Fused Silica
and
Other Transparent Window Materials

Jon Salem
NASA Glenn Research Center
Cleveland, Ohio

ICACC, Daytona Beach, January 27th, 2016
Outline

- Window Applications and Requirements
- Historical Material
- New Materials and Mechanical Properties
- ISS Windows and Damage
- Anomalous Behavior of Silica
- Comparison to Published Literature
- Conclusions
Some NASA Window Applications

- Crew Vehicles
- Ascent vehicles
- Docking Hatch
- Hatch Window
- Silica/Silica/Acryllic
- Rendezvous/Docking Windows (2)
- Side Windows (2)
- Silica/Silica/Acryllic

- Laboratories
- Visors
- Rovers
- Habitats
- Aircraft windows
- Submersibles
- Wind Tunnels
Fused Silica – Workhorse Material

• Fused silica has been the historical material of choice:
  – Apollo
  – SkyLab (73-74), Mir...
  – ISS (98-xxxx)
  – Shuttle
  – Orion

• Only one unexpected failure during an Apollo window proof test.
Window Requirements

- Thermal shock
- Mechanical (crack growth)
- Optical (haze, transmittance.....imagery, piloting)
- Chemical (atomic oxygen, radiation..)
- Impact residual strength (handling, hyper)

- Big advantages are optical and thermal.
- But why windows at all?! Psychological.
Windows in Use - ISS

- Most famous are the Cupola windows, which are shuttered:

- More typical widow ($10''\phi$):

- Some windows are not shuttered and can be damaged by MMOD....
New, Impact Resistant Materials

- A variety of “new” materials have been developed or re-developed:
  - AION
  - Spinel
  - MgO, Alumina, glass-ceramics

- One driving force has been military armor:

  Fused Silica - 35 lbs/ft²
  ALON - 17 lbs/ft²

- Might these materials work for spacecraft windows?
# Property Comparison

- **Thermals shock related:**

  \[ R'' = \frac{(1 - v)\lambda\sigma_c}{\alpha E \rho C_p} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus GPa</th>
<th>Fracture Strength (MPa)</th>
<th>CTE x 10^{-6}/°C</th>
<th>Thermal Conductivity (W/mK) λ</th>
<th>Heat Capacity (J/gK)</th>
<th>R (K)</th>
<th>R” (Wcm²/gK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>72</td>
<td>80</td>
<td>0.5</td>
<td>14</td>
<td>0.77</td>
<td>1733</td>
<td>143</td>
</tr>
<tr>
<td>Spinel (coarse grain)</td>
<td>270</td>
<td>80</td>
<td>6</td>
<td>15</td>
<td>0.88</td>
<td>73</td>
<td>3.5</td>
</tr>
<tr>
<td>Spinel (fine grain)</td>
<td>270</td>
<td>160</td>
<td>6</td>
<td>15</td>
<td>0.88</td>
<td>73</td>
<td>3.5</td>
</tr>
<tr>
<td>AION</td>
<td>314</td>
<td>210</td>
<td>5</td>
<td>13</td>
<td>0.92</td>
<td>99</td>
<td>3.8</td>
</tr>
</tbody>
</table>

- **Positive:** similar thermal conductivity.
- **Negative:** new materials have higher CTE.
- ▶ Poor thermal shock.
Mechanical Property Comparison

- **Crack growth related:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cc)</th>
<th>Young's Modulus (GPa)</th>
<th>Fracture Toughness (MPa√m)</th>
<th>Crack Growth Exponent, n</th>
<th>Fracture Strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>2.2</td>
<td>72</td>
<td>0.75</td>
<td>24</td>
<td>80</td>
</tr>
<tr>
<td>Spinel (coarse grain)</td>
<td>3.6</td>
<td>270</td>
<td>1.5</td>
<td>22</td>
<td>80</td>
</tr>
<tr>
<td>Spinel (fine grain)</td>
<td>3.6</td>
<td>270</td>
<td>2.0</td>
<td>50</td>
<td>160</td>
</tr>
<tr>
<td>AlON</td>
<td>3.7</td>
<td>314</td>
<td>2.2</td>
<td>35 - 50</td>
<td>210</td>
</tr>
</tbody>
</table>

- **Positive:** New materials are tougher and SCG resistant.
- **Negative:** New materials are denser and stiffer.
Slow Crack Growth Curve

• The SCG curve captures much of the mechanics:

![Graph showing slow crack growth curve with different materials and their stress intensity vs. velocity]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>2.2</td>
</tr>
<tr>
<td>Spinel</td>
<td>3.6</td>
</tr>
<tr>
<td>Spinel</td>
<td>3.6</td>
</tr>
<tr>
<td>AlON</td>
<td>3.7</td>
</tr>
</tbody>
</table>

• Does not account for weight…….
Launch Weight is Expensive.  
- Can Mass be Reduced? - 

- Slow crack growth life function:  
  \[ t_{f \min} = B \sigma_{proof}^{n-2} \sigma_{applied}^{-n} \]

- Combine with – Window mass:  
  \[ m = \frac{\rho \pi D^2 t}{4} \]

  – Window stress:  
  \[ \sigma_{\text{max}} = \frac{3PD^2}{32t^2} (3 + \nu) \]

  – Proof stress:  
  \[ \sigma_{proof} = \left( \frac{K_{Ic}}{Y \sqrt{a_{\max}}} \right) \]

- Mass for a lifetime:  
  \[ m = \left( \frac{t_{f \min}}{B} \right)^{\frac{1}{2n}} \left( \frac{K_{Ic}}{Y \sqrt{a_{\max}}} \right)^{\frac{2-n}{2n}} \left( \frac{3\pi^2 P \rho^2 D^6}{512} (3 + \nu) \right)^{\frac{1}{2}} \]
Relative Mass

<table>
<thead>
<tr>
<th>Material</th>
<th>Grain Size, μm</th>
<th>Relative Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinel (TA)</td>
<td>300</td>
<td>1.14</td>
</tr>
<tr>
<td>Spinel (AL)</td>
<td>180</td>
<td>1.04</td>
</tr>
<tr>
<td>Spinel (CT)</td>
<td>110</td>
<td>0.97</td>
</tr>
<tr>
<td>Spinel (LaRC)</td>
<td>25</td>
<td>0.74</td>
</tr>
<tr>
<td>Spinel (Julich)</td>
<td>5</td>
<td>0.73</td>
</tr>
<tr>
<td>AlON</td>
<td>245</td>
<td>0.83</td>
</tr>
<tr>
<td>Fused Silica</td>
<td>______</td>
<td>1</td>
</tr>
</tbody>
</table>

- Yes, mass can be reduced from a SCG Perspective!
- For spinel, the grain size needs to be small........
Impact: Shuttle Examples

STS-113 W11 HVI, .095” diameter

STS-123, 0.139” diameter

STS-126 HVI, the largest natural HVI incurred by an Orbiter window (~.5” dia)

STS-130 Impact being identified by a crew member
Impact: ISS Example

- Russian fused silica window (not shuttered):

- Window sealed.
Hyper Velocity Impact of Spinel vs Silica

- Similar sizes but very different morphologies:

  - **Large pit with gain boundary cracking.**
  
  - **Central pit with radial and circumferential cracks.**
Summary

• Spinel and AlON exhibit better fracture toughness and crack growth as compared to glasses, and thus have potential in window systems.
• They can reduce weight from a crack growth perspective.
• Thermal shock resistance metrics are poor - component level testing to qualify.
• Impact size is similar, however, the morphology is very different; residual strength needs to be measured
• Are the post impact residual strengths similar?
Fused Silica

Observations and Anomalies
Macro-crack Fracture Toughness

**Russian Quartz-Silica**

<table>
<thead>
<tr>
<th>Method</th>
<th>Fracture Toughness (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air (75°F, 45% RH)</td>
</tr>
<tr>
<td>SEPB</td>
<td>0.71 ± 0.05</td>
</tr>
<tr>
<td>VB</td>
<td>0.71 ± 0.04</td>
</tr>
</tbody>
</table>

**Shuttle Fused Silica (7980)**

<table>
<thead>
<tr>
<th>Method</th>
<th>Fracture Toughness (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air (75°F, 45% RH)</td>
</tr>
<tr>
<td>SEPB</td>
<td>0.71 ± 0.04</td>
</tr>
<tr>
<td>VB</td>
<td>0.73 ± 0.04</td>
</tr>
</tbody>
</table>

**Tosoh**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Fracture Toughness (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air (75°F, 25% RH)</td>
</tr>
<tr>
<td>VB</td>
<td>0.73 ± 0.08</td>
</tr>
</tbody>
</table>

**Literature on 7940 & 7980**

<table>
<thead>
<tr>
<th>Method</th>
<th>Fracture Toughness (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vacuum</td>
</tr>
<tr>
<td>AMDCB</td>
<td>0.72 ± 0.01</td>
</tr>
<tr>
<td>DCB</td>
<td>0.74 ± 0.03</td>
</tr>
<tr>
<td>3-Pt</td>
<td>0.75 ± 0.03</td>
</tr>
<tr>
<td>DCDC</td>
<td>0.73 to 0.76</td>
</tr>
</tbody>
</table>

- Silicas have identical fracture toughness at the macro-scale.
- Insensitive to test method, test material, or researcher.
Crack Growth Data for 7940/7980 and Optical Fiber

Strength data fit via the Power Law or as directly observed

\[ \frac{dv}{dt} = A^* \left( \frac{K}{K_{IC}} \right)^n \]

- Large variance.
- Strength methods (small cracks) give a low \( n \).
- Directly observed macrocracks give high \( n \).
- Wide range, directly observed data is nonlinear – exponential law!

Cracks size or test method effect??

[10, 11, 13, 17] 7940, DCB, .997 silica, 7980, polished
[21] 7980, ground
[25] 7980, 75% RH, DCDC
[22] optical fiber, 60% RH
[19] 997 silica
[23] 7980, 75% RH, DCDC

The exponential law provides better agreement between directly observed macrocracks and strength based velocity estimates (blends).

Still some difference between larger and smaller cracks.....
What is Different?

- Crack size and observation method used:

Strength method – estimate from strength

Macro-crack method: direct observation of the crack.

How can we determine the source of the differences??
Crack Size Effect

- Use strength method to test ground specimen (small cracks) and larger cracks (Indented specimens):

- Indented specimen give similar $n$ as directly observed macrocracks – not a method effect. Crack size effect?
Other Influences Giving a Crack Size Effect

- Residual stress
  - Correction (Fuller’s, et al.) generally increase the n value and shifts data too far...
Crack Growth of Various Fused Silicas

• Water content - need systematic measurements……..

<table>
<thead>
<tr>
<th>Material</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7980</td>
<td>39</td>
</tr>
<tr>
<td>Russian</td>
<td>43</td>
</tr>
<tr>
<td>Tosoh</td>
<td>35</td>
</tr>
<tr>
<td>GE</td>
<td>37</td>
</tr>
</tbody>
</table>

Same water content?

• Different silicas exhibit very similar $n$ when test identically! Measure water content……..
Water Adsorption

• Near surface adsorption of water creates surface residual stresses (Wiederhorn) and higher $n$ (Tomozawa).

• But does not explain the difference between small and large crack data:
  – Large cracks shouldn't be influenced, yet exhibit high $n$
  – Small cracks result in low $n$ or high $n$

• Research is needed……..
Conclusions

• Fracture toughness of several fused silicas are identical regardless of technique, vintage or researcher.

• Slow crack growth parameters of several silica are very similar when tested identically.

• Yet, the reported slow crack growth parameters are quite varied, even for a single commercial silica.

• Use of the exponential function rationalizes some of the differences between large crack, small crack, and strength-based parameters, but…..future research.

• New materials exhibit better toughness and crack growth as compared to silica, and thus have potential in window systems. More work is needed to qualify these materials.
Acknowledgements

• Thanks to Jim McMahon (JSC) and Penni Dalton (HEMOD) for funding.
• Thanks to Lynda Estes for many discussions.