THE EFFECT OF MOISTURE ON THE ADHESION AND FRACTURE OF POLYMER/METAL INTERFACES

Jianmin Qu, Ph.D.
Professor
G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405
Phone: 404-894-5687
FAX: 404-894-0186
E-Mail: jianmin.qu@me.gatech.edu

Contributors: T. Ferguson, M. Yao, A. Kuhl, Y.H. Lee
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Outline

- Effects of moisture on the interface

- Challenges/outstanding issues
  - Rate of degradation
  - Reversibility
  - Critical saturation
  - Oxidation

- Some recent results
  - Elastic modulus
  - Fracture toughness
Moisture Transport in Bulk Polymer (epoxy)

- Non-Fickian behavior [Jurf and Vinson, 1985; Wong, 1999; Ferguson and Qu, 2001, etc.]
- Surface topology, nano-pores and water polarity [Soles, et al. 1998, 2002, etc.]
- Capillary associated with voids, cracks and filler interfaces [Lu, et al., 1998; Uschitsky and Suhir, 1997, etc]
- Wicking along the interface [Comyn, et al., 1994; Zanni-Deffarges and Shanahan, 1995, etc.]

Moisture on Bulk Properties

- Reduces elastic modulus due to plasticizing [Wylde and Spelt, 1998; Shanahan, et al., 1995; Su, et al., 1992; Brewis, et al., 1990; etc.]
- Reduces elastic modulus due to crazing [Lu, et al., 2001; McMaster and Soane, 1989]
- Reduces strength [Wahab, et al. 2002]
- Increases failure strain [Crocombe, 1997]

Moisture on Interfacial Adhesion/Fracture Toughness

- Reduces Van der Waals forces [Bowditch, 1996; Crocombe, 1997; Comyn, et al., 1994, etc.]
- Plasticization [Bowditch, 1996; DeNeve and Shanahan, 1992; Bowditch, 1996, etc.)
- Chemical degradation [Crocombe, 1997; Bowditch, 1996; Zanni-Deffarges and Shanahan, 1994]
Challenges/Outstanding Issues

Critical Concentration

- Some have found a critical concentration of water below which the interface is not weakened by moisture [e.g., Kinloch, 1979; Gledhill, et al., 1980; Comyn, et al., 1994; Brewis, et al., 1990]
- Others do not see the critical concentration [e.g., Wylde and Spelt, 1998]

Recovery

- None on epoxy/aluminum [e.g., Butkus, 1997]
- Some on epoxy/aluminum [e.g., Orman and Kerr, 1971]
- All on epoxy/steel [e.g., Shaw, et al., 1992]
- All if moisture concentration < 0.3% on epoxy/aluminum, [e.g., Dodiuk, et al., 1984]

Rate of Degradation

- ?

Oxidation

- ?
Research Objectives

• Identify the physical mechanisms responsible for the loss in adhesion in the presence of moisture.
• Characterize the intrinsic change in the adhesive elastic modulus and interfacial fracture toughness as function of increasing moisture content.
• Differentiate reversible and irreversible effects from moisture uptake.
• Develop a moisture degradation model to predict loss in interfacial fracture toughness due to moisture.
Research Program

Exposure to Moisture

Moisture Absorption Kinetics

Variation in Elastic Modulus

Effect on Interfacial Adhesion

Absorption Properties
  - Inherent Change due to Uptake
  - Reversible and Irreversible Effects
  - Physical Mechanisms for Change

Test Design and Absorption Modeling
  - Effect of Moisture at Interface
  - Effect of Elastic Modulus Variation
  - Inherent Change due to Uptake
  - Hygroswelling Effects
  - Effect of Oxidation Growth
  - Fracture Failure Locus
  - Interfacial Hydrophobicity
  - Reversible and Irreversible Effects
  - Physical Mechanisms for Change

Moisture Degradation Model
Elastic Modulus

Materials:
- An epoxy based underfill (no filler)
- Copper

Three-Point Flexural Bend Test:
- ASTM D790
- United Load Frame
- Cross head rate: 1.2 mm /min

Test Sample
- 50.8 x 12.7 x 2.0 mm
- Fully cured (190°C for 40 min)

Materials:
- An epoxy based underfill (no filler)
- Copper

Test Sample
- 50.8 x 12.7 x 2.0 mm
- Fully cured (190°C for 40 min)

Test Conditions:
- All tests performed at room temperature
- Inherent wet modulus identified
- No measurable change in mass after removal from humidity chamber to completion of testing

\[ E = \frac{L^3 m}{4bd^3} \]

- \( L = \) Support span length = 38.1 mm
- \( b = \) Width = 12.7 mm
- \( d = \) Depth = 2.0 mm
- \( m = \) Slope of tangent to initial load-deflection curve
# Modulus Test Matrix

<table>
<thead>
<tr>
<th>Test Group</th>
<th>Environment</th>
<th>Duration</th>
<th>Dessicate at 95C?</th>
<th># Test Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>85C</td>
<td>168 hrs</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>85C/50%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>85C/65%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>85C/85%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>85C/50%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>85C/65%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>85C/85%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>5</td>
</tr>
</tbody>
</table>

**TOTAL # OF TESTS:** 55
# Thermal Aging and Moisture Preconditioning Effects

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>RH (%)</th>
<th>C&lt;sub&gt;sat&lt;/sub&gt; (wt%)</th>
<th>E (GPa)</th>
<th>Decrease in Modulus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>--</td>
<td>0.00</td>
<td>2.53 ± 0.06</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>--</td>
<td>0.00</td>
<td>2.51 ± 0.07</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>50</td>
<td>0.65</td>
<td>2.49 ± 0.05</td>
<td>1.6</td>
</tr>
<tr>
<td>85</td>
<td>65</td>
<td>0.77</td>
<td>2.45 ± 0.04</td>
<td>3.2</td>
</tr>
<tr>
<td>85</td>
<td>85</td>
<td>1.02</td>
<td>2.31 ± 0.04</td>
<td>8.7</td>
</tr>
<tr>
<td>85</td>
<td>95</td>
<td>1.19</td>
<td>2.09 ± 0.07</td>
<td>17.4</td>
</tr>
</tbody>
</table>

![Graph showing the change in modulus (E) with different conditions]
Recovery from Moisture Uptake Upon Fully Drying

![Graph showing the recovery from moisture uptake upon fully drying.](image-url)
Epoxy Elastic Modulus Recovery

**Recoverability:**

\[
\text{Recoverability} (\%) = \frac{E_{\text{RECOVERY}} - E_{\text{SAT}}}{E_{\text{DRY}} - E_{\text{SAT}}} \cdot 100
\]

**Physical Mechanisms for Loss:**

- Majority of moisture uptake resulted in plasticization
- Hydrolysis contributed to irreversible damage

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>RH (%)</th>
<th>C_{\text{sat}} (wt%)</th>
<th>E_{\text{sat}} (GPa)</th>
<th>E_{\text{recovery}} (GPa)</th>
<th>Recoverability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>--</td>
<td>0.00</td>
<td>2.53 ± 0.06</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>50</td>
<td>0.65</td>
<td>2.49 ± 0.05</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>65</td>
<td>0.77</td>
<td>2.45 ± 0.04</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>85</td>
<td>1.02</td>
<td>2.31 ± 0.04</td>
<td>2.46 ± 0.08</td>
<td>68.2</td>
</tr>
<tr>
<td>85</td>
<td>95</td>
<td>1.19</td>
<td>2.09 ± 0.07</td>
<td>2.40 ± 0.05</td>
<td>70.5</td>
</tr>
</tbody>
</table>
Interfacial Fracture Toughness

Materials:
- An epoxy based underfill (no filler)
- Copper

Four-Point Flexural Bend Test:
- United Load Frame
- Cross head rate: 0.5 mm /min

Test Sample
- Cu (50.8 x 9.7 x 1.5 mm)
- Epoxy (32.8 x 9.7 x 2.25 mm)
- Plane strain deformation
- Fully cured (190°C for 40 min)

Test Conditions:
- All tests performed at room temperature
- No measurable change in mass after removal from humidity chamber to completion of testing

\[ G = \frac{1}{2E_1} \left( \frac{12M^2}{h^3} \right) - \frac{1}{2E_2} \left( \frac{M^2}{lh^3} \right) \]
Uniform 1-D Moisture Diffusion

Water proof perimeter
- Prevents 3-D moisture uptake
- Forces 1-D diffusion through epoxy
- Yields uniform moisture concentrations at interface
- Prevents wicking
## Interfacial Fracture Test Matrix

<table>
<thead>
<tr>
<th>Test Group</th>
<th>Substrate</th>
<th>Adhesive</th>
<th>Environment</th>
<th>Duration</th>
<th>Dessicate at 95C?</th>
<th># Test Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Copper</td>
<td>Underfill</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C</td>
<td>168 hrs</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/50%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/65%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/85%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/50%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/65%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Copper</td>
<td>Underfill</td>
<td>85C/85%RH</td>
<td>168 hrs</td>
<td>YES</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>FR-4 Board</td>
<td>Underfill</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>FR-4 Board</td>
<td>Underfill</td>
<td>85C</td>
<td>168 hrs</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>FR-4 Board</td>
<td>Underfill</td>
<td>85C/50%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>FR-4 Board</td>
<td>Underfill</td>
<td>85C/65%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>FR-4 Board</td>
<td>Underfill</td>
<td>85C/85%RH</td>
<td>168 hrs</td>
<td>NO</td>
<td>10</td>
</tr>
</tbody>
</table>

**TOTAL # OF TESTS:** 135
# Epoxy/Cu Interfacial Fracture Toughness

Phase angle range for all test specimens: -37.41° to -37.64°

<table>
<thead>
<tr>
<th>T (C)</th>
<th>RH (%)</th>
<th>Csat (wt%)</th>
<th>Csat (mg H₂O/ mm³)</th>
<th>G_c (J/m²)</th>
<th>Toughness Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>--</td>
<td>0</td>
<td>0.0000</td>
<td>8.97 ± 0.91</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>50</td>
<td>0.65</td>
<td>0.0075</td>
<td>5.26 ± 0.47</td>
<td>41.4</td>
</tr>
<tr>
<td>85</td>
<td>65</td>
<td>0.77</td>
<td>0.0089</td>
<td>4.57 ± 0.58</td>
<td>49.1</td>
</tr>
<tr>
<td>85</td>
<td>85</td>
<td>1.02</td>
<td>0.0118</td>
<td>3.76 ± 0.36</td>
<td>58.1</td>
</tr>
</tbody>
</table>
Fracture Toughness vs. Moisture Concentration

![Graph showing the relationship between fracture toughness (Gc) and moisture concentration (C_{sat})](image)

- **Gc (J/m²)**
- **C_{sat} (mg H₂O / mm³)**

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Effect of Oxidation Growth

Copper Oxides:
- Cuprous Oxide, Cu₂O (Red Oxide)
- Cupric Oxide, CuO (Black Oxide)

Oxidation at Interface:
- CuO found on all preconditioned surfaces
- Similar development of atomic percentages of Cu₂O to CuO on all preconditioned surfaces
- Contact angle measurements indicate similar oxide thickness on all preconditioned surfaces (Yi, et al., 2000)
- Thermal aging vs. control toughness results indicate oxidation growth contributed little if any to changes in interfacial adhesion

<table>
<thead>
<tr>
<th>Preconditioning</th>
<th>Cu₂O (%)</th>
<th>CuO (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85C Thermal Aging</td>
<td>68</td>
<td>32</td>
</tr>
<tr>
<td>85C / 50%RH</td>
<td>67</td>
<td>33</td>
</tr>
<tr>
<td>85C / 85%RH</td>
<td>69</td>
<td>31</td>
</tr>
</tbody>
</table>
Recovery from Moisture Uptake Upon Fully Drying

![Graph showing the recovery of moisture uptake upon fully drying with different conditions. The graph compares Control, 85C only, 85C/50%RH, 85C/65%RH, and 85C/85%RH conditions, with environmental preconditioning and recovery phases indicated.]
Recoverability:

\[
Recoverability(\%) = \frac{G_{c,\text{RECOVERY}} - G_{c,\text{SAT}}}{G_{c,\text{DRY}} - G_{c,\text{SAT}}} \cdot 100
\]

Physical Mechanisms for Loss:

- Plasticization of adhesive from moisture did not significantly contribute to loss
- Loss dominated by direct presence of moisture at interface

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>RH (%)</th>
<th>C_{\text{sat}} (wt%)</th>
<th>G_{c, \text{sat}} (J/m^2)</th>
<th>G_{c, \text{recovery}} (J/m^2)</th>
<th>Recoverability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>--</td>
<td>0.00</td>
<td>8.97 ± 0.91</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>85</td>
<td>50</td>
<td>0.65</td>
<td>5.26 ± 0.47</td>
<td>5.52 ± 0.38</td>
<td>7.0</td>
</tr>
<tr>
<td>85</td>
<td>65</td>
<td>0.77</td>
<td>4.57 ± 0.58</td>
<td>4.81 ± 0.47</td>
<td>5.5</td>
</tr>
<tr>
<td>85</td>
<td>85</td>
<td>1.02</td>
<td>3.76 ± 0.36</td>
<td>3.88 ± 0.50</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Macroscopic Failure of an Interface

Adhesive

Substrate

Interfacial Fracture

Generation of new area $A$
Energy Conservation

Work done by applied forces = Deformation + Heat + New Surfaces

Elastic strain energy
Plastic dissipation
Viscosity etc.

Surface energy
Internal friction etc.

Work done by applied forces - Deformation - Heat = New Surfaces

Driving force
Dissipation
adhesion
Mechanics of Interfaces

Driving Force

- Mechanical Loads (Apparent Adhesion)
- Thermal & Residual Stresses

Dissipation

- Viscosity
- Plasticity

Q: Can we quantify each component (prediction/measurement)?
Chemical


Mechanical

Surface Energy Quantification

\[ W_{SL}^{\text{total}} = W_{SL}^{AB} + W_{SL}^{LW} = \gamma_S + \gamma_L - \gamma_{SL} = \gamma_L (1 + \cos \theta) \]

- van Oss *et al.* [1985]: \( W_{SL}^{LW} = 2(\gamma_S^{LW} \gamma_L^{LW})^{1/2} \)

- Fowkes [1988]: for a liquid having only LW force (\( \gamma_L = \gamma_L^{LW} \)), e.g. CH\(_2\)I\(_2\)
  \[ 4\gamma_S^{LW} = \gamma_L^{LW} (1 + \cos \theta)^2 \]

- Good [1992]: defined Lewis parameters \( \gamma^+ \) and \( \gamma^- \),
  \[ W_{SL}^{AB} = 2(\gamma_L^{-}\gamma_S^+)^{1/2} + 2(\gamma_L^{+}\gamma_S^-)^{1/2} \]

  Probe liquid 1 (apolar, \( \gamma_1^{+} = \gamma_1^{-} = 0 \)) \( \rightarrow \) \( \gamma_S^{LW} \)

  Probe liquid 2 & 3 (polar, known \( \gamma_L^{+} \) & \( \gamma_L^{-} \)) \( \rightarrow \) \( \gamma_S^{+} \) & \( \gamma_S^{-} \)

- Yao and Qu [2003]: 3-liquid methods

*Total thermodynamic work of adhesion can be determined*
THERMODYNAMIC WOA

Diodomethane  Glycerol  Water (colored)
Interfacial bonding stress \( \sigma_{12}^a = \frac{2\pi q_1 q_2 A_{12}}{9\sqrt{3}a_0} \)

Work of adhesion \( W_{12}^a = \int_{z_{0,12}}^{\infty} \sigma_{12}^a(z)dz = \frac{\pi q_1 q_2 A_{12}}{8Z_{0,12}^2} \)

\( q_1, q_2 \) = interface atomic densities
\( a_0 \) = interface equilibrium distance
\( A_{12} = 4 \times 10^{-63} \text{ Jm}^6 \)
\( q_1 \approx 6 \times 10^{23}/\text{m}^3 \) (polymers)
\( q_2 \approx 1.22 \times 10^{19}/\text{m}^3 \) (Al)

Physical Adhesion = 0.1 ~ 0.3 J/m²
Energy Release Rate – Interfacial Fracture Toughness

Griffith Energy Criterion:

Crack growth can occur if the energy required to form an additional crack size $da$ can just be delivered by the load.

$G = G_c \rightarrow$ Fracture may occur

$G = \frac{1 - \nu^2}{E} \left( K_I^2 + K_{II}^2 + \frac{K_{III}^2}{1 - \nu} \right)$

Fracture Toughness $\gg$ Work of Adhesion

GWW School of Mechanical Engineering

Jianmin Qu
Thermodynamic Work of Adhesion

Stability of adhesive / substrate interface in presence of a liquid can be ascertained from thermodynamic arguments:

\[ W_A = 2\sqrt{\gamma_a \gamma_s^D} + 2\sqrt{\gamma_a \gamma_s^P} \]

\[ W_{Al} = 2(\gamma_{lv} - \sqrt{\gamma_a \gamma_{lv}^D} - \sqrt{\gamma_a \gamma_{lv}^P} - \sqrt{\gamma_s \gamma_{lv}^D} - \sqrt{\gamma_s \gamma_{lv}^P} + \sqrt{\gamma_a \gamma_s^D} + \sqrt{\gamma_a \gamma_s^P}) \]

- \( W_A \) = work of adhesion
- \( W_{Al} \) = work of adhesion in presence of liquid
- \( \gamma^D \) = dispersion component of surface free energy
- \( \gamma^P \) = polar component of surface free energy
- \( \gamma_{lv} \) = surface free energy of liquid
Stability of Epoxy/Cu Interface in Presence of Moisture

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\gamma$ (mJ/m$^2$)</th>
<th>$\gamma^D$ (mJ/m$^2$)</th>
<th>$\gamma^P$ (mJ/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>46.2</td>
<td>41.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Copper</td>
<td>1360</td>
<td>60</td>
<td>1300</td>
</tr>
<tr>
<td>Water</td>
<td>72.2</td>
<td>22.0</td>
<td>50.2</td>
</tr>
</tbody>
</table>

$W_A = 260.7\ \text{mJ/m}^2 \quad W_{Al} = -270.4\ \text{mJ/m}^2$

Effect of Moisture at Interface

- Based on Adsorption Theory, Epoxy/Cu interface debonds in the presence of moisture
- Supported by experimental interfacial fracture toughness recovery results
Postulate: Water is transported to the interface via nano-pore channels in the epoxy. Once water reaches the interface, a debond area is formed near the nano-pore channel.

Saturation Concentration:

\[ C_{sat} = \frac{\rho_{H_2O} (N_N V_N)}{V_{tot}} \]

Intact Bond Area at Interface:

\[ A_{bond} = A_{tot} - \pi N_N r_{debond}^2 \]
Fracture Mechanics

\[ G_c = Z \sigma^2 = Z \left( \frac{P_c}{A} \right)^2 \]

\[ G_{c,\text{dry}} = \left( \frac{P_{c,\text{dry}}}{A_{\text{tot}}} \right)^2 Z \]

\[ G_{c,\text{wet}} = \left( \frac{P_{c,\text{wet}}}{A_{\text{tot}}} \right)^2 Z \]

Postulate: interface outside the debond areas remains the same.

\[ \frac{P_{c,\text{wet}}}{A_{\text{tot}} - \pi N r_{\text{debond}}^2} = \frac{P_{c,\text{dry}}}{A_{\text{tot}}} \]

\[ G_{c,\text{wet}} = \left( 1 - \frac{\pi N r_{\text{debond}}^2}{A_{\text{tot}}} \right)^2 G_{c,\text{dry}} \]
For \( N \) Nano-pores Participating:

\[
G_{c,wet}(N) = \left( 1 - \frac{N \pi r^2_{debond}}{A_{tot}} \right)^2 G_{c,dry}
\]

For \( N+1 \) Nano-pores Participating:

\[
G_{c,wet}(N+1) = \left( 1 - \frac{(N+1) \pi r^2_{debond}}{A_{tot}} \right)^2 G_{c,dry}
\]

ODE

\[
\begin{align*}
\frac{dG_{c,wet}(f)}{df} &= -2G_{c,wet}(f) \quad \text{where} \quad f = \frac{N \pi r^2_{debond}}{A_{tot}} \\
G_{c,wet}(f) \bigg|_{f=0} &= G_{c,dry}
\end{align*}
\]

\[
G_{c,wet} = G_{c,dry} \exp \left[ \frac{-8C_{sat} \text{mm}^3}{mg} \left( \frac{r_{debond}}{D_N} \right)^2 \right]
\]
Implementation

- Determine a saturation concentration of adhesive
- Obtain toughness for that saturation concentration as well as for fully dry conditions
- \( r_{\text{debond}} \) is related to hydrophobicity
- Unless otherwise known for the adhesive, use an average nanopore diameter of 5.5 Å
Epoxy/Copper Interface

The graph shows the relationship between the saturation concentration of water ($C_{sat}$, mg H$_2$O/mm$^3$) and the fracture energy ($G_c$, J/m$^2$). The data points are indicated for different conditions: dry, 85% RH at 50°C, 85% RH at 65°C, and 85% RH at 85°C. A trend line is also shown for the analytical model.
Summary and Conclusions
(for Our Epoxy/Cu Interface)

Critical Concentration
• We did not find a critical concentration

Recovery
• Elastic modulus recovered a lot (>70%)
• Interfacial fracture toughness recovered very little (< 7% after 168 h at 80C/55%RH)

Rate of Degradation

\[ G_{c,wet} = G_{c,dry} \exp \left( \frac{-8C_{sat} \text{mm}^3}{\text{mg}} \left( \frac{r_{debond}}{D_N} \right)^2 \right) \]

Oxidation
• No effects