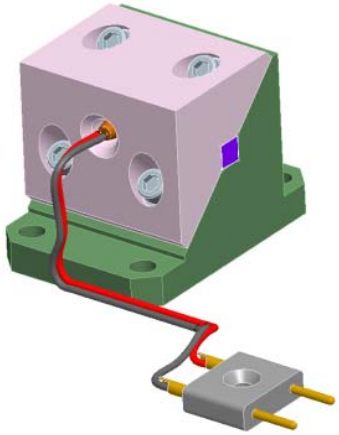
- The “Node” is more centrally located (compression) and no cleavage step or prior longitudinal crack is apparent:

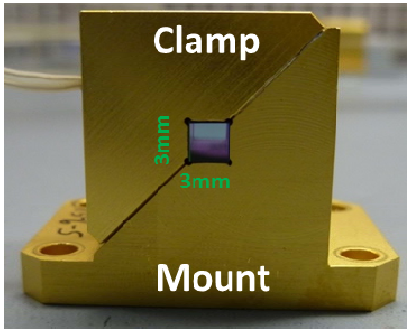



- Crack wrapped around central compression region and stalled.
- Stress state changed and fracture continued by failing central ligament as regions of compression became tension, creating the node.

# Amplifier Assembly Overview







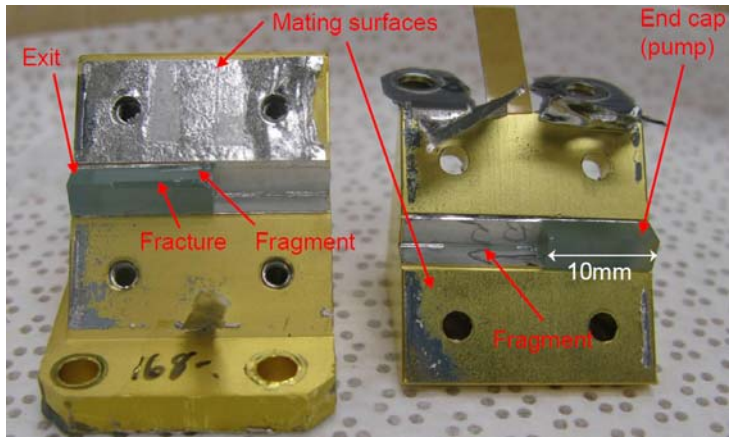
*Courtesy Fibertek Inc.*

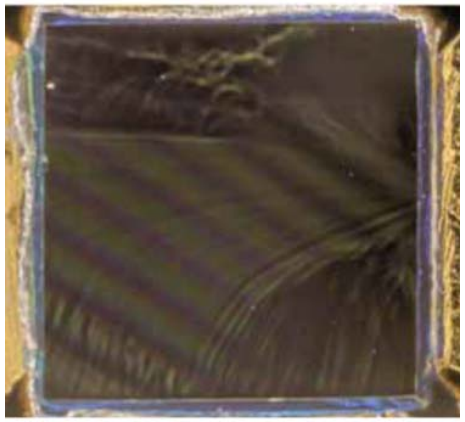
- The Nd:$YVO_4$ crystals are clamped between two gold plated heat spreaders with an indium foil thermal interface material.
- The indium foil thickness was custom selected to achieve uniform and simultaneous contact between all five planar surfaces.
- Four bolts are used to attach the clamp to the mount securing the crystal.

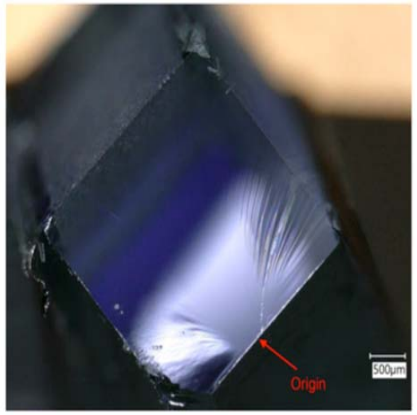
# First Flight Amplifier Fracture

- The crystal fractured about 10 mm inboard of the input face and originated in the middle of the c-facet.
- There were no obvious surface defects or corresponding mount defects at the fracture origin.
- Applied stresses were low.
- Implies that the crystal was under higher mechanical loads (pressure).
- But why?

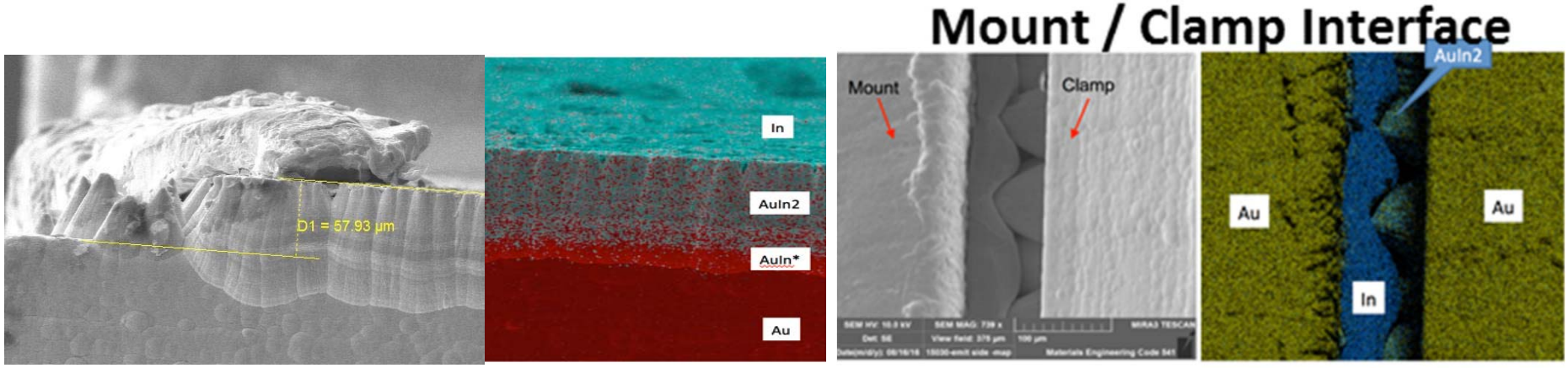
*Courtesy Fibertek Inc.*





# Time Dependent Crystal Loading

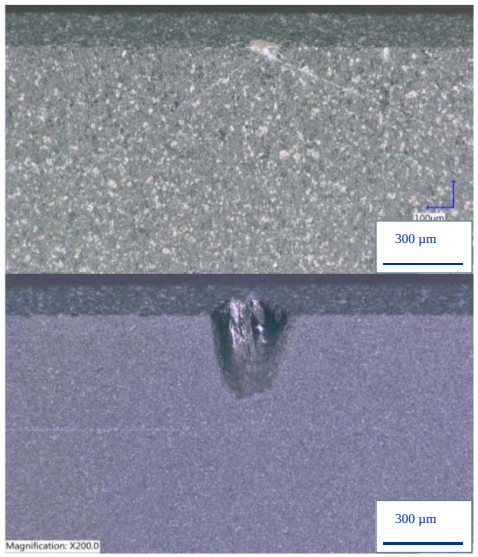



- Fractography indicated that gold and indium were forming gold-indide ($AuIn_2$) over time.
- The resulting $AuIn_2$ material is stiffer, harder and more brittle than indium; and more significantly, occupies 15% more volume.
- Intermetallic and indium are incompressible. The additional volume is displaced, resulting in higher preloads on the crystal, and eventual fracture.

➢ Failure was not due to overpumping…

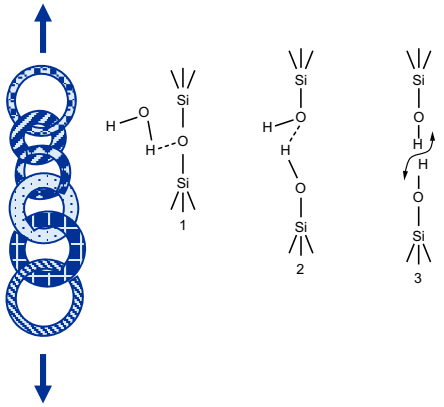
# Redesign Philosophy

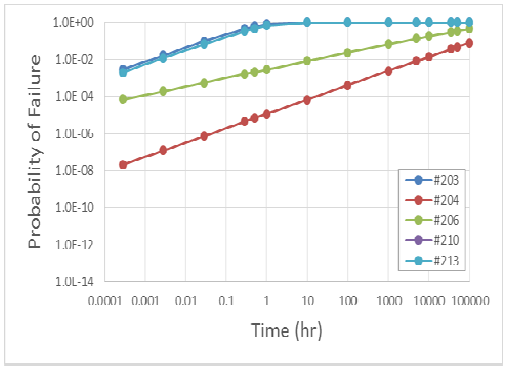
- Failure resulted from several sources:
  - Au-In reactions (worst element)
  - poor crystal finishing and handling
  - low toughness and slow crack growth




- Re-design & qualification was needed:
  - Lowered the stresses
  - Quantified the transient reliability:

- Weakest Link Behavior:
  - Structure is analogous to a chain with many links of differing strength
  - Catastrophic failure occurs when the weakest link is broken
  - A longer chain is weaker




# Conclusions

- For the first slab, cracking started from an {a}-plane semi-elliptical crack located on one side of a prior, longitudinal {a}-plane crack.
- The crack wrapped around the prior, {a}-plane crack by following high tension regions near the surface, creating a large cleavage step.
- As the crack spiraled around and inward, compression regions diminished until central tension occurred via stress redistribution. Stopped spiraling inward at the prior crack tip.
- The prior crack acted as a concentrator, attracting moving crack.
- For the second slab, cracking started from the surface.
- The crack wrapped around both sides of the central compression region and move inward as stress redistribution occurred, forming the central “node.”
- Nodal formation is the result of a growing crack being attracted to a point: reaming central ligament of a crack tip.
- Two flight hardware fractures were from the surface and driven predominantly by chemical reactions…..


# Conclusions

- The node formation and resulting pattern leads to a new fractography term:

  Hackle Node - the coalescence of hackle lines (river marks) to a point of prior compression. The feature is produced as a thermally generated, centrally located compressive region transforms to tension thereby drawing crack propagation to a point.


# Acknowledgements


- The work presented involved efforts by a large team of NASA and industry engineers, scientists and managers including. Without their may efforts, this presentation could not be realized. The author would like to thank



Nicholas W. Sawruk*[a], Patrick M. Burns [a], Ryan E. Edwards [a], Viatcheslav Litvinovitch [a], Nigel Martin [a], Greg Witt [a], Elias Fakhoury [a], John Iskander [a], Mark S. Pronko [a], Elisavet Troupaki [b], Peter M. Bay [b], Charles C. He [b], Liqin L. Wang [b], John F. Cavanaugh [b], Babak Farrokh [b], Eric Baker [c]

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# ICESat-2 Integration After Redesign

- ICESat-2 was integrated at the Orbital/ATK facility in AZ.
- EMI testing completed in April, 2018.
- Transported to Vandenberg AFB in May for integration onto the rocket.
  - The system was powered on for the last time on Earth in mid-June 2018!

# ICEsat-2 Launched from Delta II Pad SLC 2W

## *Vandenberg AFB – California 9-15-2018*

Mobile Service Tower (MST) in place (around vehicle) for Integration and Fairing install

MST rolls back to here the day before Launch


- SLC-2W has been used for launches since 1966
- Delta II has been launched since 1989 (98.6% success)
  - ICESat-2 was the last launch & the 100th consecutive successful launch
- Delta II 7420-10C (7000 series, 4 boosters, 2nd stage with Aerojet AJ10, no third stage) is 38.9 meters tall