FAILURE of Nd:YVO₄ AMPLIFIER CRYSTALS

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Fractography of Advanced Ceramics VI
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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.
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$\sqrt{m}$
- Fracture strength = 46 MPa (~7 ksi)
- Slow crack growth $n = 17$

➢ Very brittle!!
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:

    - Fracture Origin
    - Mirror
    - Hackle

    Low stress

    High stress

    1 mm

    0.5 mm
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:

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

- 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)

- 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.

\[ S_f = \frac{K_{lc}}{Y \sqrt{a}} \]

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Meas. Type</th>
<th>a (mm)</th>
<th>2c (mm)</th>
<th>Y surface (mm)</th>
<th>Y depth (mm)</th>
<th>Klc MPa(\sqrt{m})</th>
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<td>70.0</td>
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<td>0.021</td>
<td>0.052</td>
<td>1.30</td>
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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

- The Nd:YVO₄ 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.

*Courtesy Fibertek Inc.*
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?
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.
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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

- 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