FAILURE of Nd:YVO$_4$ AMPLIFIER CRYSTALS

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Fractography of Advanced Ceramics VI
2019
Ceramics are used in Many NASA Applications

- Solar concentrators
- Laser amplifiers
- Specialty windows
- Spectrometer components
- Low expansion mounting plates
- Lenses
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
  - ATLAS carries two lasers, one primary and one backup.
Within the System are Nd:YVO₄ Crystals

- The YVO₄ single crystals are laser “slabs”
- Elastic modulus = 220 GPa <a> axis
- Fracture toughness = 0.48 MPa√m
- Fracture strength = 46 MPa (~7 ksi)

➢ 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.

• I’ll discuss these in varying detail.
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 principal stresses:
  - Center compression with edge tension, where the worst flaws are often located.
  - Compressive strength is \( \gg \) 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

- But why the coalescence of rivers marks to a central region of 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.
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, 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.

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

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Meas. Type</th>
<th>( a ) (mm)</th>
<th>( 2c ) (mm)</th>
<th>Surface Y (mm)</th>
<th>Depth Y (mm)</th>
<th>( K_{lc} ) MPa( \cdot )m</th>
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<tbody>
<tr>
<td>70.0</td>
<td>OPT</td>
<td>0.021</td>
<td>0.052</td>
<td>1.30</td>
<td>1.30</td>
<td>0.42</td>
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</tbody>
</table>

![Optical Image](image1.jpg)

![SEM Image](image2.jpg)

![Graph](image3.jpg)
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

- “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.
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.
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.
- 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:
  - Lowed 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 stalled until stress redistribution allowed further fracture, forming the central node.

- Two flight hardware fractures were from the surface and driven predominantly by chemical reactions….
ICESat-2 Integration After Redesign

- ICESat-2 was integrated at the Orbital/ATK facility in AZ.
- EMI testing completed in April.
- 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