Building with Adhesion: Pressure Sensitive Adhesion and the Geckskin® Technology

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Adhesion All Around
THINK YOU KNOW TAPE?
What is Tape?

- Backing
- Pressure Sensitive Adhesive
- Release Liner

What is in a Pressure Sensitive Adhesive?

- Entangled and crosslinked polymers
  - Typically with low glass transition temperatures
- Tackifiers
  - Small molecule resins, with high glass transition temperature
- Stabilizers
S: Spreading Coefficient

\[ S = f(\text{surface energies}) = \gamma_{sv} - \gamma_{sl} - \gamma_{lv} \]

\( S \geq 0 \) --- spread completely and spontaneously

However other forces may act---and overcome barriers

Maximizing interfacial area is always the first strategy for strength

Surface preparation, primers can help
Described by fracture mechanics theory

\[ G: \text{Strain Energy Release Rate} \]

\[ G = f(\text{applied force or displacement, mechanical properties of adhesive and substrate, size and shape of bond}) \]

\[ G \geq G_c --- \text{debonding (fracture)} \]

\[ G_c = f(\text{materials properties of both the adhesive and substrate (which are typically dependent upon time, temperature, rate, humidity, etc.)}) \]
## Materials Properties Controlling Separation

### Bond Types and Typical Energies

<table>
<thead>
<tr>
<th>Type</th>
<th>Bond Energy (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Bonds</strong></td>
<td></td>
</tr>
<tr>
<td>Ionic</td>
<td>600-1100</td>
</tr>
<tr>
<td>Covalent</td>
<td>60-700</td>
</tr>
<tr>
<td>Metallic</td>
<td>110-350</td>
</tr>
<tr>
<td><strong>Secondary Bonds</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrogen bonds</td>
<td>10-40</td>
</tr>
<tr>
<td>Van der Waals bonds</td>
<td>0.08-40</td>
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</table>

$G_o$, $G_c$, $W$: Describes the strength of the interfacial bond, units are energy per area

**Elastic Modulus ($E$):** Describes material’s resistance to deformation. Units are force per area, or stress, e.g. MPa, PSI. ($E'$ and $E''$ are related viscoelastic parameters.)

**Poisson’s Ratio ($\nu$):** Describes a material’s propensity to strain in a direction orthogonal to an applied strain
Typical Peel and Tack Curves
Classical Theories for Quantifying Adhesion

Johnson, Kendall, and Roberts - 1971

\[ a^3 = \frac{3R}{4E^*} \left( P + 3\gamma \pi R + \sqrt{6\gamma R P_o + (3\gamma \pi R)^2} \right) \]


Maugis and Barquins – 1978

\[ G = -\left( \frac{4a^3E^*}{3R} - P \right)^2 \]


Adherence Force

\[ P_{\text{adherence}} = -\frac{3}{2} \gamma \pi R = -\frac{3}{2} G_c \pi R \]
Classical Theories for Quantifying Adhesion

Kendall - 1975

\[ G = \left( \frac{F}{b} \right)^2 \frac{1}{2dE} + \left( \frac{F}{b} \right) (1 - \cos \theta) \]

Elastic Contribution  Potential Contribution

\[ \left( \frac{F_c}{b} \right)^2 \frac{1}{2dE} + \left( \frac{F_c}{b} \right) (1 - \cos \theta) - G_c = 0 \]

\[ \theta \to \frac{\pi}{2} \quad F_c = bG_c \]

\[ \theta \to 0 \quad F_c = \sqrt{2b^2 dG_c E} \]

Classical Theories for Quantifying Adhesion

Gent - 1974  \textit{Short, thick joint under shear loading}

\begin{align*}
G &= \frac{F^2 t}{2 A^2 \mu} \\
F_c &= \sqrt{\frac{2 G_c A^2 \mu}{t}}
\end{align*}

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Nature and Technology
Gecko = evolutionary innovation
• Micro- and Nano-scale fibrils partial solution for geckos and insects

• Direct mimicry did not lead to scalable engineering

What is the scaling parameter to guide adhesion force control on all length scales?
Scaling adhesion to large sizes?
• Developed **theory** to hypothesize what controls **force capacity** \( (F_c) \) for reversible adhesives used for biological locomotion.

• **Assumptions:**
  • **Forces balance** (equilibrium)
  • **Energy in = Energy Out**
    • Contrary to current adhesives!!!
    • Organisms that climb with adhesion don’t want to lose energy!
  • **Nature designs around instability**

\[
\text{Force Capacity} = \left[ \text{van der Waals} \right] \frac{\text{Area}}{\text{Compliance}}
\]
Can we define a problem to give general guidance:

\[ U_{Total} = U_{Elastic} + U_{Work} + U_{Interface} \]

1. Assume equilibrium
\[ \frac{\partial U}{\partial A} = 0 \]

2. Assume unstable failure when maximum load is achieved
\[ \frac{\partial^2 U}{\partial A^2} \leq 0 \]

3. Consider systems that want stored energy to be recoverable,
\[ \Delta U = U_{final} - U_{initial} = 0 \]

\[ F_C = \sqrt{G_C} \sqrt{\frac{A}{C}} \]

\( F_C \): Maximum sustainable force
\( G_C \): Adhesion Energy
\( A \): Interfacial area
\( C \): Compliance in direction of loading

Bartlett, Croll, King, Paret, Irschick, Crosby, *Advanced Materials* 2012.
Scaling Theory Confirmed

\[ F_c = \sqrt{G_c} \sqrt{\frac{A}{C}} \]

\[ \frac{1}{C} \]

\[ F, \Delta \]

\[ t/h < 0.76 \]
Force capacity follows scaling

\[ F_c = \sqrt{G_c \sqrt{\frac{A}{C}}} \]

Normal Adhesion: Experimental Design

Rigid Punch

2a

Soft Substrate

t

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<tr>
<th>a (mm)</th>
<th>0.17</th>
<th>0.75</th>
<th>1.4</th>
<th>1.98</th>
<th>2.59</th>
<th>3.17</th>
<th>3.83</th>
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<tr>
<td>t (mm)</td>
<td>0.53</td>
<td>1.4</td>
<td>3.2</td>
<td>10.6</td>
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0.016 < a/t < 7.22

Materials
[PMMA-PnBA-PMMA] triblock copolymers in 2-ethylhexanol
-15 wt% (~11 vol%)
Normal Adhesion

Nanopositioner →
Load Cell →
Rigid punch →
Substrate →
Microscope →

\[ \text{Force}, F \text{ (mN)} \]
\[ \text{Displacement}, \Delta \text{ (\(\mu\)m)} \]

- Approaching
- Retracting

Increasing \(a\)

Force Capacity Predictions

\[ C = \frac{3}{8Ea} \left[ 1 + 1.33 \frac{a}{t} + 1.33 \left( \frac{a}{t} \right)^3 \right]^{-1} \]

\[ A = \pi a^2 \]

\[ F_c \sim \sqrt{G_c} \sqrt{\frac{A}{C}} \]

\[ \frac{F_c}{a^{3/2}} \sim \sqrt{1 + 1.33 \frac{a}{t} + 1.33 \left( \frac{a}{t} \right)^3} \]

Applying the Scaling Relationship

How do take advantage?

\[ F_c = \sqrt{G_c} \sqrt{\frac{A}{C}} \]
Tuning Force Capacity

NYLON ~ 90 LBS
CARBON FIBER / KEVLAR ~ 300 LBS
CARBON FIBER ~ 700 LBS
Draping with High Stiffness Fabrics

Mike Bartlett, Ph.D. student
Dan King, Ph.D. student

\[ F_C = \sqrt{G_C} \sqrt{\frac{A}{C}} \]
Conform to Reality
Expanding the Scaling Theory

$$F_c \sim \sqrt{G_c} \sqrt{A/C}$$

$$\sigma = \exp\left(\frac{-\beta}{10 \times G_{c,N}/E_p}\right)\left(\frac{2G_{c,S}}{L_s^2 \left(\frac{1}{t_p E_p + t_s F} + \frac{3t_p}{E_p}\right)}\right)^{1/2}$$

Optimal modulus identified for roughness range and desired performance

Stability: Tendon-Skin Connection
Can a 3 year old use it?

Ability to conform at multiple length scales is related to both elastomer and fabric weave.

The two feet of a 50 g tokay gecko can produce about 20 N of adhesive force ~ a bag of 20 apples

\[ F_c = \sqrt{G_c} \sqrt{\frac{A}{C}} \]

Tokay Gecko on Glass
Scaling

\[ F_c = \sqrt{G_c} \sqrt{\frac{A}{C}} \]

- PDMS w/o fabric
- Fabric backing
- Engineering fabric
- Macro patterns
- Advanced pad
- Natural data

G. Huber, et al., *Biology letters*. 1, 2 (2005)
insectes-net.fr

Imageshack.us
Measuring Performance Variation

Scaling Across Species

Renewable Materials

Hemp Fabric/Natural Rubber

Load (N) vs. Extension (mm)

- Force Capacity, $F_c$ (N)
- $F_c$ (max) = 637 N
- $F_c$ (avg) = 572 N

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Final Thoughts

- Pressure sensitive adhesives provide a tunable, robust materials platform for building construction
- Scaling principles provide critical lessons for enable design of high performing adhesive interfaces
- Unstable fracture provide new insight into climbing----and maybe new opportunities for novel building design
Funding

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Center for UMass Industry Research on Polymers

Felsuma, LLC was founded in April 2013 as a private entity to commercialize Geckskin™. Professor Crosby and Professor Irschick have a financial interest in Felsuma, LLC. A conflict of interest committee at the University of Massachusetts is established to manage potential conflicts.

Professor Crosby also serves as the academic advisor for the Pressure Sensitive Tape Council and receives an honorarium for this service.
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Current

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(UMass, Biology)