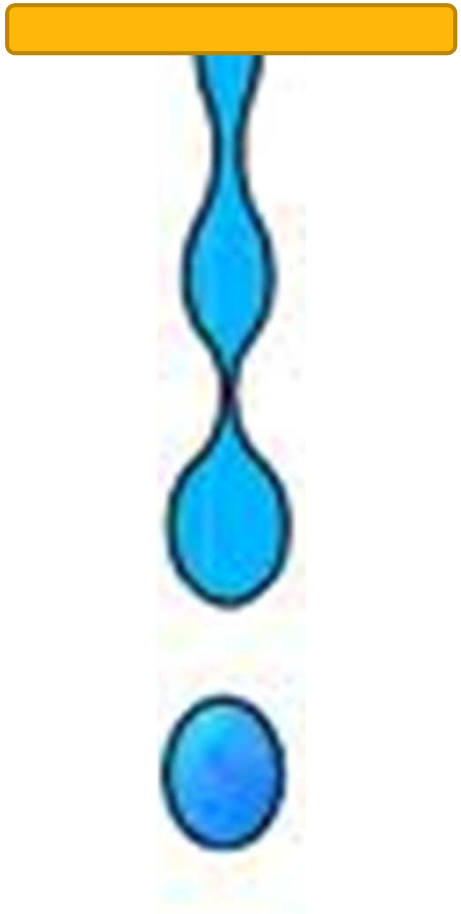
DETERMINE THE FORCE NECESSARY TO REMOVE A PIECE OF ADHESIVE TAPE FROM A HORIZONTAL SURFACE. INVESTIGATE THE INFLUENCE OF RELEVANT PARAMETERS.

Adhesive tape

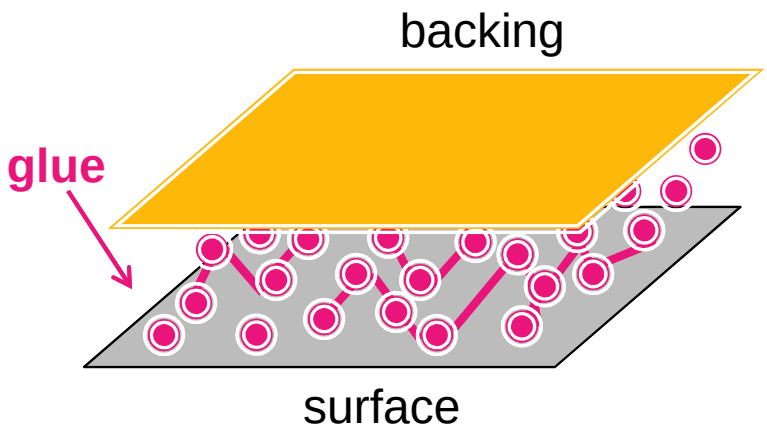
Overview

- microscopic view
  - adhesion and cohesion - rupture
- macroscopic view
  - fracture energy of adhesives
- experimental setup
  - adhesive tape properties
  - conditions
    - angle
    - width
    - temperature
      - surface tension model
- conclusion



Adhesion and cohesion

- intermolecular interactions
- ADHESION force between two different bodies (or different surface layers of the same body)
  - tape-glue, glue-surface
- COHESION force attraction between like-molecules
  - van der Waal's forces
  - glue ~ forms threads

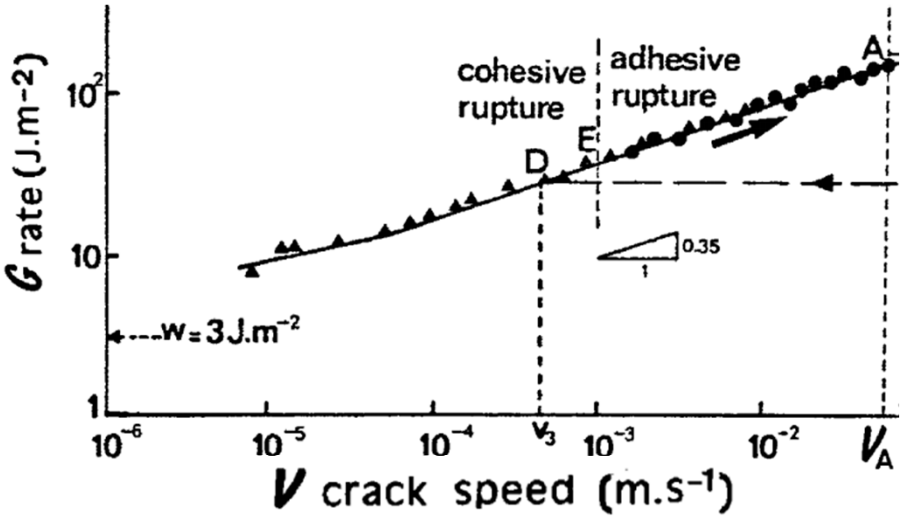


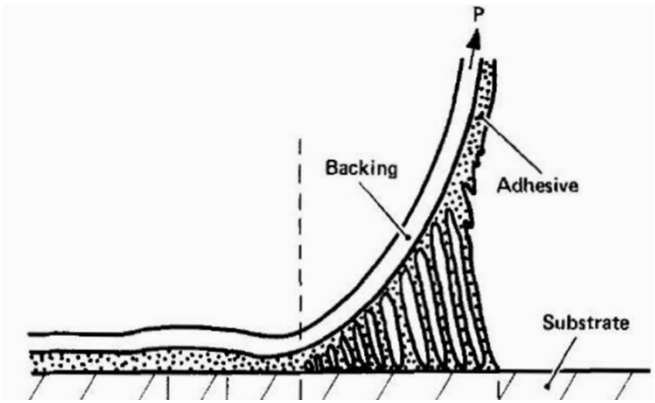
Cohesive rupture

Adhesive rupture

Rupture

- cohesive/adhesive rupture
  - obtained peel rates ~
  - force necessary!
    - greater force
      - higher peel rate
  - peel off starting
    - glue forms N_0 threads
      - as the peel-off starts
      - number ~ conserved

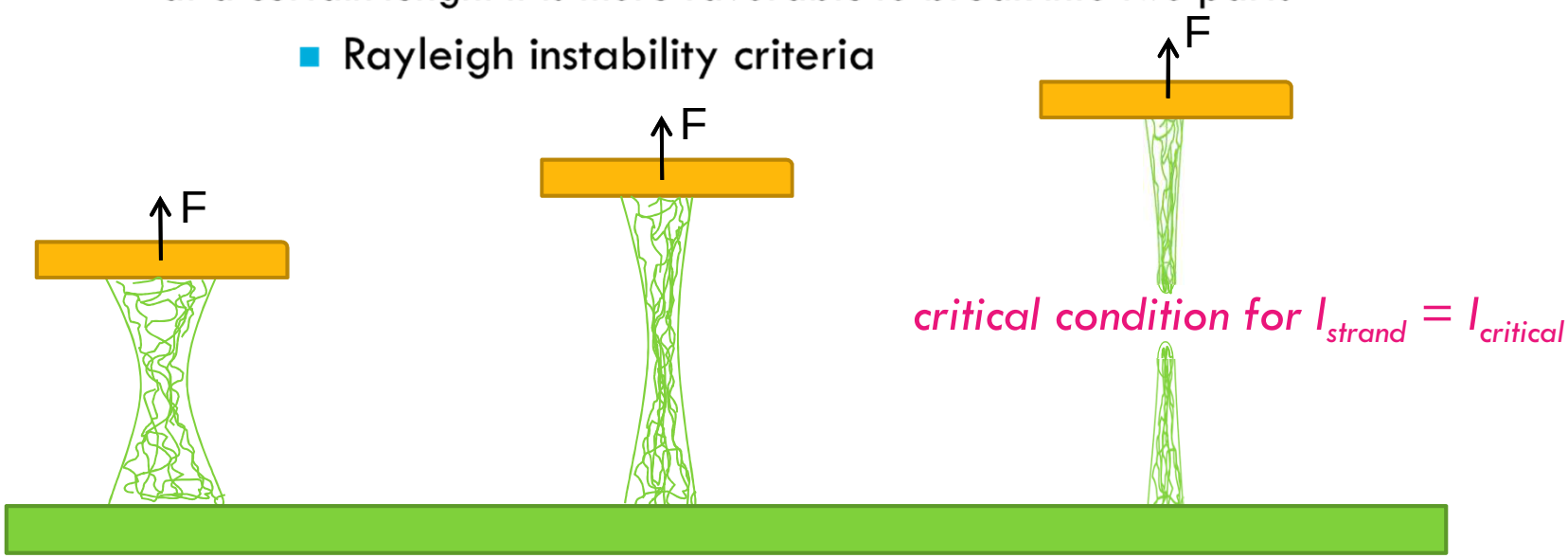




*A. J. Kinloch, C. C. Lau, J. G. Williams, The peeling of flexible laminates. Int. J. Fracture (1994) c

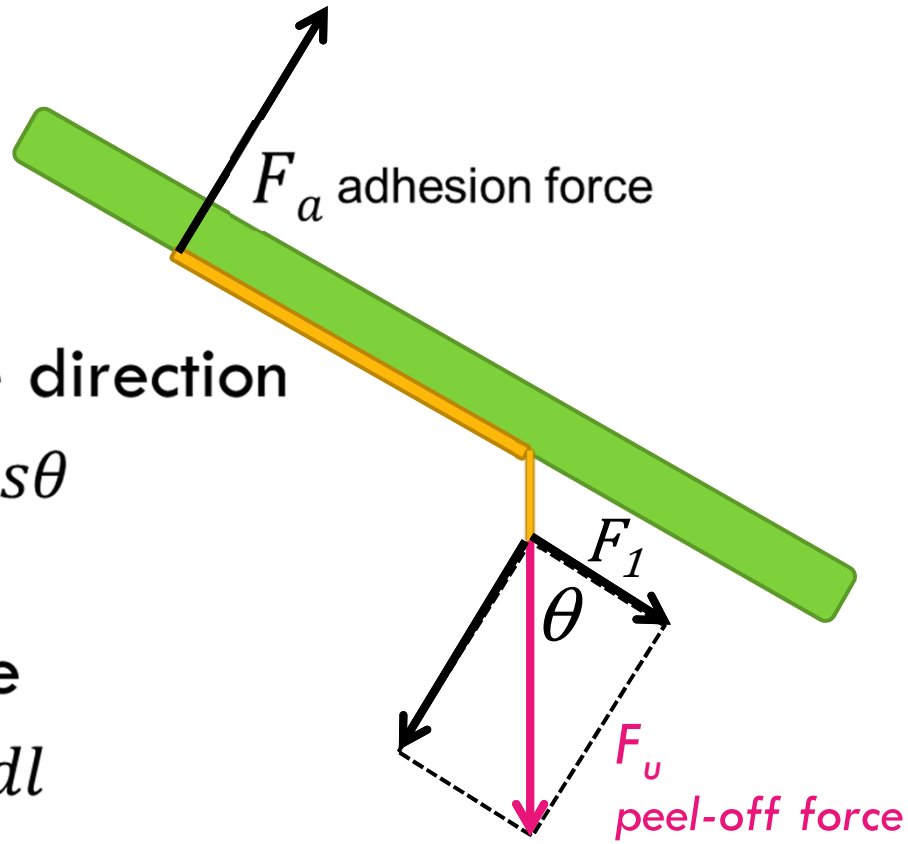
Adhesion and cohesion

- total glue volume is conserved
  - $V = Nr^2\pi l$
    - N - number of formed threads (remains constant over peel-off)
    - r – radius, l – lenght of a thread
  - critical condition of thread fracture depends on surface tension minimisation
    - at a certain lenght it is more favorable to break into two parts
      - Rayleigh instability criteria



Adhesive energy/surface G_a

- work needed to pull-off the force to overcome
  - adhesion and elongation
  - $dU = Fu(1+\varepsilon)dl$
  - ε *elongation* $(\frac{\Delta l}{l_0})$
- no work done in the plate direction
  - $W(F_1) = 0$ subtract $F_u cos\theta$
    - $F_1 = Fucos\theta$
- work of the peel-off force
  - $dU = Fu(1+\varepsilon - cos\theta)dl$



Adhesive energy/surface G_a

- describes tape-surface bond

$$G_a = \frac{1}{b}\left(\frac{dU}{dl} - \left(\frac{dU_s}{dl} + \frac{dU_d}{dl}\right)\right)$$

b width
l lenght
ε elongation
σ tensile strength

- MOSTLY COHESIVE RUPTURE
  - PEEL RATE 1mm/s

- **ADHESIVE ENERGY/SURFACE**
  - work done peel-off force – stretching and dissipation

- peeling-off work $dU = F_u(1+\varepsilon-\cos\theta)dl$
- stretching + dissipation work $d(U_s+U_d) = bh\int_0^{\varepsilon}\sigma d\varepsilon dl$

Adhesive energy/surface G_a

- describes tape-surface bond per glued surface area
  - final expression:

$$G_a = \frac{F_u(1+\frac{\varepsilon}{2}-\cos\theta)}{b}$$

b width
l lenght
ε elongation
σ tensile strength

- ε varies for different loads according to
  - variable parameters angle θ, tape width b
  - E – Young's modulus

$$\varepsilon = \frac{F_u}{bhE}$$

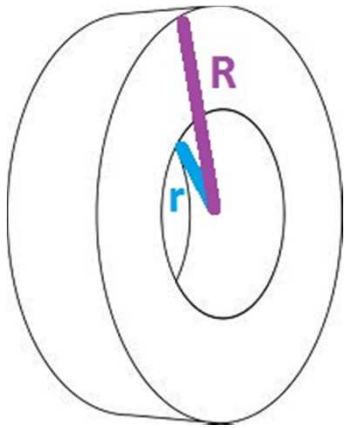
Relevant tape properties

width b=25 mm, lenght l=50m, thickness h, Young's modulus

- V tape volume
- R full radius
- r central circle raius

$$V = b(R-r)^2\pi = bhl$$

$$h = \frac{(R-r)^2\pi}{l}$$



creped

- low temperature universal masking tape
  - slightly-creped paper backing, rubber adheive
- measured thickness (h) (backing+adhesive)
  - 0.151 mm

transparent

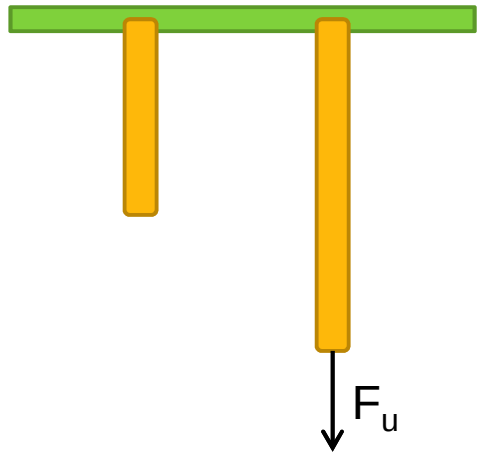
- biaxial oriented polypropylene tape
  - biaxially oriented polypropylene backing, synthetic rubber adhesive
  - 0.0475 mm

Relevant tape properties

width b=25 mm, lenght l=50m, thickness h, Young's modulus

- Young's modulus describes the elastic properties of a solid undergoing tension
  - weight (m) - force $F_g = Fu$ is hanging on the tape, elongates it
  - elongation and mass measured
    - Hook's law relation
    - σ – *stress*
    - ε – *elongation* $\Delta l / l_0$

$$E = \frac{\sigma}{\varepsilon} = \frac{F_u}{\varepsilon b h}$$



creped	transparent
$E = 2 \cdot 10^8 \, N/m^2$	$E = 1.04 \cdot 10^8 \, N/m^2$

Parameters

- two tapes (creped/transparent)
  - elongation, adhesion to backing
- two surfaces (aluminium, laminate)
  - adhesion to surface, roughnes
- peel-off angle
  - component of F_u which overcomes adhesion force
  - expressed with $(1+\frac{\varepsilon}{2}-\cos\theta)$
- tape width
  - glued surface areas
- temperature
  - adhesive surface tension changes

$$G_a = \frac{F_u(1+\frac{\varepsilon}{2}-\cos\theta)}{b}$$

Experimental setup - angle

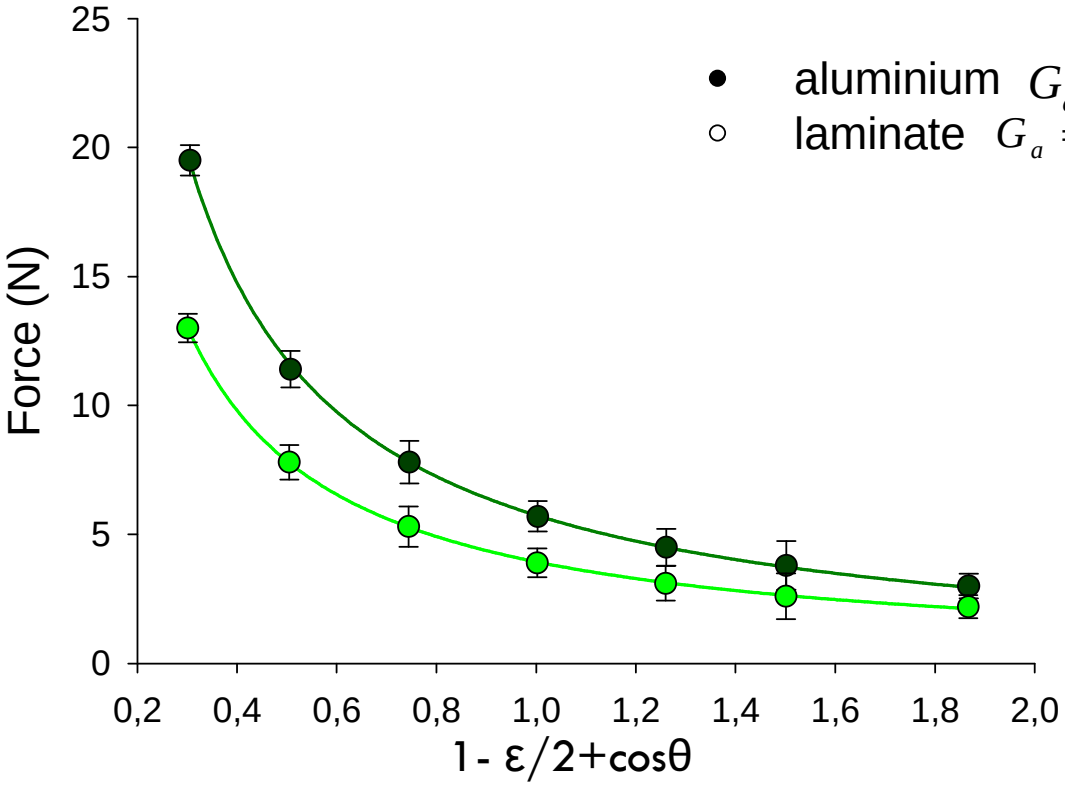
- adjustable slope
- laminate and aluminium plate attached
- piece of tape 15 cm
- an easily filled pot
  - various sizes
- protractor
- 1 kg cylinder to maintain even pressure
- stopwatch
  - PEEL RATES < 1 mm/s

Experimental setup - angle

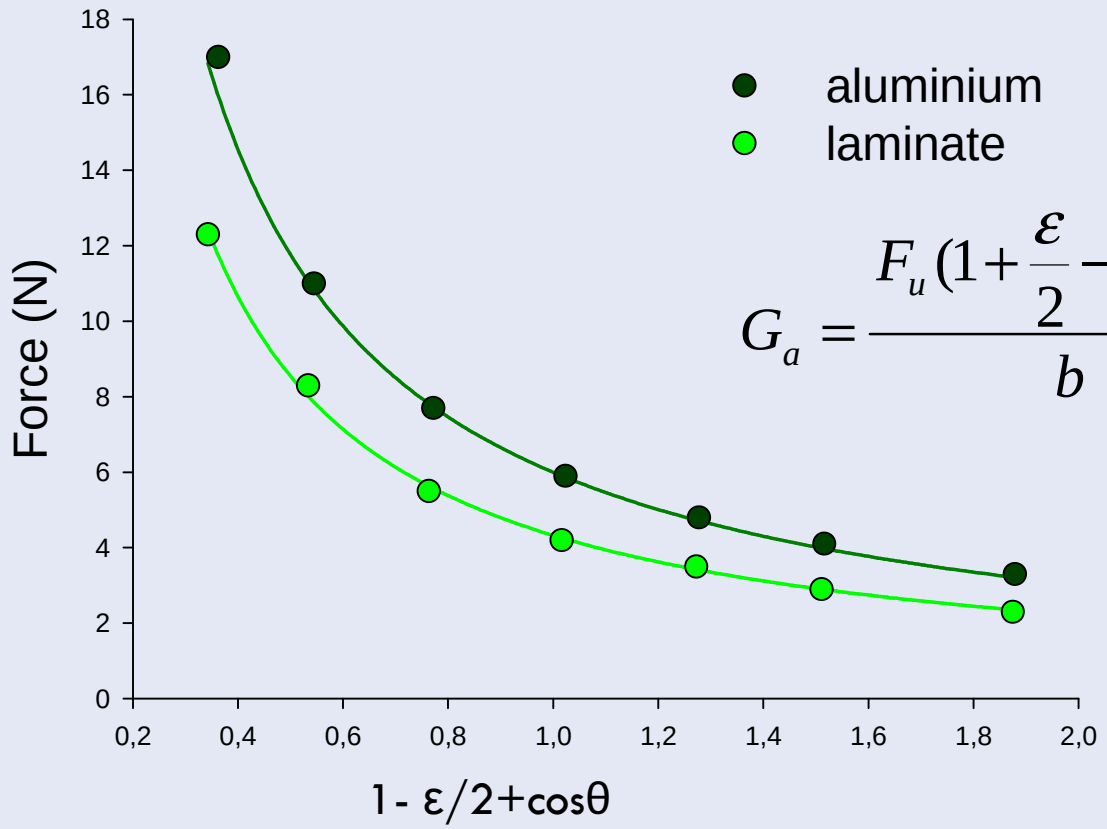
- adhesive tape is placed on the plate and pressed
  - m=1kg, 2.5cm*10cm (p=const=4kPa)
    - 15 cm total lenght
    - 10 cm pressed, 5 cm thread for pot
- slope – measured angle (every 15°)
- pot filled until the adhesive starts to peel off
  - time measured every 2.5 cm
    - if ~constant velocity of peel progression
      - valid measurement
- pot weighed (digital scale) $F_g = mg$

Surface comparison

- angle/force dependency
- first order inverse function
- temperature 20°C



$$F_u = \frac{const(G_a)}{1 + \frac{\varepsilon}{2} - \cos\theta}$$



$$G_a = \frac{F_u(1+\frac{\varepsilon}{2}-\cos\theta)}{b}$$

TRANSPARENT TAPE – COMPARISON

angle/force dependence

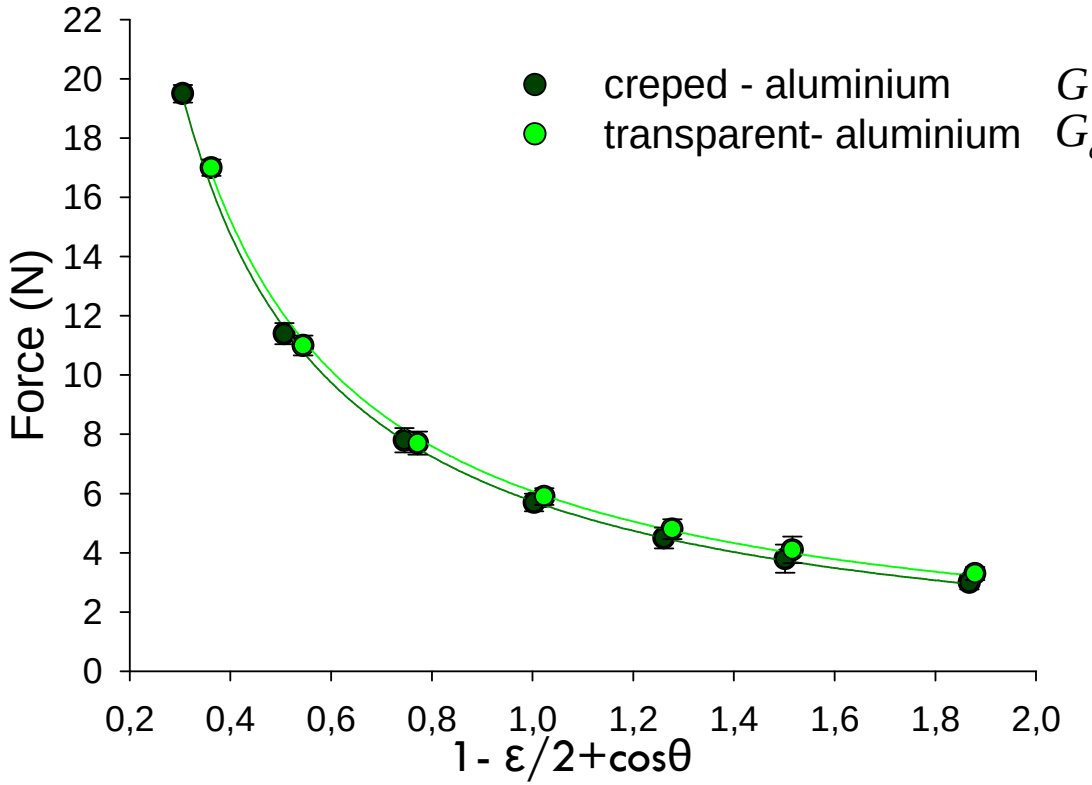
first order inverse function

temperature 20°C

$$F_u = \frac{const}{1+\frac{\varepsilon}{2}-\cos\theta}$$

Tape comparison

- angle/force dependence
- first order inverse function
- temperature 20°C



$G_a = (230 \pm 8) J / m^2$

$G_a = (244 \pm 5) J / m^2$

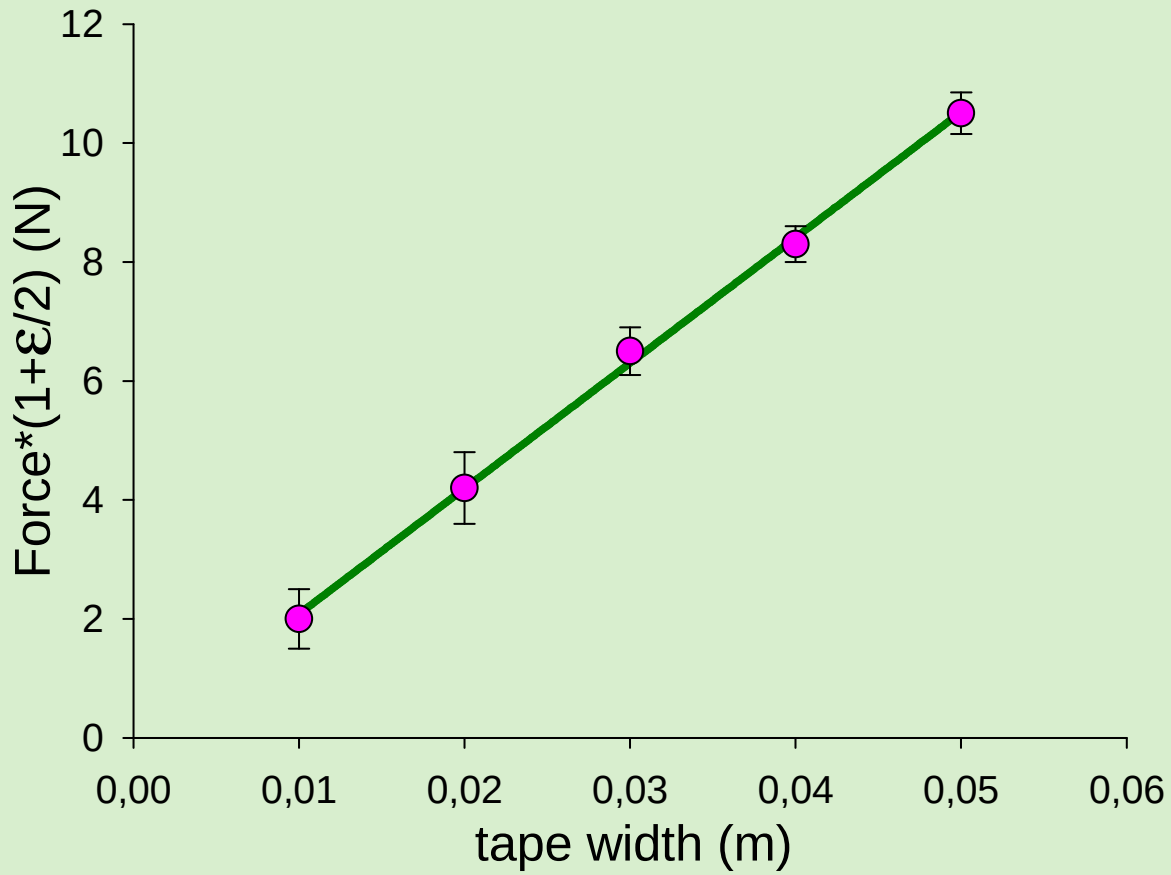
$$F_u = \frac{const(G_a)}{1 + \frac{\varepsilon}{2} - \cos\theta}$$

Tape width dependence

b width
ε elongation

- Initial width: 50 mm
- marked tape
  - every 10 mm
    - cut on the surface
- described method
  - angle 90°
  - temperature 20°C

$$G_a = \frac{F_u(1+\frac{\varepsilon}{2}-\cos\theta)}{b}$$



TAPE – WIDTH (laminate)

width/force dependence

linear progression

temperature 20°C

$$F_u(1+\frac{\varepsilon}{2}) = bG_a \qquad \varepsilon = \frac{F_u}{bhE}$$

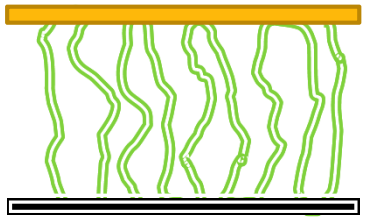
$$G_a = 173 \pm 5 J/m^2$$

Temperature dependence

- thermodynamic system
  - minimum free energy
    - gives the number of forming threads
    - surface tension depends on temperature
- temperature gradient plate development (aluminium)
  - creped and transparent tape
  - angle 90°

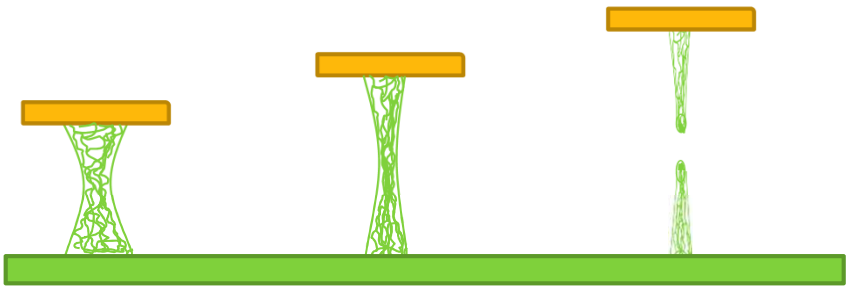
Temperature dependence

- thermodynamic free energy F
  - amount of work that a thermodynamic system can preform
  - $\mathrm{F} = U - TS$
    - U *is the internal energy of the system* – surface energy
    - $U = N\ 2r\pi l\ \gamma(T)$
      - surface tension $\gamma(T)$ of a surface formed of N threads
    - S is the system entropy
      - greater number of threads more favorable
      - $S \sim kNlnN$ (entropy of an ideal 2D gass)
- there is a minimum free energy condition
  - gives the N_0 number of formed threads
  - $U = TS\ / \frac{d}{dN}$



Temperature dependence

- force needed to peel-off the tape
  - surface energy/lenght derivation
  - $F = \frac{\partial U}{\partial l} U = N\, 2r\pi l\, \gamma(T) \rightarrow F = \alpha \frac{\gamma(T)^2}{T}$
    - r expressed by the constant volume relation $V = Nr^2\pi l$
    - $surface\ tension\ temperature\ dependence$
    - $* \gamma(T) = \gamma 0 \left(1 - \frac{T}{Tc}\right)^n, \gamma_0 \left[\frac{J}{m^2}\right]$
      - n is an empirical value (11/9 for organic liquids such as glue)
- $F = \beta \frac{\left(1-\frac{T}{Tc}\right)^{22/9}}{T}$



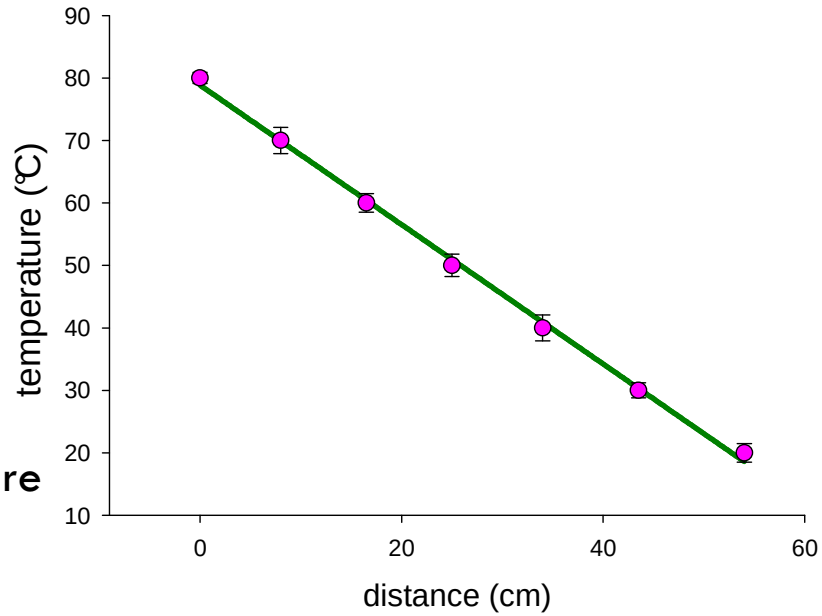
*wikipedia: surface tension http://en.wikipedia.org/wiki/Surface_tension

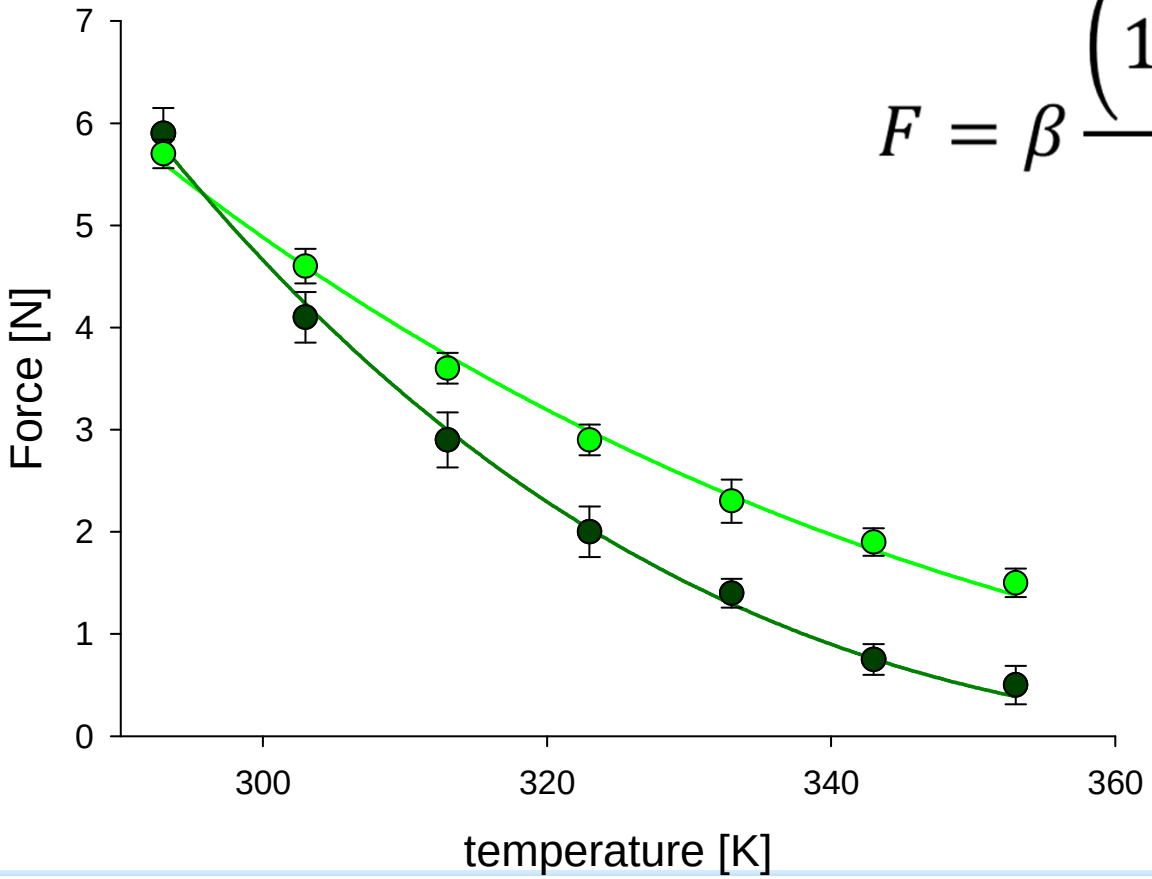
Gradient plate

- small stove
  - heated at one end
- water (20°)
  - cooled at other
- wait until equilibrium occurs
- measured temperatures
  - infrared thermometer
  - marked every 10°C

Gradient plate

- aluminium plate 90 cm*50 cm, 3 mm ± 0.1 mm thick
- heat flows from the hot end to the cool end
  - thermal conduction
    - calibration
      - 20°C - 80°C (± 2 °C)
- factory data
  - creped tape 105 °C
  - transparent tape 70 °C
    - pressed along the ~ same temperature
      - marked distance
  - described method
- critical temperatures effective values
  - internal energy is defined as the surface energy





$$F = \beta \frac{\left(1 - \frac{T}{T_c}\right)^{22/9}}{T}$$

CREPED – TRANSPARENT COMPARISON

temperature/force dependency

regression fit

agreement with theoretical explanation

Conclusion

- set peel-conditions
- fracture energy / surface G_a evaluated for
  - creped tape
    - aluminium $G_a = 230 \pm 8 J/m^2$, laminate $G_a = 157 \pm 6 J/m^2$
  - transparent tape
    - aluminium $G_a = 244 \pm 5 J/m^2$, laminate $G_a = 173 \pm 5 J/m^2$
- <u>determines the necessary force</u>
- conducted experiment for relevant parameters
  - changed F_u (in accordance to prediction) – same G_a
    - angle (45°-135°)
    - width
  - temperature (surface tension model) agreement

References

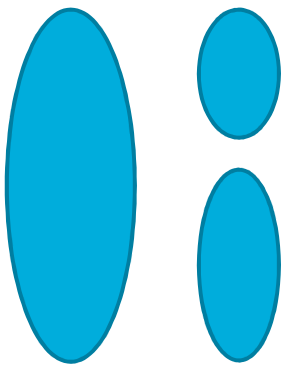
- A. N. Gent and S. Kaang. Pull-off forces for adhesive tapes. J. App. Pol. Sci. 32, 4, 4689-4700 (1986)
- A. J. Kinloch, C. C. Lau, and J. G. Williams. The peeling of flexible laminates. Int. J. Fracture 66, 1, 45-70 (1994)
- Z. Sun, K. T. Wan, and D. A. Dillard. A theoretical and numerical study of thin film delamination using the pull-off

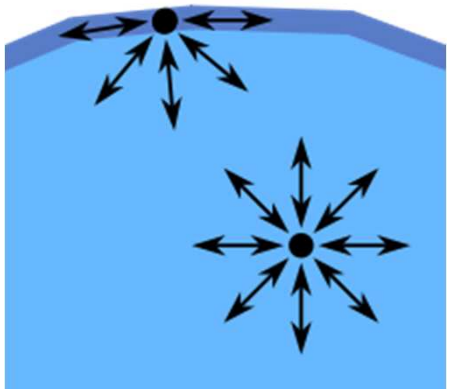
THANK YOU!

Rayleigh instability criteria

- surface tension
  - property of surface that allows it to resist external force
  - explains why a stream of fluid breaks up into smaller packets with the same volume but less surface area
    - overcomes surface energy tension – minimises surface energy

- breaks into just two parts due to viscosity





Relevant tape properties

Young's modulus E accordance to factory data

creped

- factory data
  - elongation at break ε
    - 12 %
  - tensile strength σ
    - 90 N/ 25 mm
- Hook's law

$$E = \frac{\sigma}{\varepsilon} = \frac{F_u}{\varepsilon bh}$$

$$E = 2 \cdot 10^8 \, N/m^2$$

transparent

- 90 % $\varepsilon = \frac{\Delta l}{l_0}$
- 110 N/ 25 mm $\sigma = \frac{F_u}{bh}$

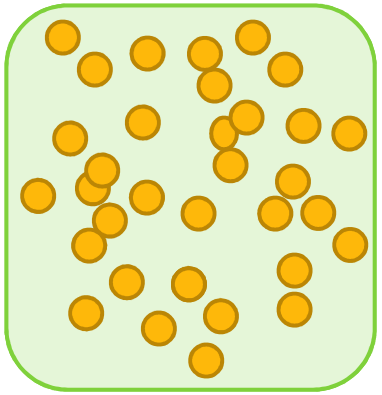
Young's modulus

describes the elastic properties of a solid undergoing tension

$$E = 1.04 \cdot 10^8 \, N/m^2$$

Temperature dependence derivation

- entropy S of a 2D ideal gass
  - equals the entropy of the threads
    - observation from above
    - number of ways they could be re-ordered
    - $S = kNlnN$
      - as the lnN factor is small in comparison to N
      - $S \approx kN$
  - $U\ is\ the\ internal\ energy\ of\ the\ system$ – surface energy
  - $U = N\ 2r\pi l\ \gamma(T) \quad V = Nr2\pi l \rightarrow r{\sim}l^{-1/2}$
- there is a minimum free energy condition which gives the N_0 number of formed threads
- $\mathrm{F} = U - TS = \min$



Temperature dependence derivation

- $\mathrm{F} = U - TS = \min$
  - $U = TS \ / \frac{d}{dN}$
  - $AN^{-1/2} l^{1/2} \gamma(T) = kT(lnN + 1) \approx kT$
    - k – Boltzmann constant
  - $N_0 \sim \left(\frac{l_0{}^{1/2}\gamma(T)}{kT}\right)^2 \rightarrow \left(\frac{\gamma(T)}{T}\right)^2$
  - $F = \frac{\partial U}{\partial l} \; U = N \; 2r\pi l \; \gamma(T) \rightarrow F = \alpha \frac{\gamma(T)^2}{T}$
    - $V = Nr^2\pi l \rightarrow r \sim l^{-1/2}$
    - $* \; \gamma(T) = \gamma 0 \left(1 - \frac{T}{Tc}\right)^n$

$$\left(1 - \frac{T}{T_c}\right)^{22/9}$$