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Adhesive Failure and the Aging of Adhesive Joints

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Research Focus

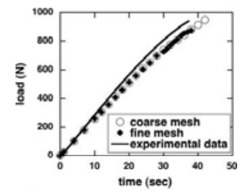
Materials

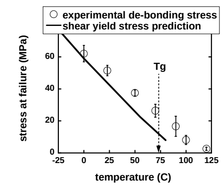
Polymers: coatings, underfills, encapsulants, foams, PWBs

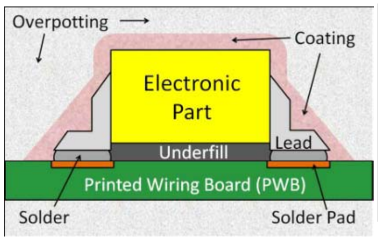
Solders: tin-lead, lead-free

Performance Metrics

Solder Thermomechanical Fatigue
Component Stresses
Polymer: Cohesive Failure/Adhesive Failure



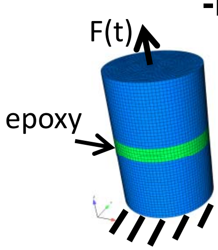


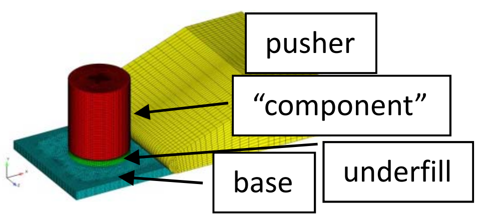


Surface Mount Technology Packaging:
Develop a fundamental understanding of how materials and design choices for packaging affect electrical components in thermal and dynamic loadings

Predictive Tools

-Constitutive equation
-Model Validation





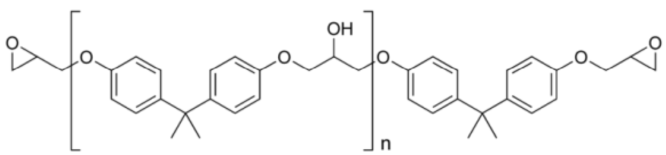
Processing Schemes

UV cure

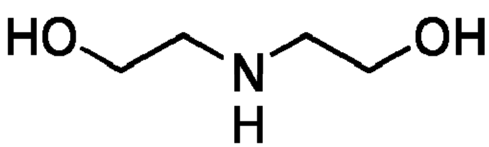
Adhesive Joints

Adhesive: 828/DEA

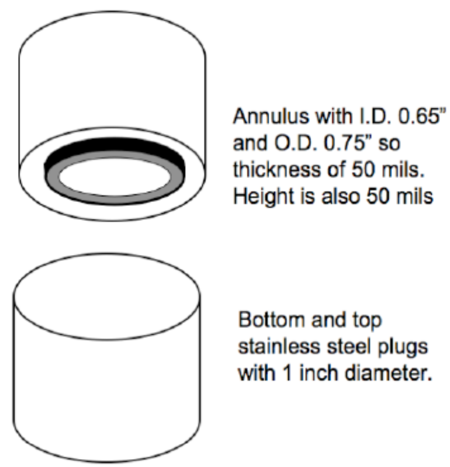
EPON® Resin 828
Diglycidylether of Bisphenol-A

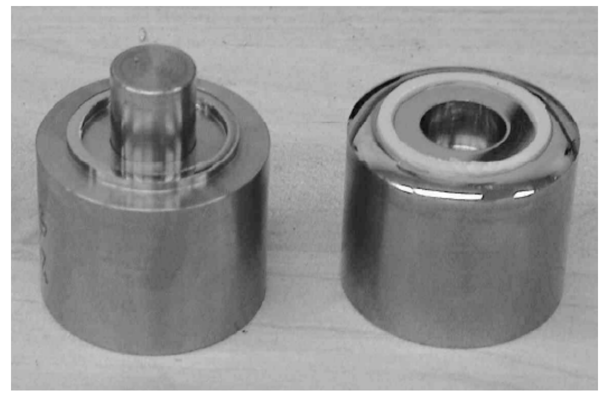


Diethanolamine



Test Geometry: Napkin-Ring





de Bruyne and Houwink (eds) *Adhesion and Adhesives*, Elsevier, London p.92 (1951)

http://www.sandia.gov/polymer-properties/828_DEA.html

Discussion Topics

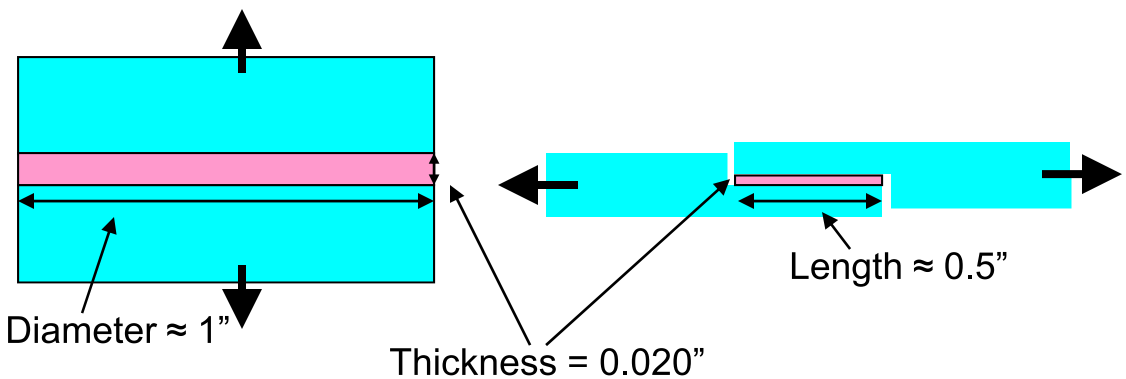
1. **Adhesive joint geometry and stress states**

2. **Measuring and predicting the critical stress for debonding and how this changes with age in a humid environment**

Stress State of Adhesive During Cure and Cool-down

ASTM Standards:

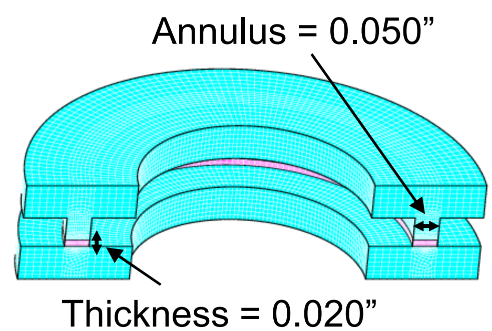
Butt Tension | **Lap Shear**



Large diameter(length)-to-thickness ratio: ~25-50

- **large aspect ratio in epoxy bondline leaves little free surface to relieve shrinkage strains**
- **constrained volume generates significant residual stresses during cure and cooling before any load is applied**

Napkin-Ring



Relatively small annulus-to-thickness ratio: ~2

- **more free surface and less volume constraint**
- **minimal cure and thermal stress build-up in adhesive before test loading**

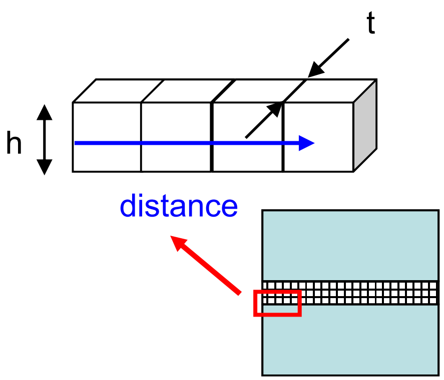
If residual stresses are high, then epoxy is closer to failure load

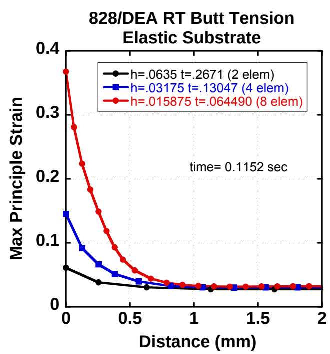
Review of Test Geometry: Why the Napkin-Ring?

Stress State of Adhesive During Load

ASTM Standards:

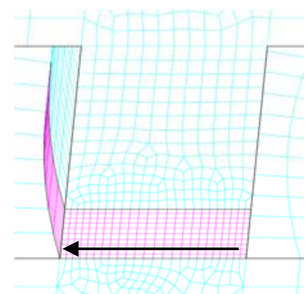
Butt Tension

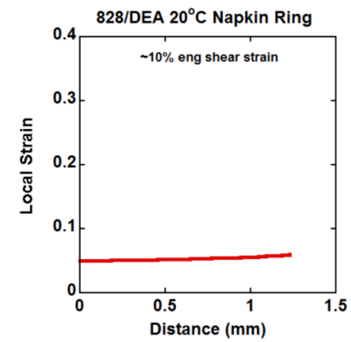


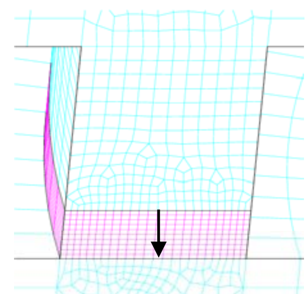


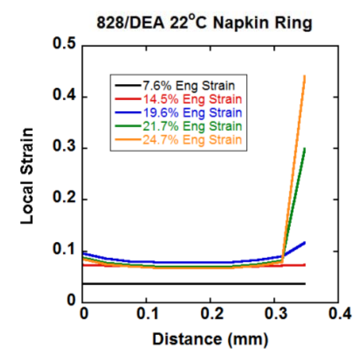
- •Sample has high stress/strain concentration at triple interface
- •Model results are sensitive to mesh refinement at that point

Napkin-Ring









Relatively uniform stress/strain distribution across entire bond

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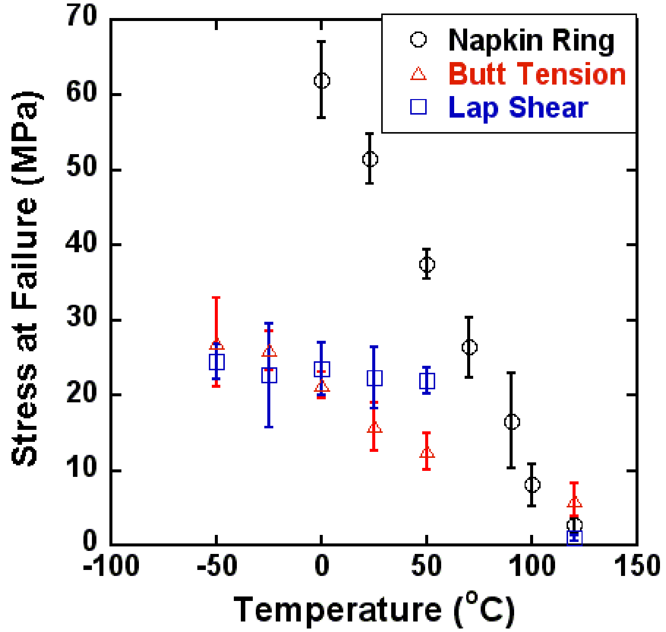
Review of Test Geometry: Why the Napkin-Ring?

Assume: Stress = (Applied Load)/Area



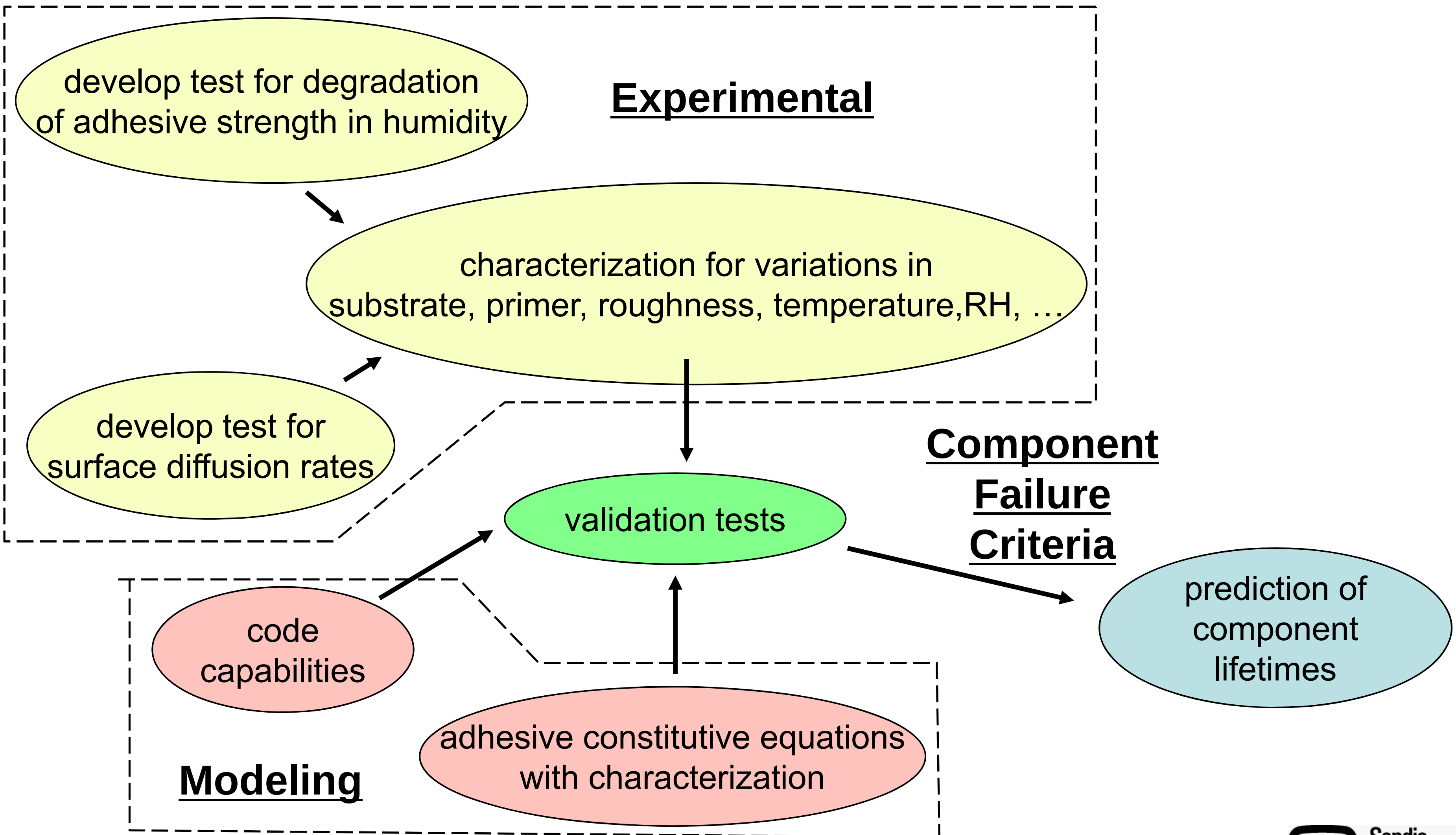
- Cure/Thermal residual stresses in BT/LS are much higher than napkin ring, so epoxy begins test closer to failure point
- On loading BT/LS strains are concentrated at the triple interface rather than being distributed more uniformly like napkin ring
- BT/LS samples are more susceptible to edge defects

Discussion Topics

1. **Adhesive joint geometry and stress states**

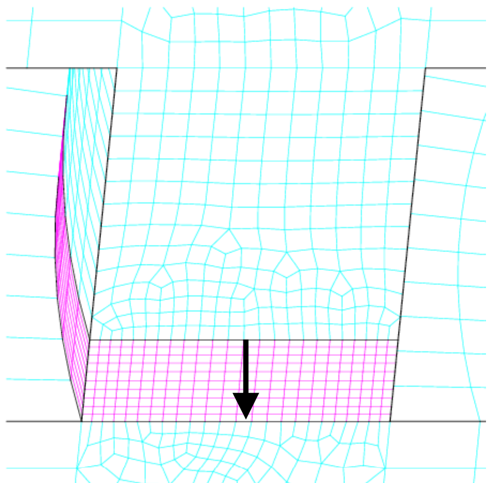
2. **Measuring and predicting the critical stress for debonding and how this changes with age in a humid environment**

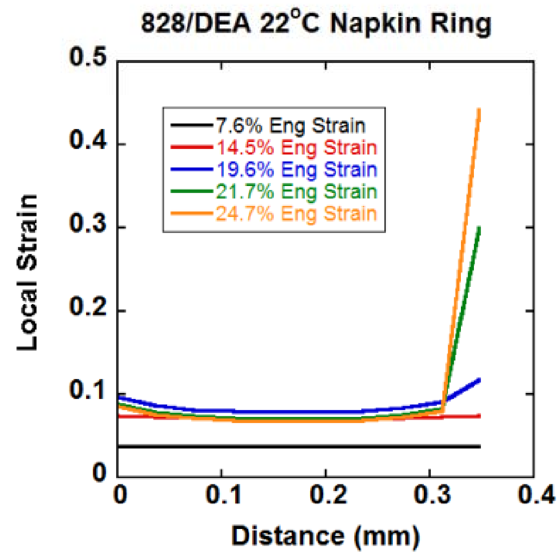
Adhesive Joint Aging in Humid Environments



Dry Adhesive Failure on Napkin-Rings

Predicting the Critical Stress/Strain for Debonding





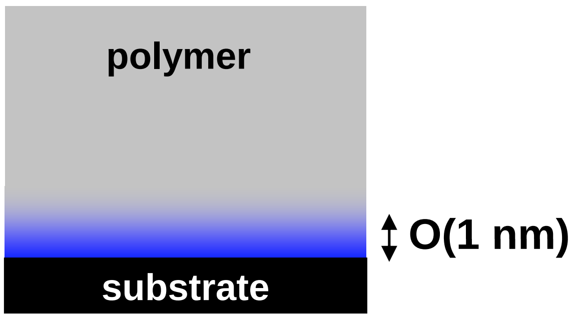
<u>Failure Mechanism:</u>

- Highest stress regions at bonding interfaces
- Highest adhesive confinement at lower interface
- Polymer in interfacial region shows highest strains and yields prior to bulk polymer
- Premature yield concentrates strain in the interfacial region
- High strain concentrations further increase relaxation rates until strain levels are no longer sustainable

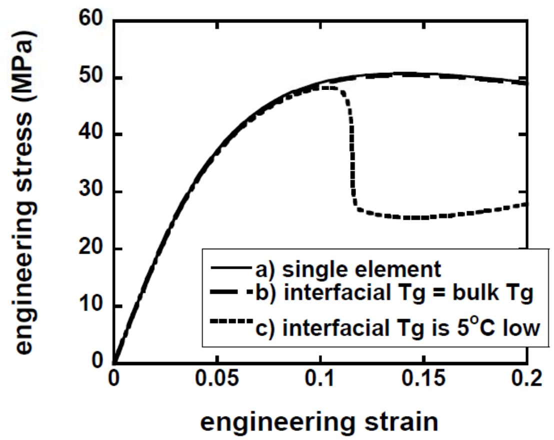
Failure is cohesive, although it visually appears adhesive

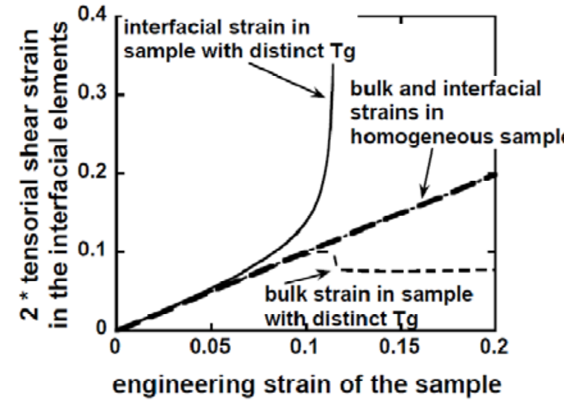
Dry Adhesive Failure on Napkin-Rings

A "Weak" Interfacial Layer will further Promote Failure at the Interface



Entropic, $\Delta T_g \sim 5^oC$





Same failure mechanism, exacerbated by reduced polymer T_g at interface

Failure Mechanism:

- Highest stress regions at bonding interfaces
- Highest adhesive confinement at lower interface
- Polymer in interfacial region shows highest strains and yields prior to bulk polymer
- Premature yield concentrates strain in the interfacial region
- High strain concentrations further increase relaxation rates until strain levels are no longer sustainable

Failure is cohesive, although it visually appears adhesive

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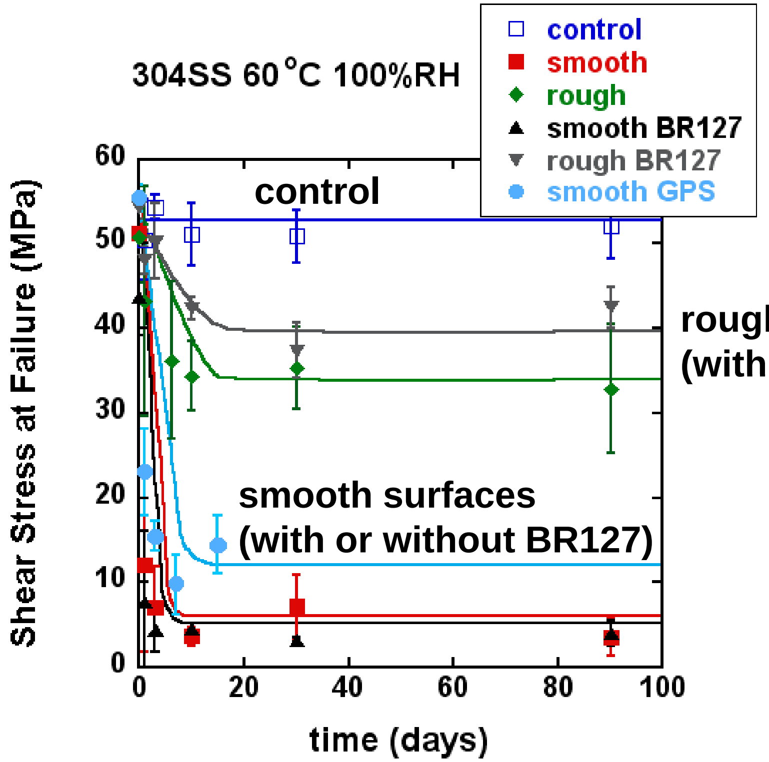
Wet Adhesive Failure on Napkin-Rings

<u>**828/DEA bonding 304SS of varied surface preparations**</u>



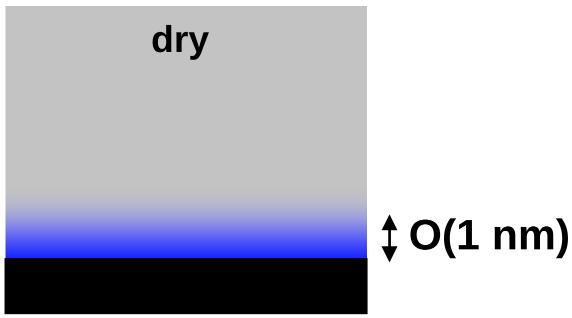
Effects of humidity can be measured:

- Equilibrium effect of water on bond strength reached in days
- Surface roughness critical in determining magnitude of water effect on bond strength

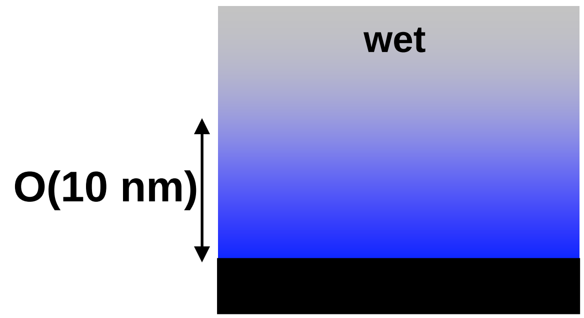
Adolf, D. B., *Predicting Stresses in Thermosets*, Sandia National Laboratories, Albuquerque, NM, 2010.

Wet Adhesive Failure Mechanism

Reduced T_g: wet vs. dry

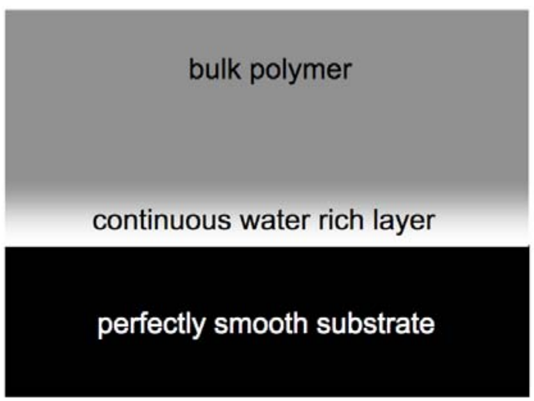


Entropic, ΔT_g ~ 5^{o}C

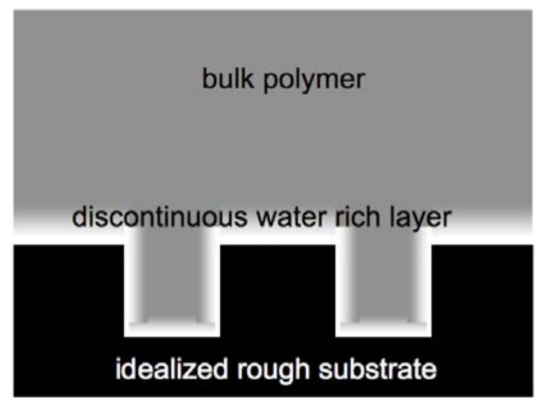


Plasticization, ΔT_g ~ 50^{o}C

Moisture Effects on Bond Strength: smooth vs. rough surface



Clean break across reduced T_g interface



Bulk polymer must be traversed

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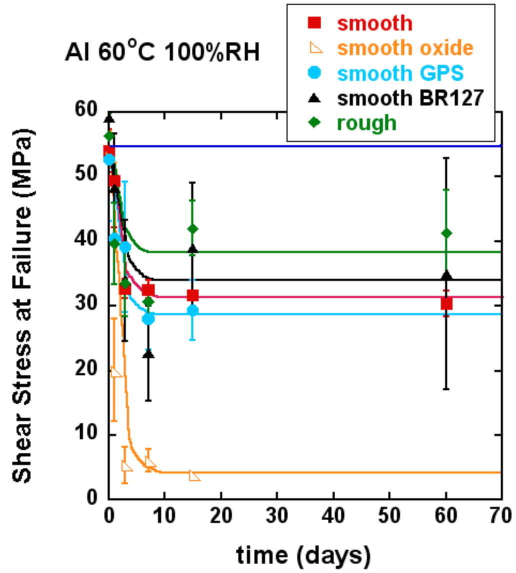
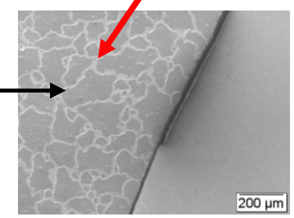
Wet Adhesive Failure: Adherend Composition

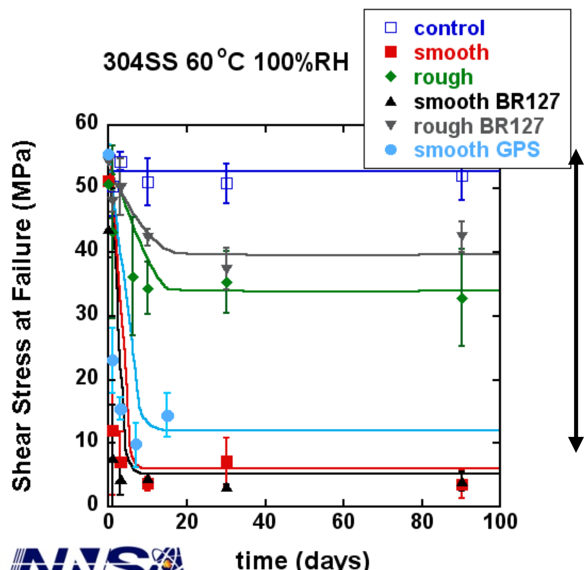


decrease on rough aluminum

decrease on smooth aluminum (with or without GPS or BR127)

decrease on smooth oxide





decrease on rough steel (with or without BR127)

decrease on smooth steel (with or without GPS)

- decrease in strength on smooth surfaces is less for Al than steel
- GPS does not minimize loss of adhesive strength
- oxide layer on Al significantly decreases wet strength

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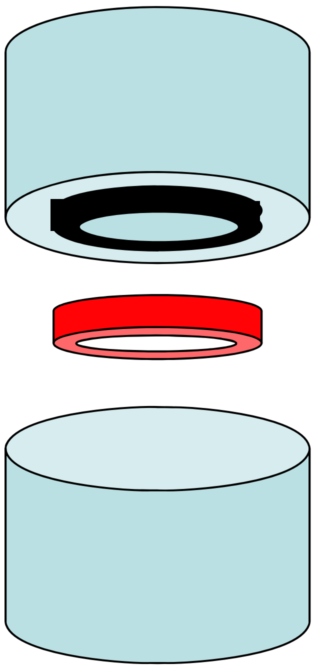
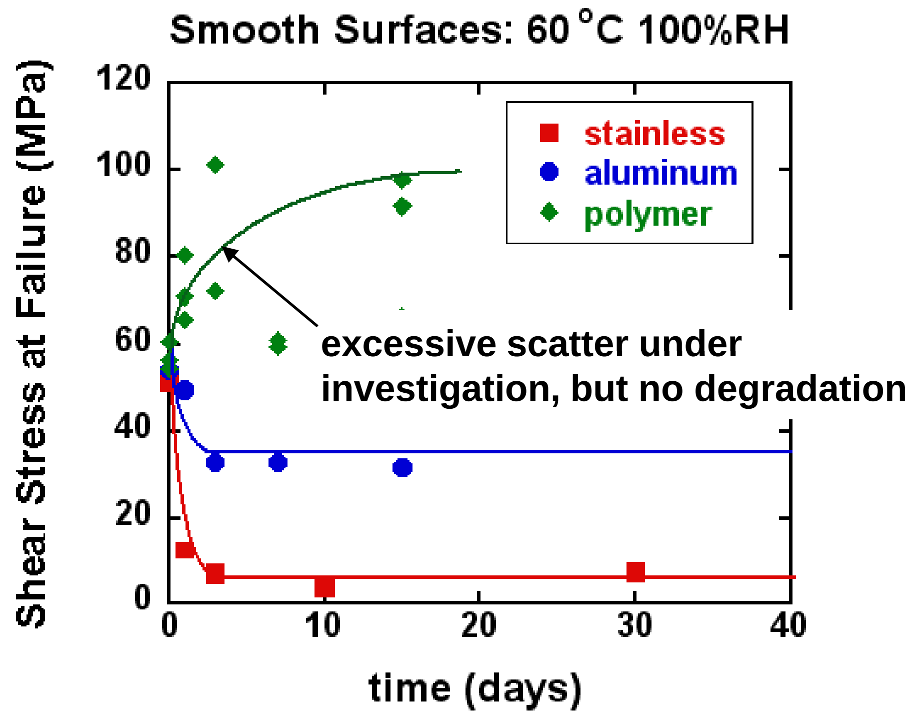
Wet Adhesive Failure: Adherend Composition



upper plug with annulus
alumina-filled epoxy (T_g~160°C)

bonded adhesive
unfilled epoxy (T_g~70°C)

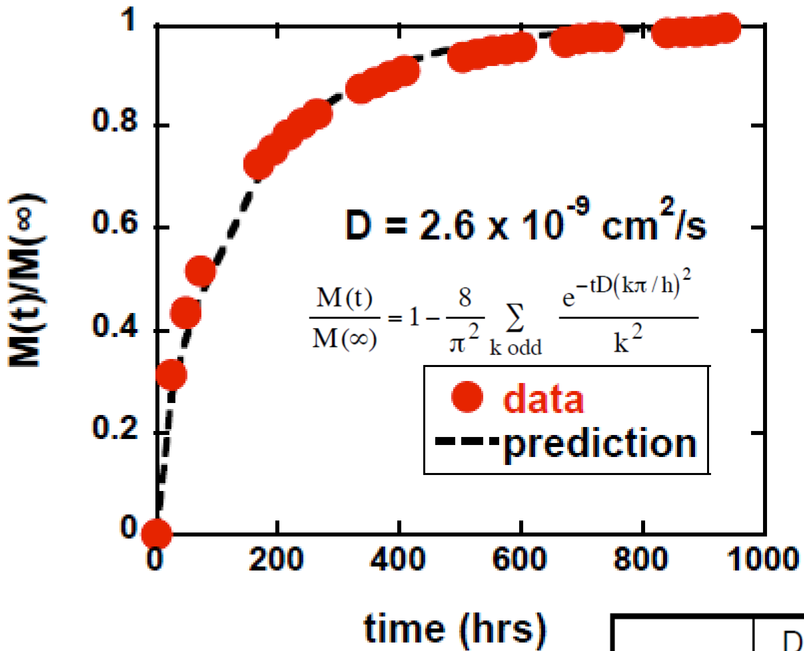
lower plug
alumina-filled epoxy (T_g~160°C)



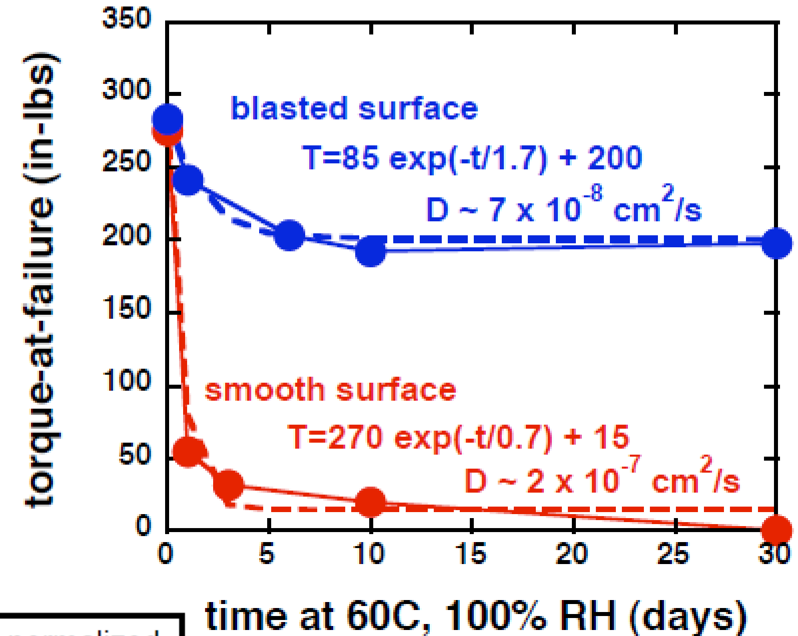
polymer-polymer interfaces (e.g., adhesive to composite) show no degradation
- **no thermodynamic driving force for water to migrate to interface**

Predicting Humid Joint Aging: Water Diffusion

Mass Gain: 60°C 100% RH



Napkin Ring Adhesion: 60°C 100% RH



	D (cm^2/s)	normalized to bulk D
smooth	1.6 x 10^{-7}	62
rough	6.8 x 10^{-8}	26
bulk	2.6 x 10^{-9}	1

Interfacial diffusion ~50 times faster than bulk diffusion

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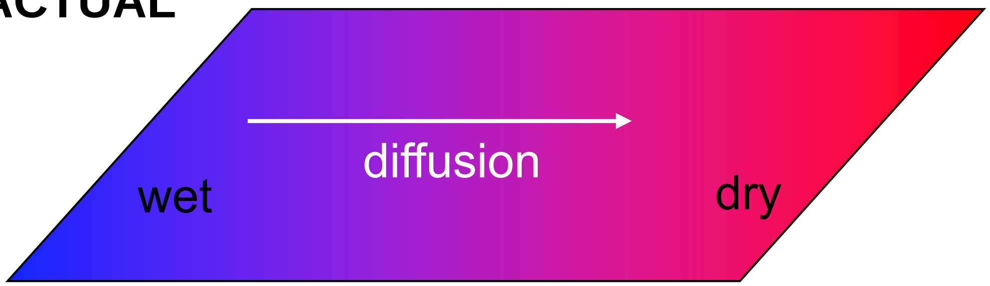
Predicting Humid Joint Aging: Simplest Scheme

ACTUAL

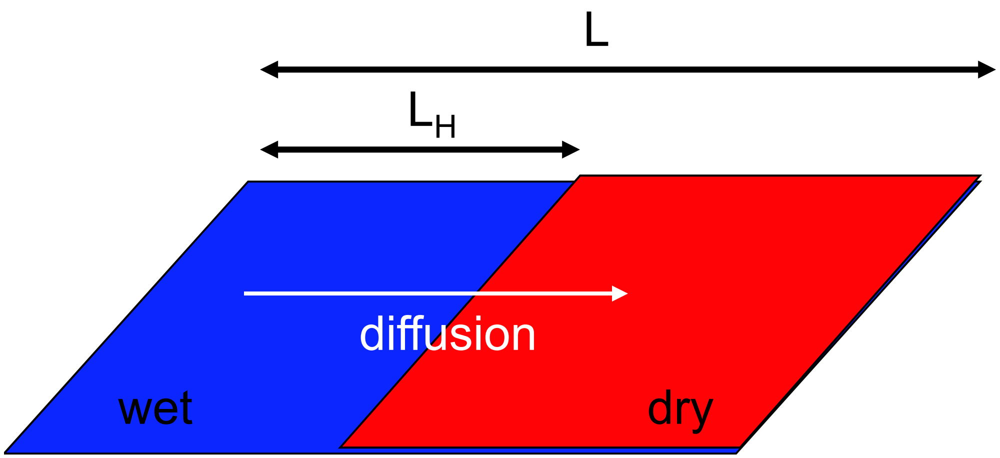


EXAMPLE CALCULATION

$$\text{total strength} = H\left(\frac{L_H}{L}\right) + V\left(\frac{L - L_H}{L}\right)$$

where $L_H = (Dt)^{1/2}$

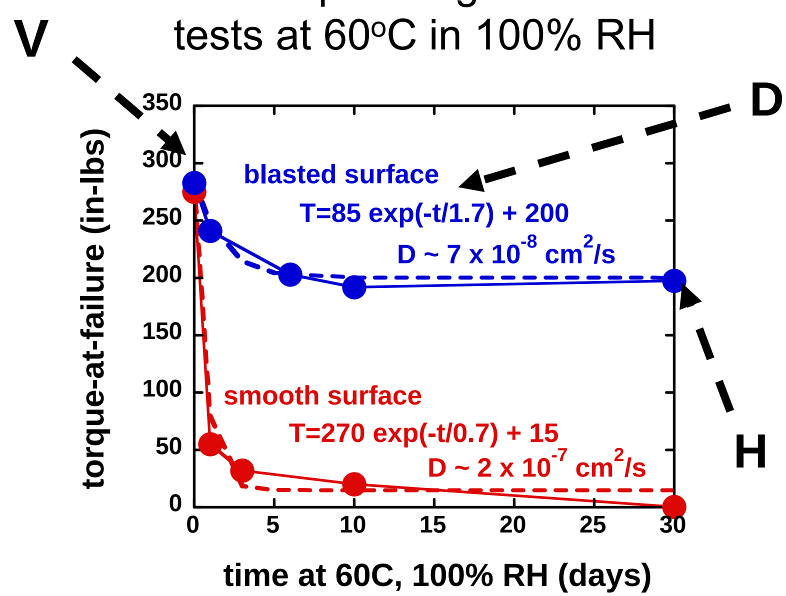
IDEALIZED



“humid” strength = H

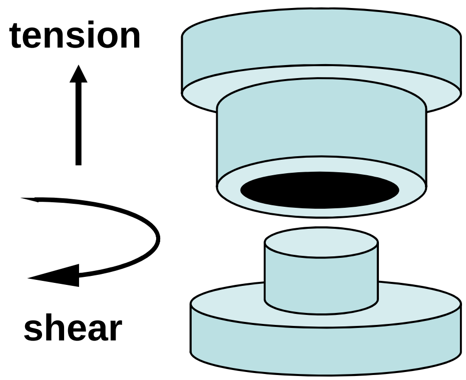
“virgin” strength = V

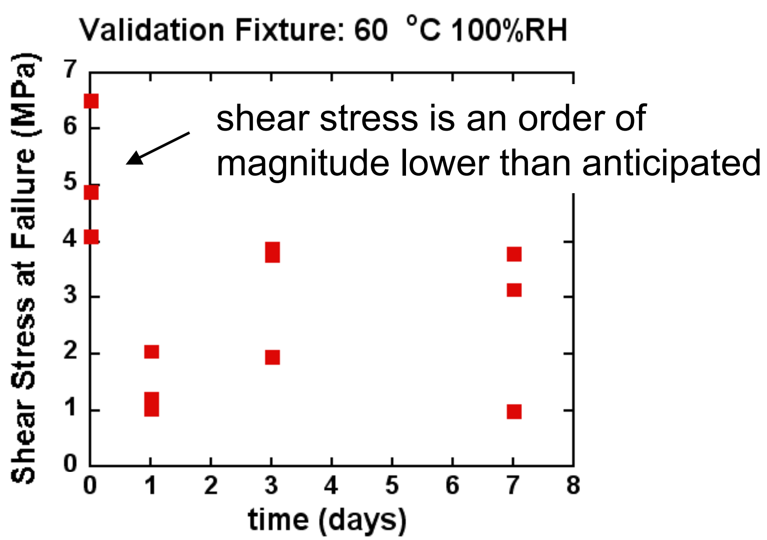
from napkin ring adhesion tests at 60°C in 100% RH



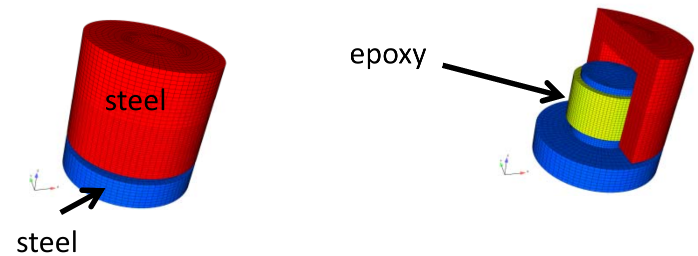
Testing Predictions: Validation Geometry

Experimental

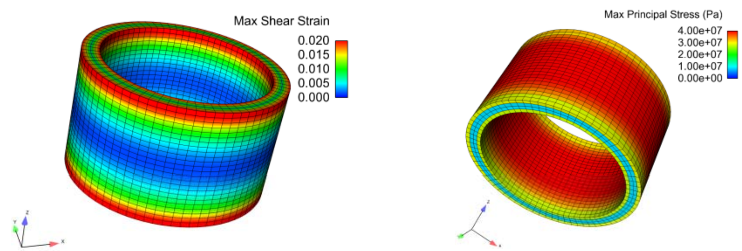




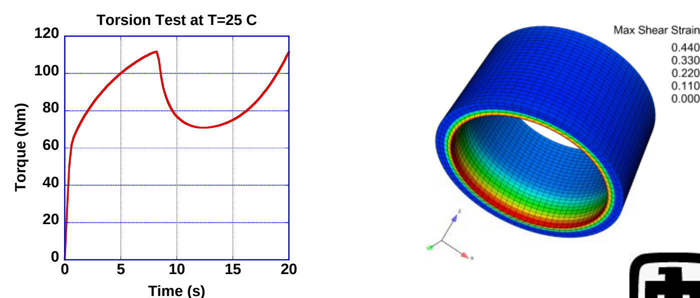
Stress Analysis



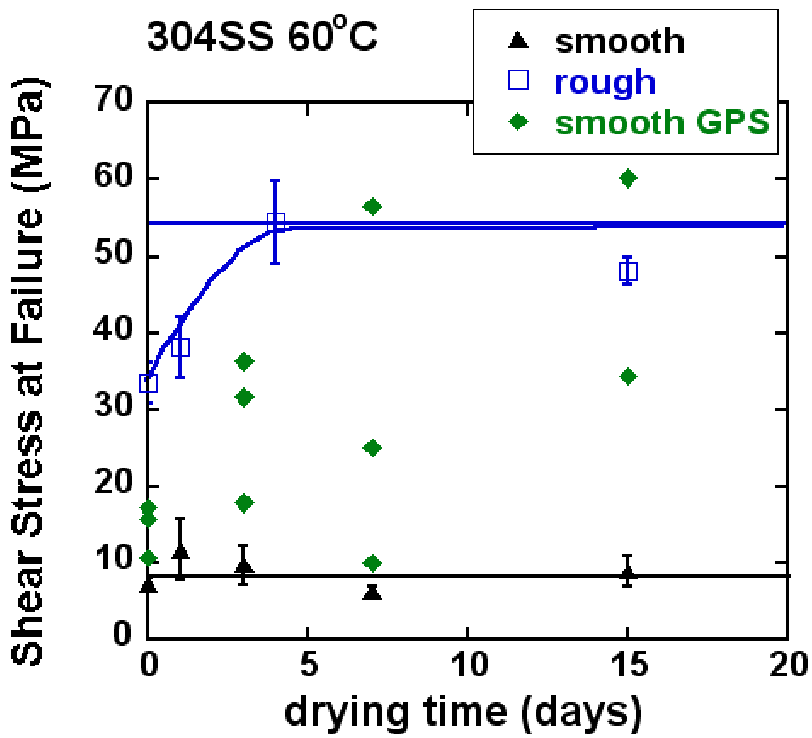
Thermal Stress/Strain

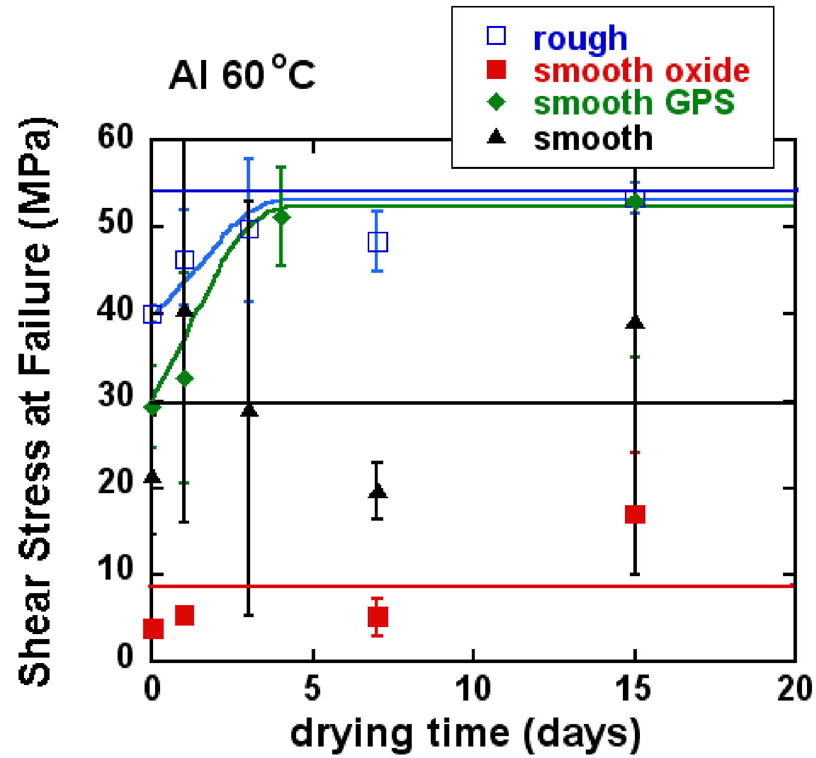


Rotational Loading Strain



Can Adhesive Joints be "Healed"





- Original strength is regained on rough surfaces
- No regaining of strength on smooth, unprimed surfaces
- GPS allows regaining of original strength on smooth Al but scattered results on steel

Summary

- Failure isn't truly adhesive failure, typically the polymer fails cohesively and this can occur in a weak interfacial layer
- Loads to adhesive failure do depend on the joint geometry…choose carefully
- Napkin-Ring geometry is an excellent tool to characterize wet adhesive failure: fast (~2 weeks to equil.), directly yields stress-to-failure, simplicity allows mechanistic interpretation
- Bonding materials and surface preparation significantly affect the role of moisture on adhesive strength
- Degradation effects of moisture can be healed in some cases

Back Up Slides

Adhesion Task Four-Question Chart

What are you trying to do in this task?

- Measure and predict the critical stresses for adhesive de-bonding
- Measure and predict the change in de-bonding stress when components age in dry and humid environments
- Relate the de-bonding stress to processing history

What makes you think you can do it?

- Leverages previous SNL-funded research on measuring and predicting adhesive strength
- Adhesion working group involves DOE and DoD members to direct goals and share knowledge/experience

What difference will it make?

- Component designs can be more robust if de-bonding stress margins are known
- Knowledge of aging mechanisms improve material selection for given environments
- Processes can be defined to improve adhesive strength

What / When / To Whom Will You Deliver?

- Deliverables are metrics and procedures to measure and predict de-bonding
- Delivery will be staged to provide capability on successively more difficult systems
- Adhesion working group will identify a DoD contact to share capabilities