

Adhesion and Adhesives

11.11.2020

Ville Jokinen

E5150 Surfaces and Films Lecture 9

Content and Learning outcomes

1. How adhesion depends on surface (and interface) energies and other surface properties.
2. Liquid adhesives (glues). Why pure liquids do not work as adhesives in most cases and instead a glue is needed.
3. Pressure sensitive adhesives (tapes). What determines how a tape sticks to a surface?

Homework will be gecko mimic adhesives, related to the third topic.

Note: lecture 3B handles bonding in the context of semiconductor/vacuum technology. This lecture mainly discusses adhesives outside semiconductor industry. (Lecture 3A cleaning is also relevant)

Part 1: Adhesion and surface properties

Surface energies, Recap

Surface energy means the energy required to create a unit area of new surface

Fundamental definition of surface/interfacial energy (surface tension):

$$\gamma = \delta W / \delta A \quad [\text{J} / \text{m}^2]$$

$$\gamma = \delta F / \delta x \quad [\text{N} / \text{m}]$$

Concept applicable to all surfaces and interfaces:

solid-solid, solid-liquid, liquid-liquid, solid-gas, liquid-gas

Interfacial energy

*Surface energy (in the case of liquid-gas
the word surface tension is also used)*

The indexes denote which surface energy we are talking about.

For example:

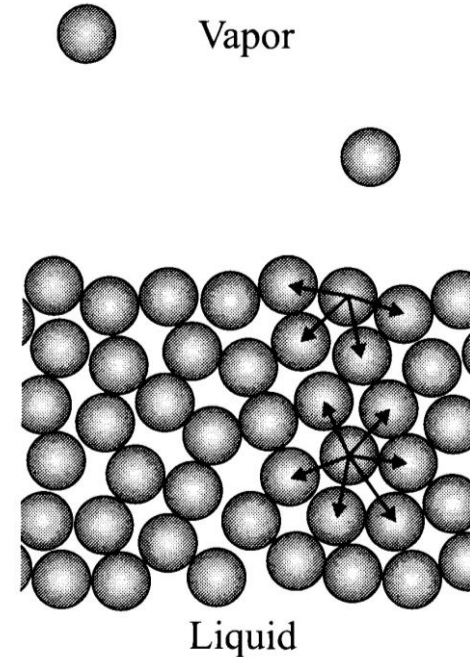
γ_{sl} = interfacial energy between solid and liquid

$\gamma_{s1,s2}$ = interfacial energy between solid 1 and solid 2

γ_{12} = interfacial energy between material 1 and material 2

γ_s = surface energy of a solid.

(the terminology is not uniform across fields)



Surface energies, lets re-think

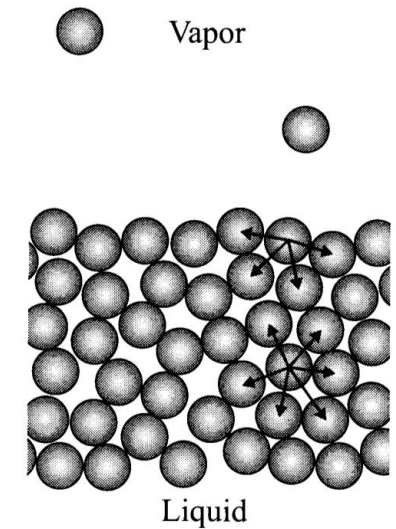
Previously surface energies were explained by considering the number of missing bonds of atoms/molecules on the surface compared to those in the bulk.

This is correct but the thought model is not applicable to all cases.

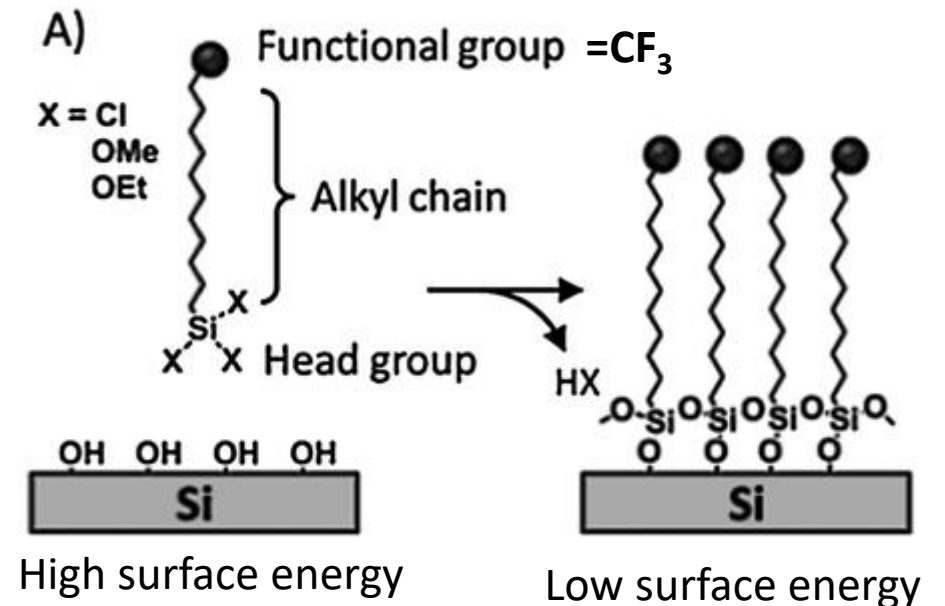
Many (most?) solids have a surface chemistry that differs from the chemistry of the bulk either by an intentional surface modification or just by adsorption, reactions or rearrangement.

Instead, you can think of surface energy as the potential energy available for bonds (physical and chemical) per unit area. The more bonding sites there are and the stronger the bonds they could make, the higher the surface energy.

In the example, the hydroxyl groups have a reasonably high bonding capability (can form covalent bonds or strong physical bonds due to their polar nature). When they get replaced by methyl groups that only form Van der Waals bonds, the surface energy is lowered.



Surface energy of a liquid



Surface energies of a surface modified solid

Surface energy and adhesion

Adhesion means two surfaces sticking to each other.
Let's look at two solid surfaces (surrounded by air).

When two materials are adhered, there is only one interface: γ_{12}

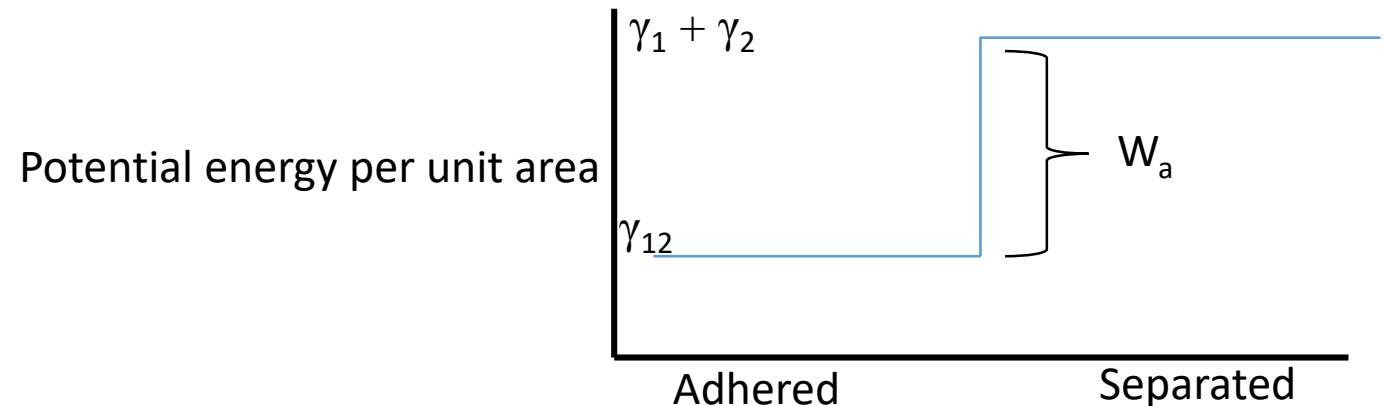
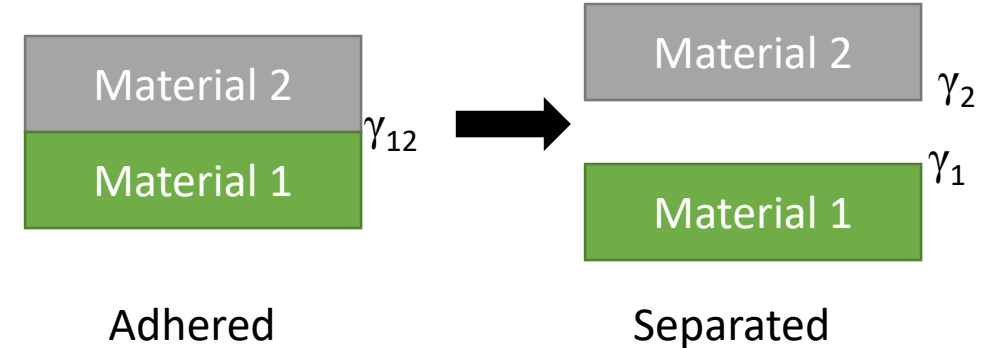
When the materials are separated, we got rid of γ_{12} but created two new surfaces, γ_1 and γ_2

The amount of energy needed to separate the two surfaces, per unit area, is thus: $\gamma_1 + \gamma_2 - \gamma_{12}$

This is called the work of adhesion, W_a

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$$

Indices for surface energies in this lecture:
If only numbers, they are solid phases
Gas phases are sometimes omitted
In this lecture liquid phase is always marked

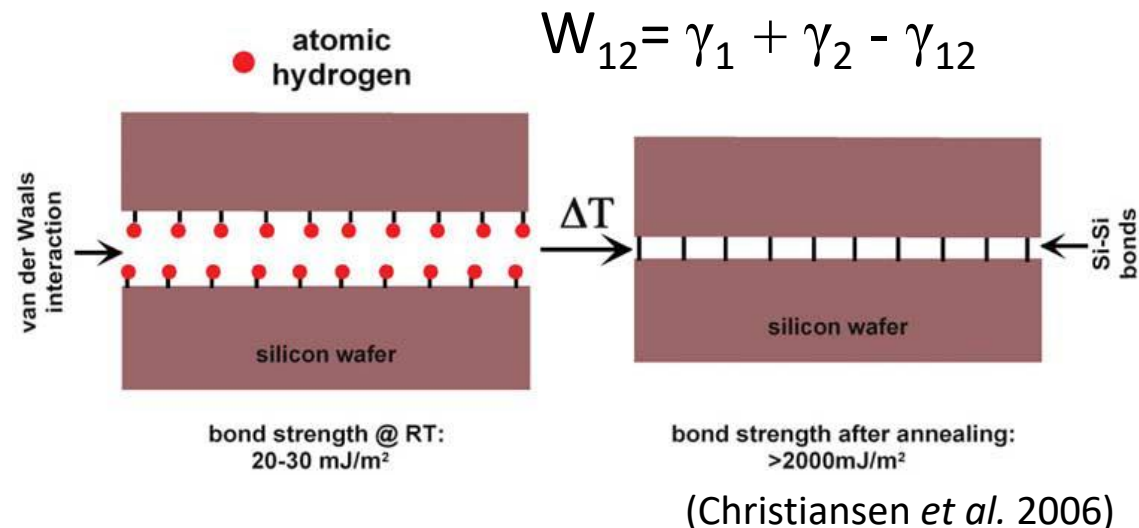


Bonds and adhesion

The surface energies γ_1 and γ_2 of solids are related to the type and amount of bonds that they could make.

The interfacial energy term γ_{12} is related to how many of those bonds are actualized when the two solids are brought together.

The more they interact the lower γ_{12} is compared to the sum of γ_1 and γ_2 .



Chemical bonds (of the order 100s of kJ/mol):

Covalent

Ionic

Metal

Physical bonds (Van der Waals): (of the order 10s of kJ/mol):

Dipole-dipole (*polar*) (special case: hydrogen bond)

Dipole-induced dipole

Induced-induced (*dispersive*) (special case: pi-stacking)

Before heating, low adhesion, why?

- Si-H surfaces, quite low γ_1 and γ_2
- Surfaces interact with VdW forces: γ_{12} is low but not lowered much compared to $\gamma_1 + \gamma_2$

After heating, high adhesion, why?

- Si surfaces without the hydrogen, γ_1 and γ_2 very high due to potential to make a covalent bond
- Surfaces interact by making a covalent bond. γ_{12} is much lower than $\gamma_1 + \gamma_2$

Adhesion under water (or other medium)

The equation for work of adhesion works in all mediums, we just need to have the correct indices.

Under water:

$$W_{12} = \gamma_{1,w} + \gamma_{2,w} - \gamma_{12}$$

Air/vacuum: very little bonding/interaction

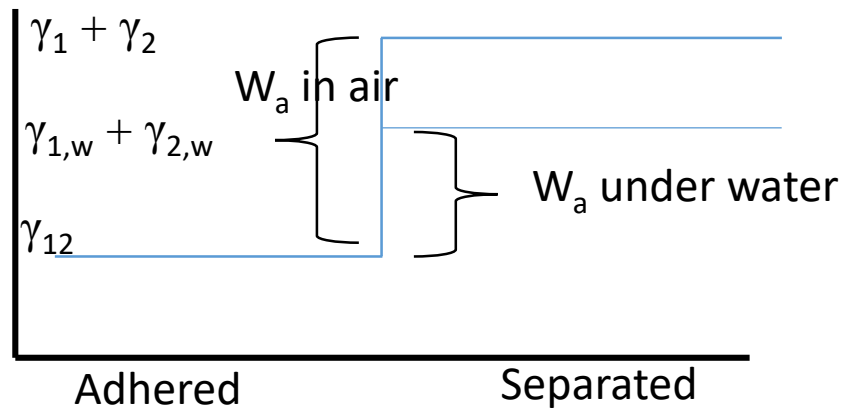
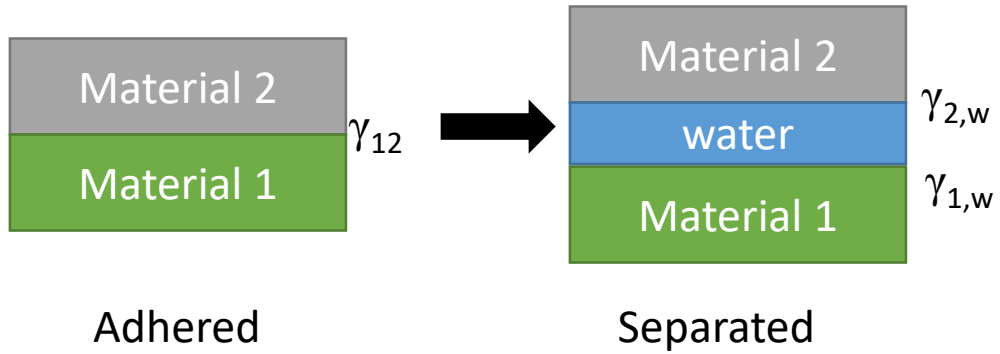
Water: does not make chemical bonds but can interact by VdW, especially hydrogen bonds.

Therefore:

Hydrophilic surfaces have weaker adhesion under water than in air.

Hydrophobic surfaces have stronger adhesion under water than in air.

(sometimes two hydrophobic surfaces even adhere quite strongly under water through a pseudo force called *hydrophobic interaction*, next lecture)



Hydrophilic surface under water and in air

Cohesion

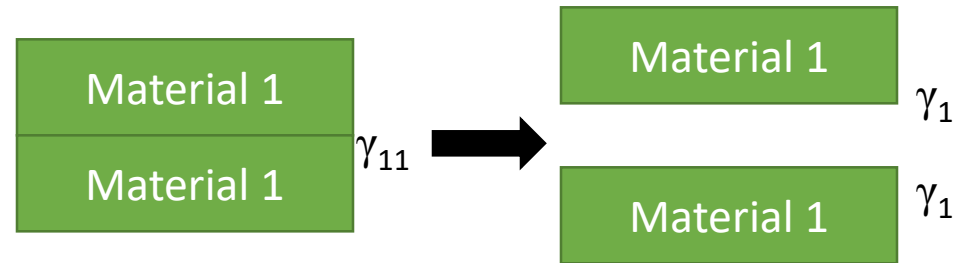
Adhesion is sometimes contrasted to cohesion, which is related to the strength of the bulk bonds. We can derive the work of cohesion in the same way we derived the work of adhesion.

Work of cohesion, W_{11} :

Before separation: $\gamma_{11}=0$

After separation: $2\gamma_1$

$$W_{11} = 2\gamma_1 - 0 = 2\gamma_1$$



It also emerges from the work of adhesion by setting $\gamma_1 = \gamma_2$ and $\gamma_{12} = 0$

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$$

Solid surface energy measurement

The fundamental concept of surface energy applies to solid and liquid surfaces alike. *However, there is a practical difference:* Unlike liquids, **solid surface energies can not be measured directly**. The reason for this is that bulk bonds in solids are too strong compared to surface forces.

Instead, solid surface energies are measured indirectly by measuring contact angles between the solid and several different probe liquids. In addition to this, a model is needed, commonly:

- Critical surface tension (Zisman method) (old)
- Good and Girifalco (old)
- Owens-Wendt **(in use today)**
- Van Oss et al. **(in use today)**

Take home messages:

Solid surface energy as a concept is 100% valid but all measured values are estimates.

The same applies to interfacial energies.

You can find some solid energies tabulated for lower surface energy materials but they are not universally available.

Name	Surface free energy (SFE) at 20 °C in mN/m	Temp. coefficient SFE in mN/(m K)	Dispersive contrib. of SFE in mN/m	Polar contrib. of SFE in mN/m
Polyethylene-linear PE	35.7	-0.057	35.7	0
Polyethylene-branched PE	35.3	-0.067	35.3	0
Polypropylene-isotactic PP	30.1	-0.058	30.1	0
Polyisobutylene PIB	33.6	-0.064	33.6	0
Polystyrene PS	40.7	-0.072	(34.5)	(6.1)
Poly- α -methyl styrene PMS (Polyvinyltoluene PVT)	39.0	-0.058	(35)	(4)
Polyvinyl fluoride PVF	36.7	-	(31.2)	(5.5)
Polyvinylidene fluoride PVDF	30.3	-	(23.3)	(7)
Polytrifluoroethylene P3FE1/PTrFE	23.9	-	19.8	4.1
Polytetrafluoroethylene PTFE (Teflon™)	20	-0.058	18.4	1.6
Polyvinylchloride PVC	41.5	-	(39.5)	(2)
Polyvinylidene chloride PVDC	45.0	-	(40.5)	(4.5)
Polychlorotrifluoroethylene PCTrFE	30.9	-0.067	22.3	8.6
Polyvinylacetate PVA	36.5	-0.066	25.1	11.4
Polymethylacrylate (Polymethacrylic acid) PMAA	41.0	-0.077	29.7	10.3
Polyethylacrylate PEA	37.0	-0.077	30.7	6.3
Polymethylmethacrylate PMMA	41.1	-0.076	29.6	11.5
Polyethylmethacrylate PEMA	35.9	-0.070	26.9	9.0
Polybutylmethacrylate PBMA	31.2	-0.059	26.2	5.0
Polyisobutylmethacrylate PIBMA	30.9	-0.060	26.6	4.3
Poly(tert-butylmethacrylate) PtBMA	30.4	-0.059	26.7	3.7
Polyhexylmethacrylate PHMA	30.0	-0.062	(27.0)	(3)
Polyethyleneoxide PEO	42.9	-0.076	30.9	12.0
Polytetramethylene oxide PTME (Polytetrahydrofurane PTHF)	31.9	-0.061	27.4	4.5
Polyethyleneterephthalate PET	44.6	-0.065	(35.6)	(9)

Surface energies tabulated, measured with the Owens-Wendt method

How it works:

Let's measure the contact angle between a liquid and a solid and use this to calculate the surface energy of the solid.

The simplest assumption (Good and Girifalco) assumes that:

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2\Phi\sqrt{\gamma_1\gamma_2}, \quad (\Phi \text{ is an interaction parameter } \approx 1)$$

Let's disregard the Φ and write the equation for a liquid-solid pair:

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2\sqrt{\gamma_{sv}\gamma_{lv}}$$

Then we insert this into the equation for **work of adhesion** to get:

$$W_{sl} = 2\sqrt{\gamma_{sv}\gamma_{sl}}$$

We equate this to **Young-Dupre equation** to get: *This step shows why it is necessary to have a liquid phase*

$$2\sqrt{\gamma_{sv}\gamma_{sl}} = \gamma_{lv}(1 + \cos(\theta)),$$

And since we can measure γ_{lv} and θ we only have 1 unknown and can solve:

$$\gamma_{sv} = \gamma_{lv} \frac{(1 + \cos(\theta))^2}{4}$$

Work of adhesion, written as:

general case

liquid-solid case

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$$

$$W_{sl} = \gamma_{sv} + \gamma_{lv} - \gamma_{sl}$$

↓ +

Young's equation

$$\gamma_{lv} \cos(\theta) = \gamma_{sv} - \gamma_{sl}$$

↓ =

Young-Dupre equation

$$W_{sl} = \gamma_{lv} + \gamma_{lv} \cos(\theta) = \gamma_{lv}(1 + \cos(\theta))$$

Interaction assumption (equation of state) according to Good and Girifalco

$$W_{12} = 2\Phi\sqrt{\gamma_1\gamma_2}$$

The other models:

Good and Girifalco: $\gamma_{12} = \gamma_1 + \gamma_2 - 2\Phi\sqrt{\gamma_1\gamma_2}$

The assumption was needed since there was one too many unknown. Making the assumption allowed the equations to be solved after measuring the contact angle with one liquid.

The problem: the assumption is very inaccurate.

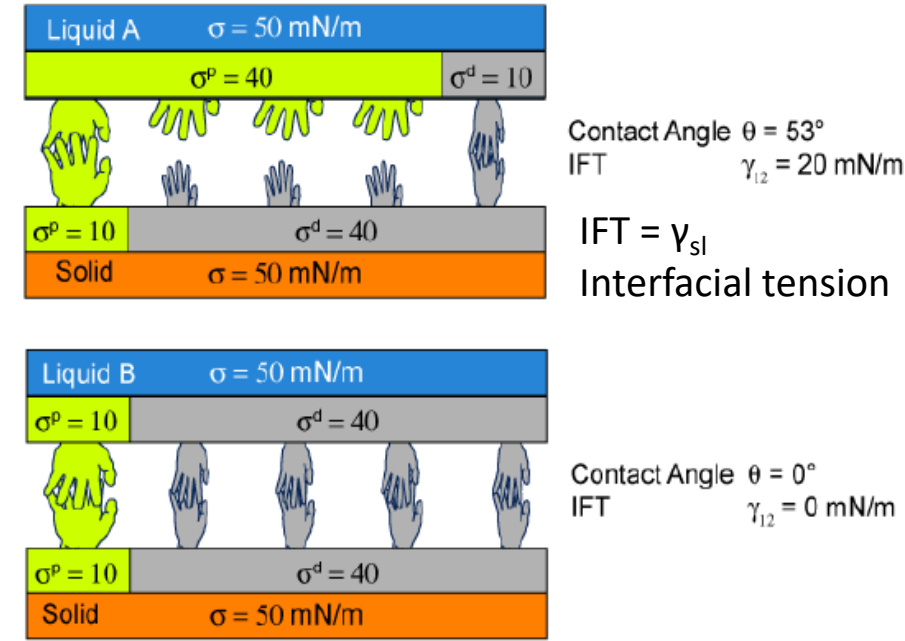
The two methods below make **more accurate assumptions**, but the cost is that contact angles need to be measured with **at least two** (Owens-Wendt) **or three** (van Oss et al.) liquids.

Owens-Wendt: surface energy divided into dispersive and polar components

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2(\sqrt{\gamma_{sv}^D \gamma_{lv}^D} + \sqrt{\gamma_{sv}^P \gamma_{lv}^P}) \quad \gamma_i = \gamma_i^D + \gamma_i^P$$

Van Oss et al.: Polar component further divided into acid and base (+ and -)

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2(\sqrt{\gamma_{sv}^D \gamma_{lv}^D} + \sqrt{\gamma_{sv}^+ \gamma_{lv}^-} + \sqrt{\gamma_{sv}^- \gamma_{lv}^+}) \quad \gamma_i = \gamma_i^D + \gamma_i^+ + \gamma_i^-$$



This is the assumption the two component Owens-Wendt method makes: the polar and dispersive components interact only with their counterpart on the other surface.

Figure: Kruss, technical note: *Custom-made models: from contact angle to surface free energy*

Owens-Wendt

Owens-Wendt: surface energy divided into dispersive and polar components
Commonly also called Owens-Wendt-Rabel-Kaelble (OWRK)

$$\gamma_{sl} = \gamma_{sv} + \gamma_{lv} - 2(\sqrt{\gamma_{sv}^D \gamma_{lv}^D} + \sqrt{\gamma_{sv}^P \gamma_{lv}^P}) \quad \gamma_i = \gamma_i^D + \gamma_i^P$$

By inserting work of adhesion and Young-Dupre equation we get:

$$\frac{\gamma_{lv}(\cos(\theta) + 1)}{2\sqrt{\gamma_{lv}^D}} = \sqrt{\gamma_{sv}^P} \frac{\sqrt{\gamma_{lv}^P}}{\sqrt{\gamma_{lv}^D}} + \sqrt{\gamma_{sv}^D}$$

Looks bad but:

1. **Green terms** we know / can measure, leaving two **unknowns** (hence two different liquids need to be measured)
2. In terms of the unknowns it is in the form of $y = kx + b$

In practice: make 2+ measurements with known test liquids, plot them on the axes shown in the image.

The y-axis intercept is the dispersive component of surface energy. The slope is the polar component of surface energy.

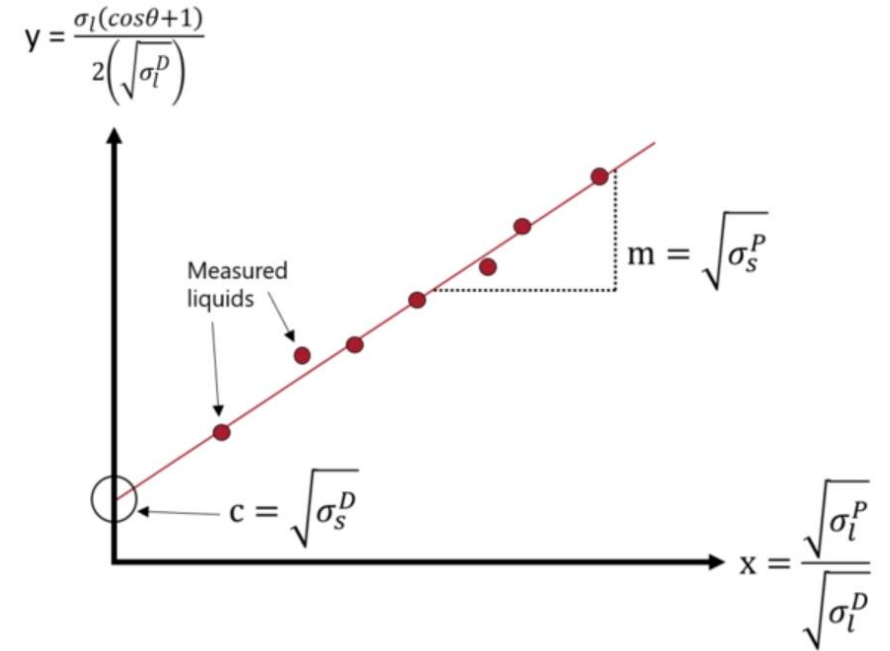


Figure: <https://www.ossila.com/pages/a-guide-to-surface-energy>

Adhesive force and work of adhesion

Work of adhesion is the amount of work that needs to be done to separate the surfaces.

But the force needed peel the two surfaces apart depends also on the way the peeling is done (which can then also include other materials parameters.)

Case 1. Peeling

The force required to peel two surfaces off is*:

$$F = W_a * b * (1 - \cos(\Phi))^{-1}$$

Where W_a is the work of adhesion

b is the width of the peel

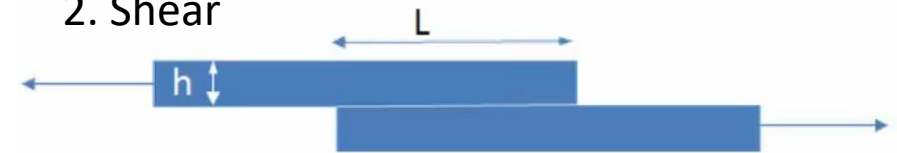
Φ is the peeling angle (straight up is 90°)

When $\Phi=90^\circ$, $F = W_a * b$

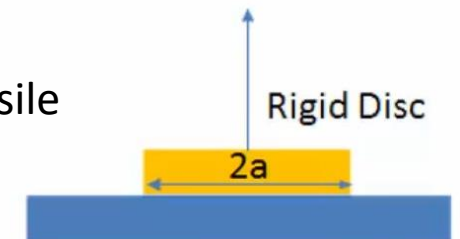
1. Peeling



2. Shear



3. Tensile



Adhesive force and work of adhesion

Case 2. Pulling apart by shearing force

The force required to separate the surfaces by pulling is*:

$$F = b * (2W_a E h)^{1/2}$$

, where b and W_a are the width and the work of adhesion

E is the Young's modulus

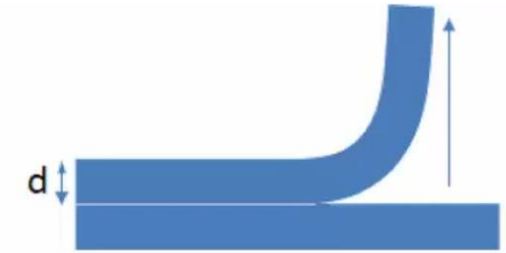
h is the thickness of the sample.

Case 3. Pulling apart by tensile force

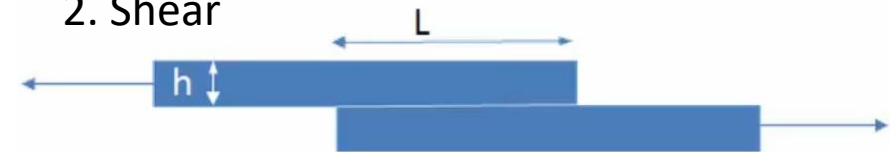
$$F = (10\pi W_a E a^3)^{1/2}$$

, where a is the radius of the circular disc.

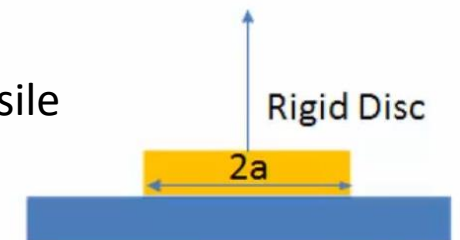
1. Peeling



2. Shear



3. Tensile



Adhesion, theory and practice

What do these all the adhesion failure mechanisms have in common?

They all have W_a in them!

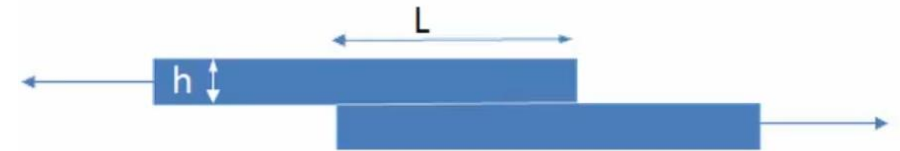
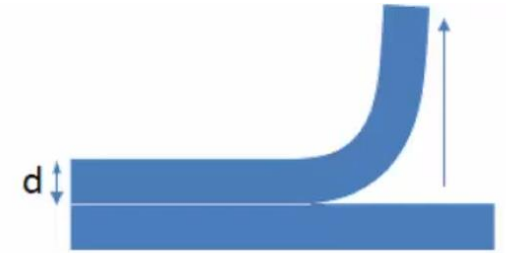
In reality, adhesion is very complicated and no theory thoroughly explains the typical experimental case.

Adhesion is a property of the entire system. What are the exact materials and what is the exact adhesion test matters. And so do defects, cleanliness etc.

However, W_a still forms the basis.

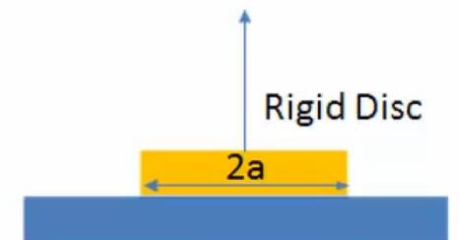
(except in some cases where overhanging geometries are involved the failure can become cohesive)

$$F = W_a * b * (1 - \cos(\Phi))^{-1}$$



$$F = b * (2W_a E h)^{1/2}$$

$$F = (10\pi W_a E a^3)^{1/2}$$



How to maximize adhesion?

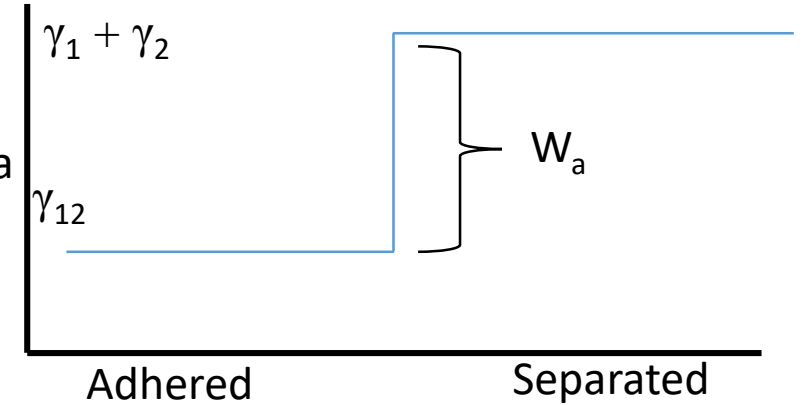
How to maximize adhesion with surface properties?

1. Maximize $W_a = \gamma_1 + \gamma_2 - \gamma_{12}$

Maximize γ_1 and γ_2 -> High energy surfaces

Minimize γ_{12} strong bond formation

Potential energy per unit area



Examples:

1. Two Teflon surfaces, $\gamma_1 = \gamma_2 \approx 10 \text{ mJ/m}_2$, even if they bond to maximum extent W_a is maximum 20 mJ/m_2
2. Silicon ($\gamma \approx 1000 \text{ mJ/m}_2$) bonding to glass ($\gamma \approx 1000 - 2000 \text{ mJ/m}_2$), even if only part of the potential bonds form one can still get e.g. $W_a > 500 \text{ mJ/m}_2$

2. 3. 4. What else? Write suggestions to chat!

How to maximize adhesion?

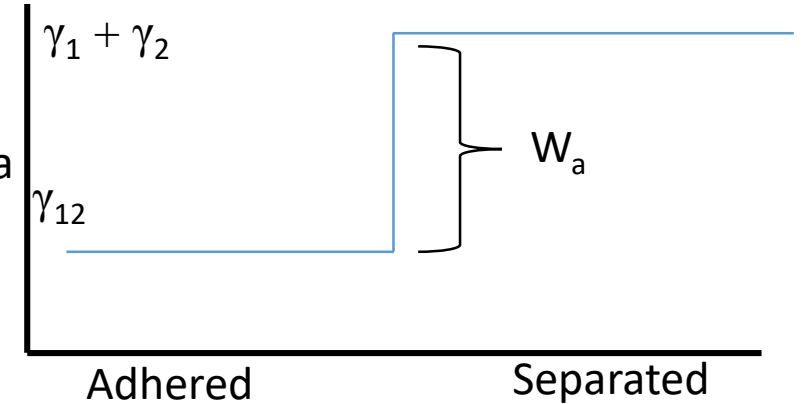
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2. Maximize contact area

Surface roughness comes into play here.

3. Exploit overhanging geometries

Can lead to cohesive failure instead (which is good from the point of view of an adhesive)

We will look at 2 and 3 separately for liquid adhesives (glues) and pressure sensitive adhesives (tapes)

Part 2: Liquid adhesives

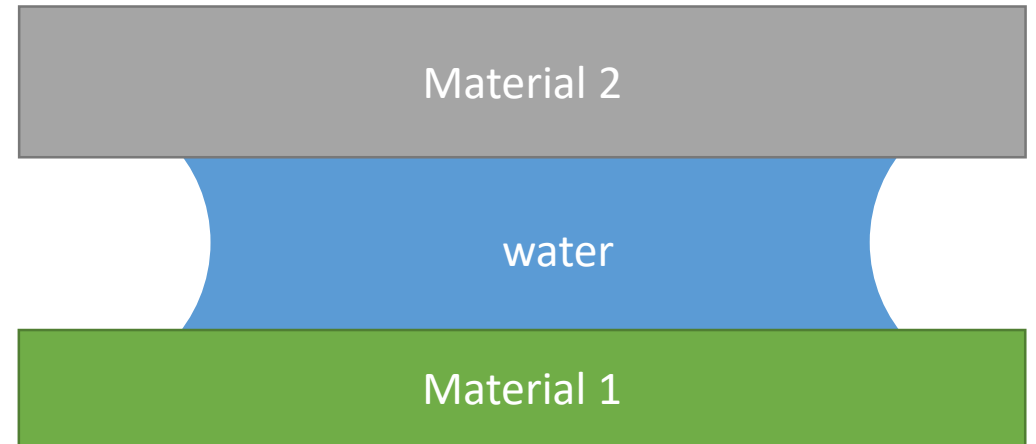
Pure liquids do not typically work as adhesives

Let's have two surfaces that are slightly hydrophilic. They are joined by a droplet/film of water.

This would lead to some adhesion. But if you would start to pull the surfaces apart by peeling, shearing or tensile force, you would most likely find out that water was not the best choice for an adhesive

Why? Pitch answers to chat

- 1.
- 2.
- 3.



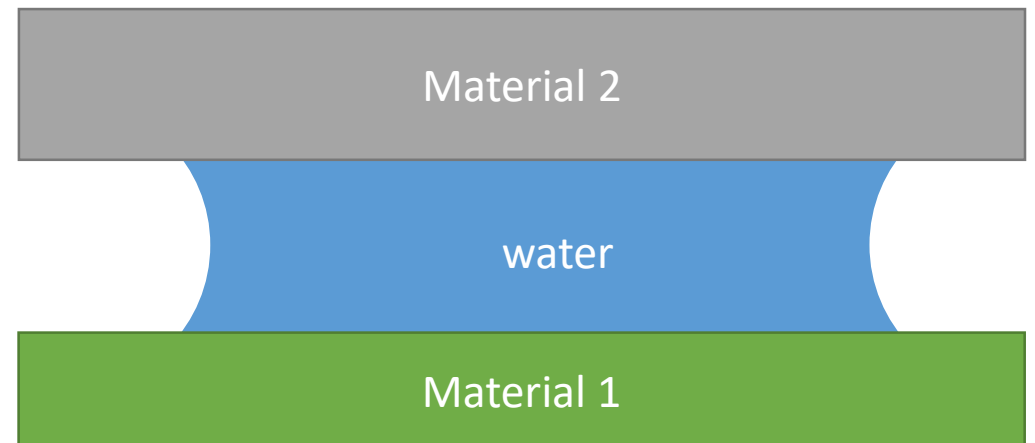
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Why?

1. Water flows! So the adhesive itself can deform with even minimal force by viscous shearing.
2. Because of 1, any resistance to peeling would come from surface tension forces, which are not that strong.
3. Besides one would need to worry about dewetting and evaporation



Special case, self alignment of microchips

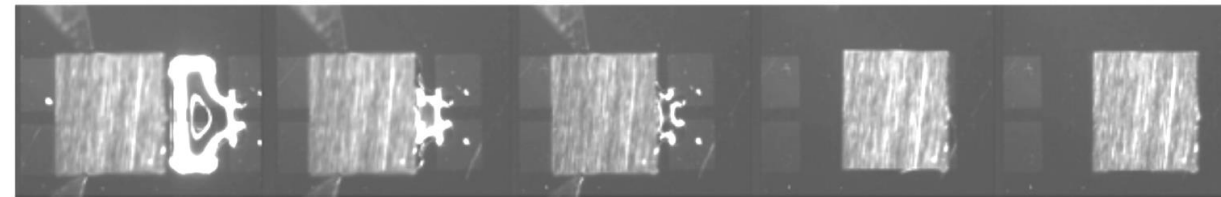
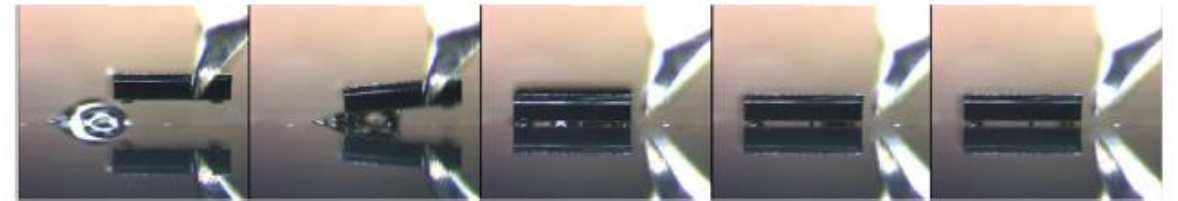
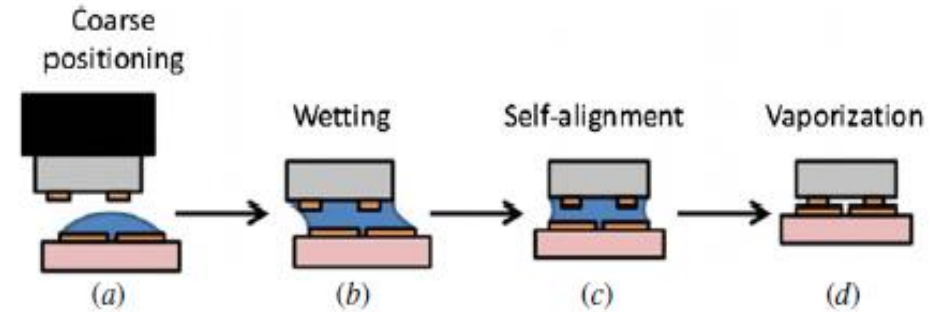
Hydrophilic (Al) and hydrophobic (Teflon) patterned surface was used to accurately position RFID tags through an evaporating water droplet.

The benefit is that the initial robotic positioning can be off by 100s of μm but the selective adhesion leads to much higher positioning accuracy.

This demonstrates the features of water as adhesive:

1. Adhesion is weak (but for this application there are no heavy forces pulling the RFID tag apart)
2. It is temporary due to evaporation (but this is also intended in this application)

For the typical case where adhesives would be used, the above would be serious drawbacks.



Glues

Glue is an adhesive that starts out as a liquid but is then solidified to form the final adhesive.

Ancient technology: natural adhesives such as pitch or beeswax 10000s years ago. Animal hide glues 1000s of years ago. Nowadays commonly polymers.

What is the point of solidifying?

1. To eliminate viscous flow in the liquid adhesive.
2. To make stronger bonds (in some cases, but not usually, also chemical bonds)
3. To give possibility for also cohesive energy losses and not just adhesive
4. (to eliminate evaporation)

What is the point of it being liquid in the first place?

1. Wetting, spreading, penetration into pores.



White glue / elmers glue
=Polyvinyl acetate

Curing mechanisms

There are many different curing mechanisms. *For example:*

Evaporation

White glue is an emulsion of polyvinyl acetate droplets in water. Once removed from the tube, the water starts to evaporate leading to a fully solid film.

Reaction with something in the atmosphere/environment

“Superglues” are ethyl and methyl cyanoacrylates. They polymerize by a reaction catalyzed by water. Most surfaces have some adsorbed water on them.

Polymerization reaction initiated by mixing:

Some glues require mixing two components that start to polymerize when mixed. Polymerization is not instant so there is some time for the glue to spread as liquid even after mixing.

Curing by UV

Polymers can be cured by exposure to UV

Cooling:

Some glues are spread above their melting point and then cooled

Superglue

Usually ethyl cyanoacrylate

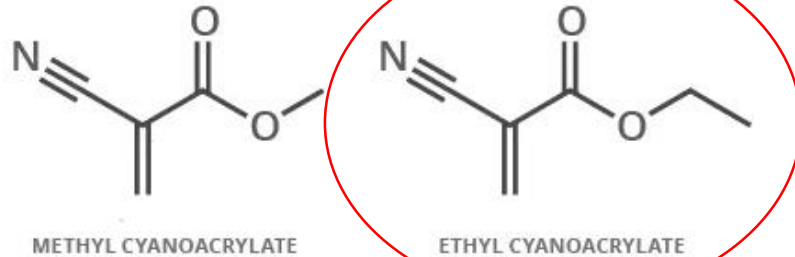
Very fast curing

Suitable for many types of surfaces

Water from atmosphere / surface
(in most cases there is adsorbed water on a surface)

Superglue curing process

THE CYANOACRYLATES

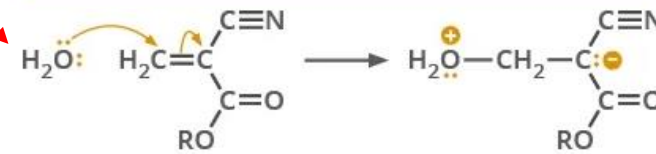


Medical grade adhesives instead typically use:

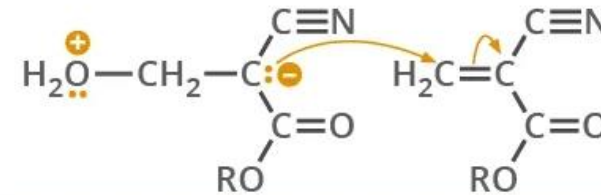
2-Octyl cyanoacrylate (e.g. SurgiSeal)

n-Butyl cyanoacrylate (e.g. GluStitch)

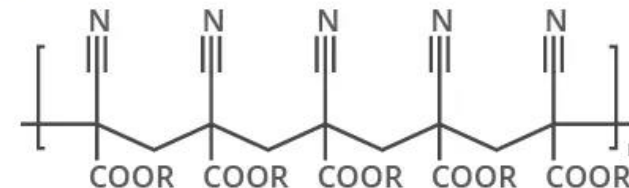
HOW SUPERGLUE WORKS



Cyanoacrylates 'cure' in the presence of water. Only a small amount of water is required to kick off the reaction – even the water vapour in the air is enough.

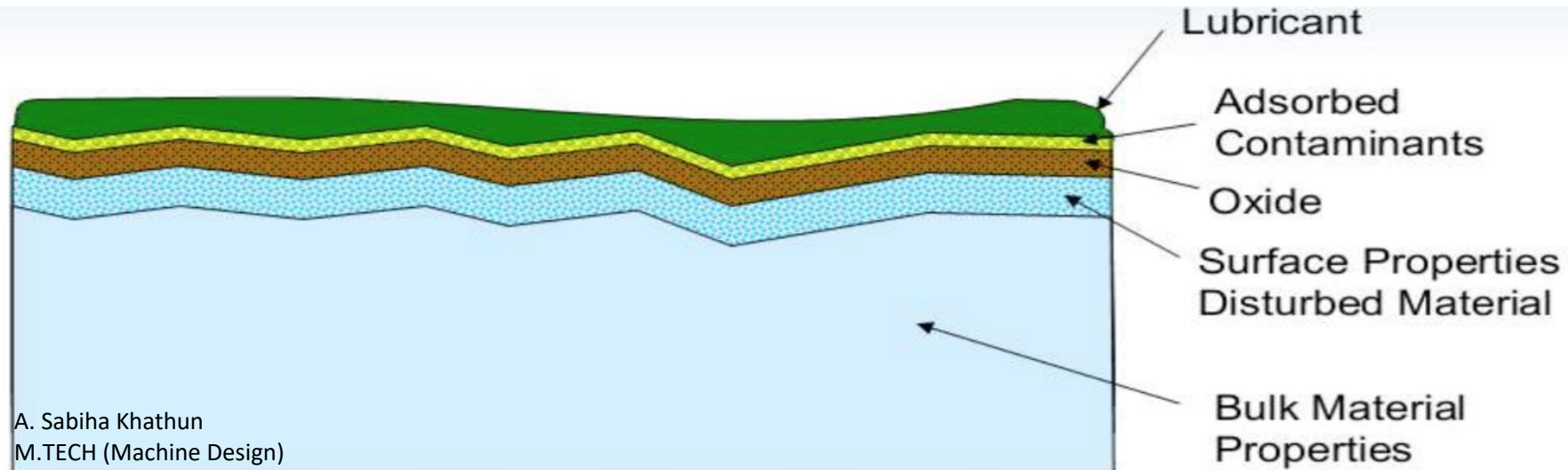
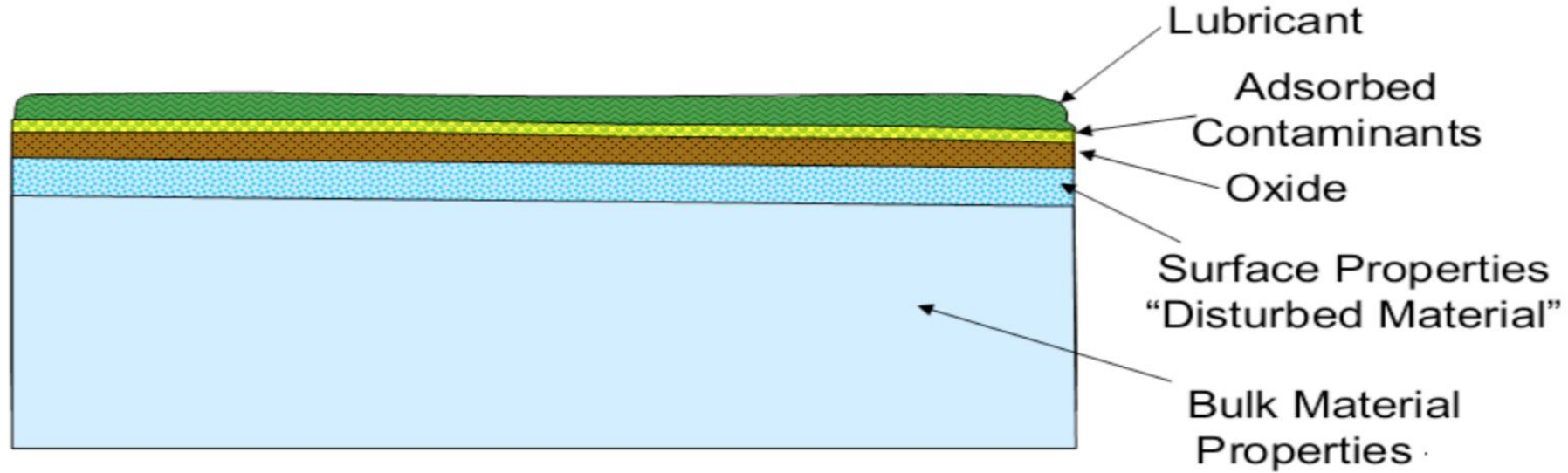


The reaction produces an anion which can add to more of the original cyanoacrylate, a process that repeats to form the adhesive polymer chains.



Slide from lecture 1

So let's begin by looking closely at a surface...

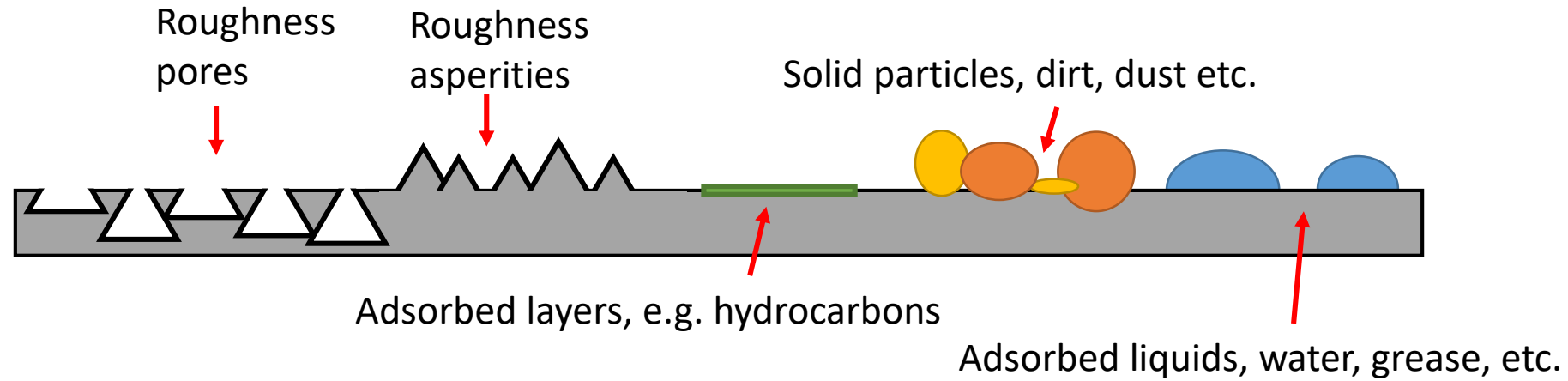


Ideal vs real surface

Ideal surface



Real surface



Roughness and glues

Roughness typically helps to create a stronger bond.

1. The **more surface area**, the more total energy is needed to break the adhesion. (Remember work of adhesion is in J/m^2 .)
2. In the case of pores, there can be **mechanical interlocking**: the solidified glue cannot be separated by pure adhesion failure but some cohesive failure is also needed.

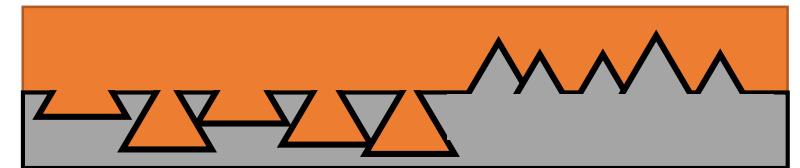
There is very strong interlocking if e.g. wood or paper is glued together since these are porous/fibrous matrices that the glue can penetrate into and completely envelop.

3. Roughness in most cases **enhances the wettability** of the glue, leading to lower chance of unwetted areas.

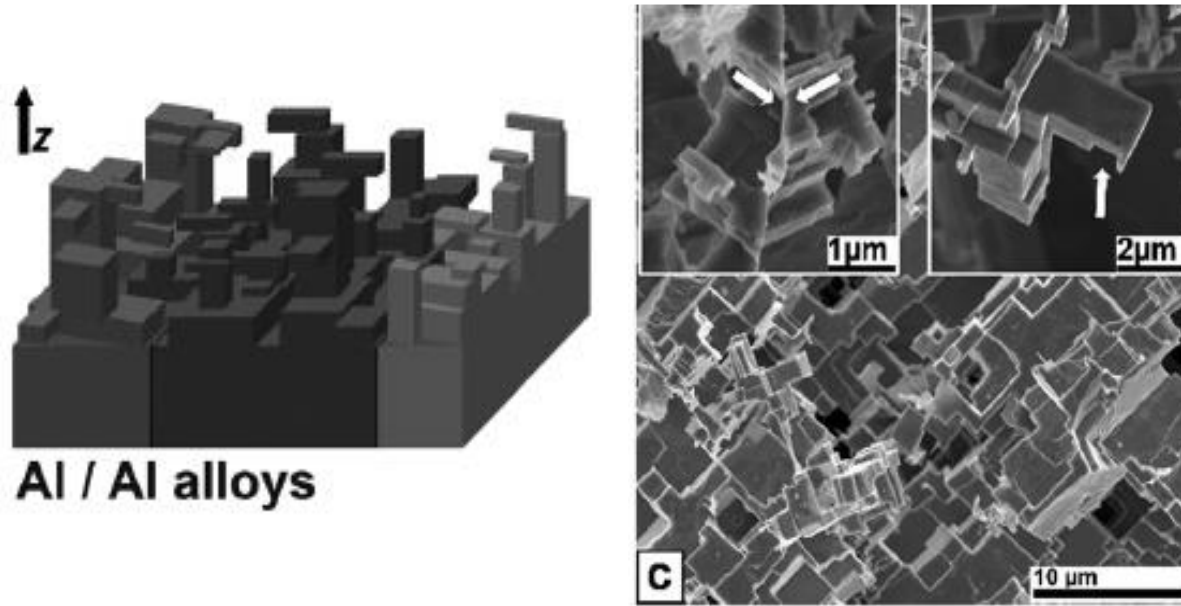
Glue on flat surface



Glue on porous/rough surface

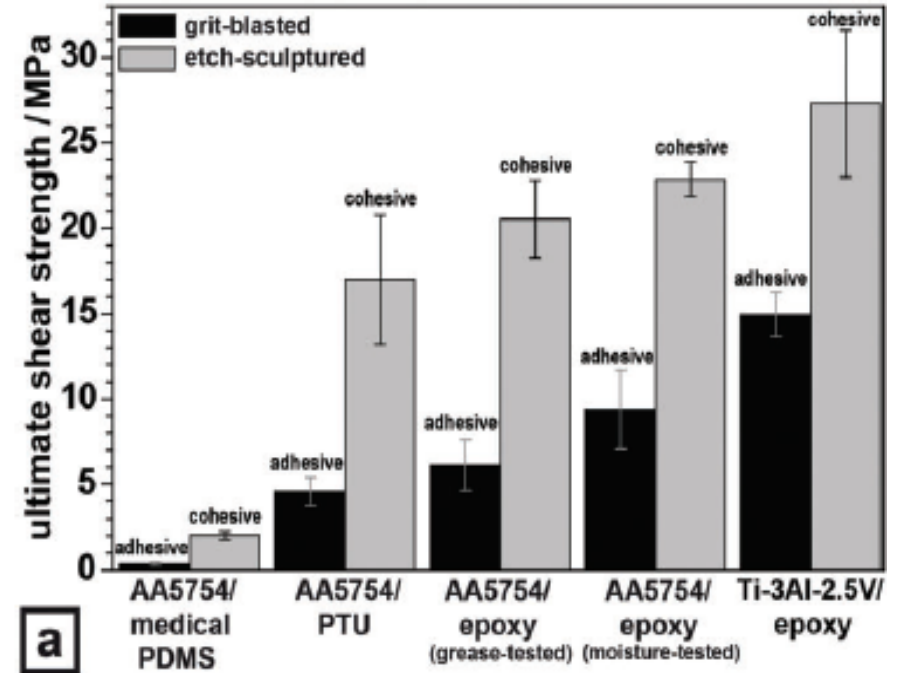


Roughness, overhanging geometries and adhesion



Etching was used to make Al very rough and contain re-entrant (overhanging) geometries.

This dramatically increased the adhesive strength of several tested glues.



Gray bars: Rough + overhanging Al

Black bars: Control, grit-blasted Al (cleaned but not polished)

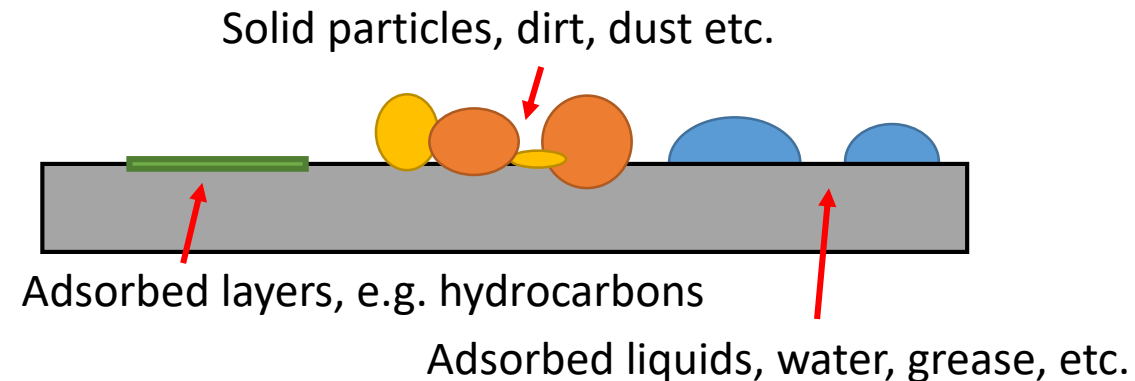
Grit-blasted Al: adhesion breaks in the test

Etched: adhesion does not break, instead cohesive failure in the glue.

Cleanliness and glues

Surfaces should be clean if good adhesion is desired.

1. Any loose particles: these are not bonded to the surface and will lead to lower total adhesive area.
2. Loosely bound layers: the glue will adhere to these, which will then risk that the adhesion breaks between the adsorbed layer and the substrate.
3. Water/grease: glue likely does not stick strongly on these.
4. Spontaneously adsorbed layers tend to be hydrophobic (due to surface energy minimization) and this can make the wetting of the glue worse.



Lets make a Gallup/quiz (unless we are low on time)

You are gluing together two identical surfaces. Based on the lecture so far, make an educated guess in which case the adhesion is stronger.

So the comparison in e.g. 1 is gluing two porous silicon surfaces together vs gluing to flat silicon surfaces together.

1. Porous silicon vs flat silicon
2. Flat Teflon vs flat glass
3. Wood vs flat glass
4. Clean flat glass vs Joksas living room window glass

Part 3: Solid adhesives (tapes)

Pressure sensitive adhesives

Tapes utilize pressure sensitive adhesives, PSAs

The PSA is a **loosely crosslinked polymer** layer that is **viscoelastic**. (properties of both a solid and a liquid)

The three most common PSA:s are:

1. Acrylic
2. Silicone
3. Rubber (natural and synthetic)

They bond to surfaces by Van-der-Waals forces.

Adhesion to different substrates is determined by:

1. Surface energy has double effect:
 - It affects how strong the physical bonds are.
 - **It affects the wetting properties of the tape.** Remember the tape is viscoelastic so it both flows and wets.
2. Roughness (next slide)

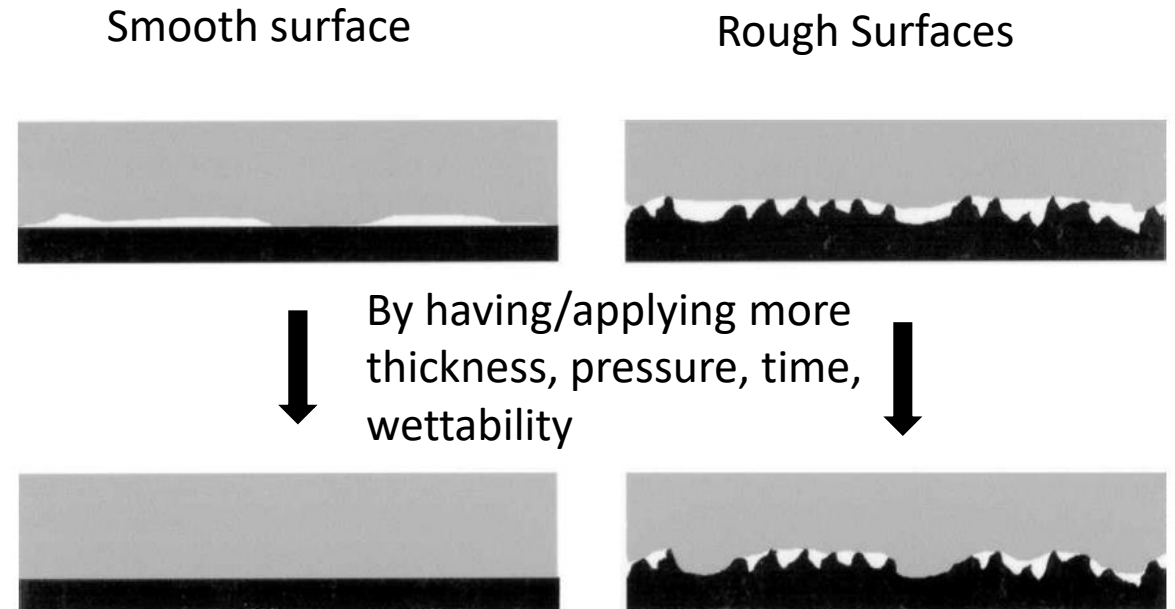
Pressure sensitive adhesives and roughness

In most cases, roughness leads to less strong adhesion.

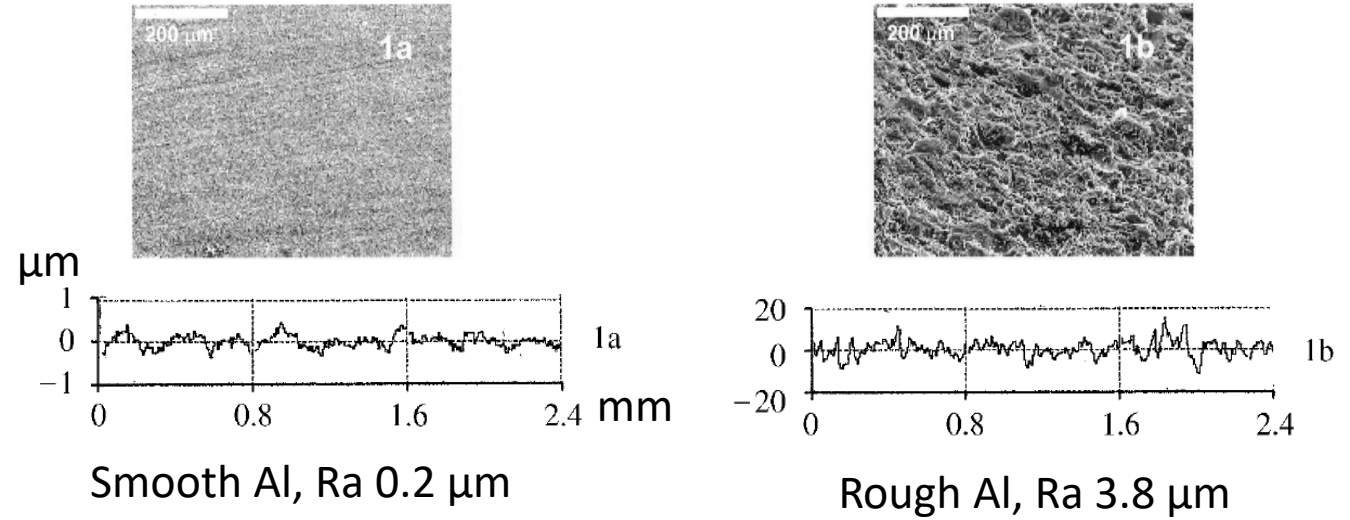
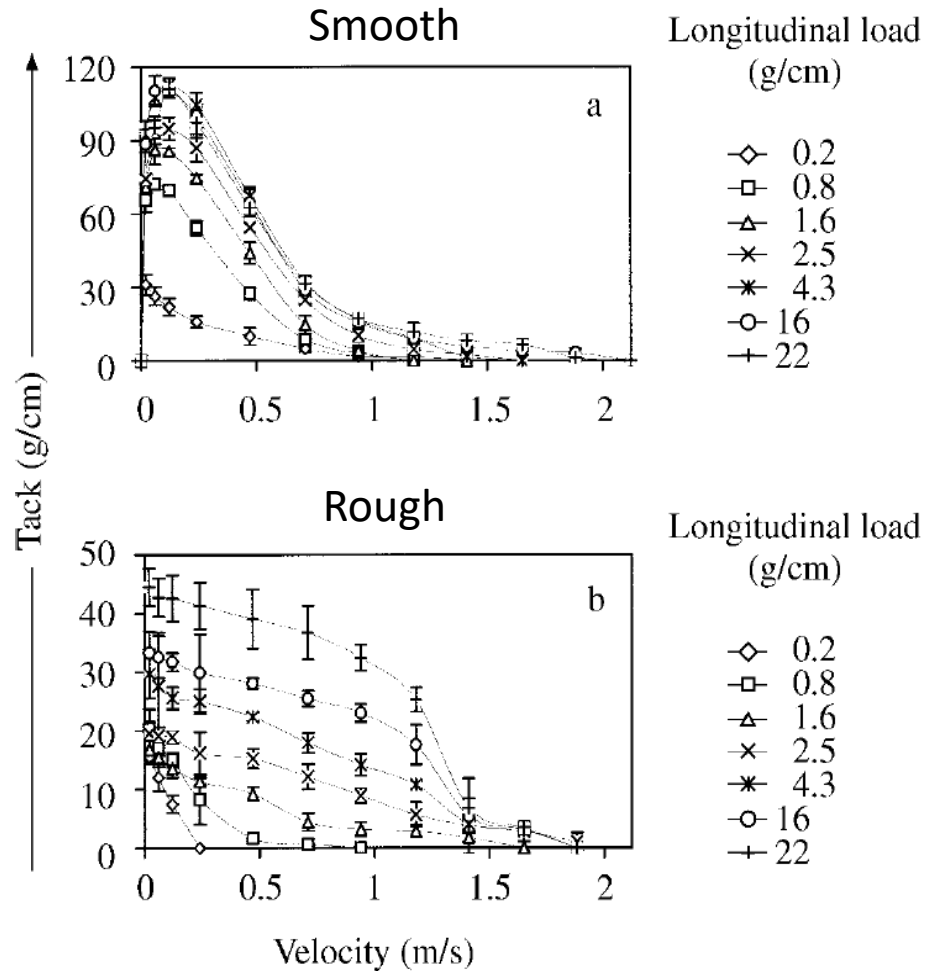
(In theory, this can be reversed if the adhesive fills the roughness to a large degree, but this seems to be very uncommon.)

Adhesion on rough surfaces is improved by.

1. Having a thicker adhesive layer: Thicker viscoelastic layers deform more easily with the same force.
2. Applying more pressure: more pressure leads to more and faster shear deformation of the viscoelastic layer.
3. Applying the pressure for longer time: viscous flow takes time.
4. Better wettability. Wetting works together with the viscoelastic deformation created by the external pressure.



3M acrylic tape on smooth and rough Al

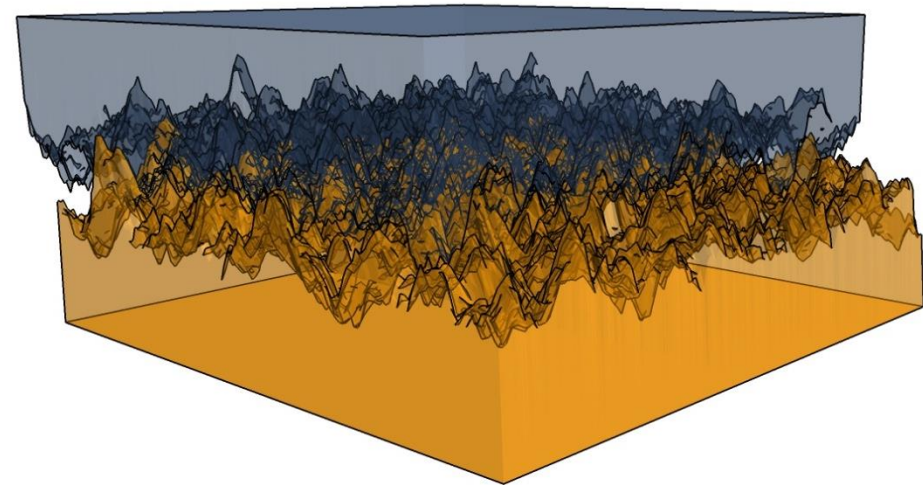


Tack (measure of adhesion) was higher when:

1. The surface was smoother (because of contact area)
2. Pressure (load) was higher (more contact)
3. Time of contact was longer (velocity of test on x axis is lower), once again more contact due to more time for viscous flow.

Mechanics of joining (slide from lecture 3B)

- Even polished surfaces have roughness $R_{\text{peak-to-valley}}$ 3-10 nm → not perfect contact
- Heat to 1000°C → viscous flow
→ Intimate contact

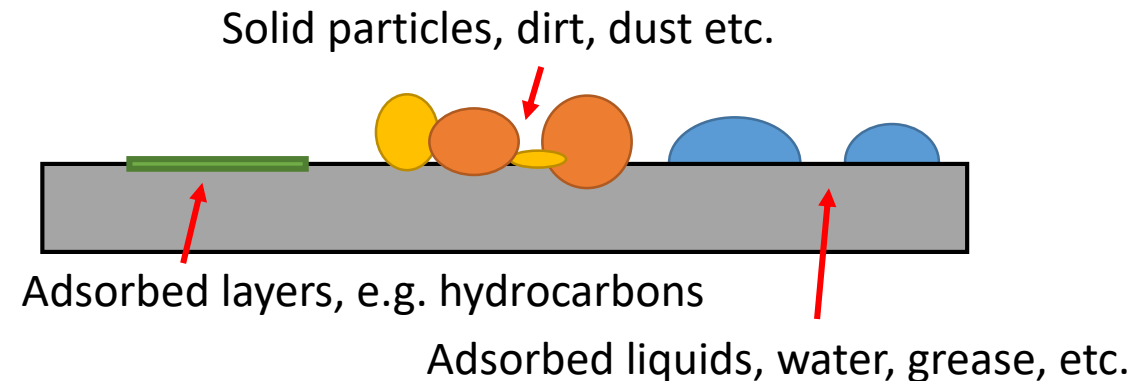


Bonding can use high temperature to achieve better contact.
An adhesive tape cannot. Hence the need for viscoelasticity to ensure contact.

Cleanliness and PSAs

Surfaces should be clean if good adhesion is desired.

1. Any loose particles: these are not bonded to the surface and will lead to lower total adhesive area.
2. Loosely bound layers: the PSA will adhere to these, which will then risk that the adhesion breaks between the adsorbed layer and the substrate.
3. Water/grease: PSA likely does not stick strongly on these.
4. Spontaneously adsorbed layers tend to be hydrophobic (due to surface energy minimization) and this can make the wetting of the glue worse.



This is the exact same slide as for the glues. Remember point 4 also applies.

Common Scotch tape

Most famous/common standard tape is the Scotch Magic tape.

The exact materials are trade secrets. There are also many different products and formulations.

1. The film itself is a solid polymer, cellulose acetate. It provides the cohesive mechanical strength.

-Typical **thickness** $\approx 40 \mu\text{m}$

2. The adhesive is a synthetic pressure sensitive acrylic adhesive

- **Adhesive thickness:** $22 \mu\text{m}$

3. On the other side of the film is a silicone coating. **Silicone has low surface energy**, and the acrylic adhesive does not bind strongly to it. That is why you can get the tape out of the roll.

Adhesion to steel: 2.5 N / cm in standard peel test ASTM D3330 / D3330M

“Scotch tape test”: Scotch tape is so common that it is sometimes used as a qualitative adhesion test itself. The “Scotch tape test”. In it you laminate the tape on a film/coating on top of a substrate. Then you peel the tape off and see if your film/coating sticks to the substrate or to the tape.



Kuva:
<https://www.verkkokauppa.com/fi/product/33818/mdttf/Scotch-Magic-nakymaton-yleisteippi-tayttorulla-19-mm-x-33-m>

Duct tape

Duct tape is made from three layers

1. Polyethylene outer layer, protects from environment (moisture)
2. Cloth mesh layer, this provides the mechanical durability of the tape itself
3. A pressure sensitive natural rubber adhesive.

The big secret to duct tape adhesive power? The adhesive layer is thicker than in normal tape. Because of this it makes better contact with rough surfaces. (and remember all surfaces are rough).

Typical adhesive thicknesses is not easy to find, I am guessing 30-100 μm . (If anyone finds this info, I will be thankful for providing a link.)

3M Venture Tape*

Peel adhesion: 5 N/cm (PSTC-101)

Shear adhesion: >24h, 15.2 kPa (PSTC-107)

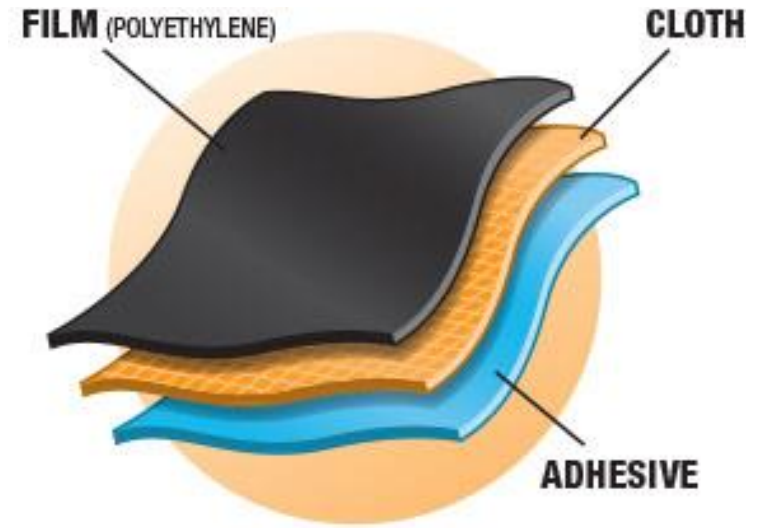


Figure: <https://www.sigmasupply.com/sigma-products/duct-cloth-tape>



<https://go.discovery.com/tv-shows/mythbusters/videos/duct-tape-boat>

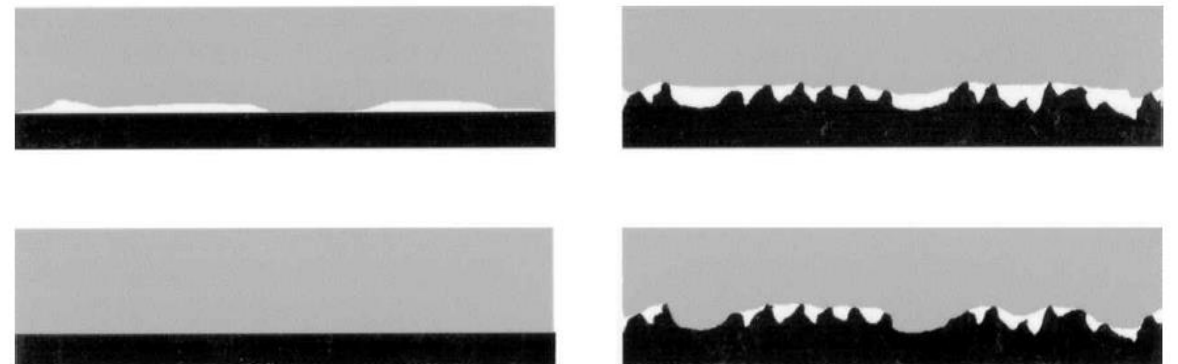
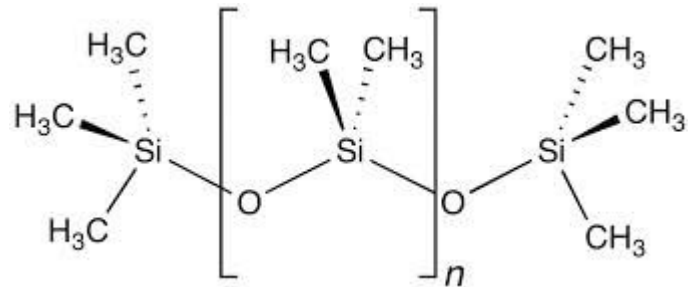
* <https://multimedia.3m.com/mws/media/10927500/3m-venture-tape-cloth-duct-tape-1501-technical-data-sheet.pdf>

Quiz time!

An experiment: Elasticity vs adhesion in PDMS

Demonstration of how increased elasticity (viscoelasticity?) leads to increased real contact area, which in turn increases the adhesive force.

PDMS has methyl terminated surface chemistry which mainly interacts through Van der Waals bonds.



Samples

PDMS of three different mixing ratios (monomer to crosslinker) were prepared and cut into 1cm diameter circular discs.

The mixing ratio affects the crosslinking density.

Elasticity (Young's modulus and compressive modulus) depends on mixing ratio. Approximatively:

10:1 -> 2 MPa

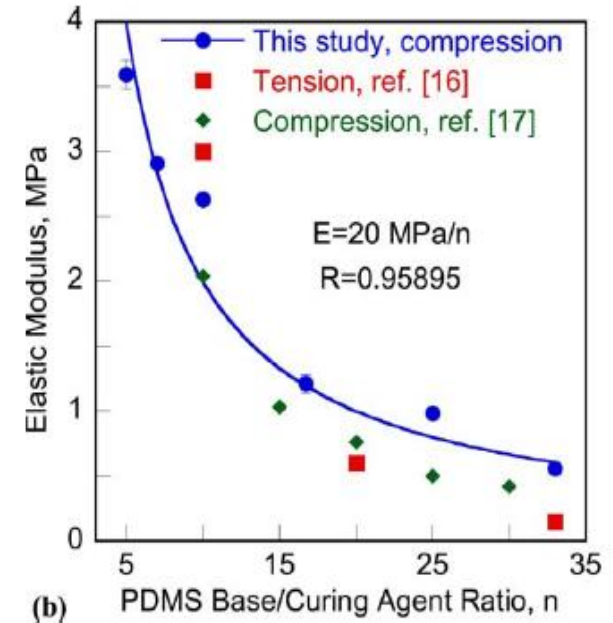
20:1 -> 1 MPa

30:1 -> 0.5 Mpa

The surface chemistry and thus the surface energy is expected to be unchanged.

Are these viscoelastic PSA:s?

I do not know. On the 30:1 ratio the crosslinking density is starting to get low and silicone was one the 3 main PSA types. But I would still guess that even that mixing ratio is an elastic solid.



J. APPL. POLYM. SCI. 2014, DOI: 10.1002/APP.41050

Experimental (short version)

A sample disc was pressed into contact between two polystyrene petri dishes (Cellstar, Greiner Bio-one). The location of the disc was roughly in the center of the petri dish.

The bottom petri dish contained the weight to be lifted (30 g – 200 g)

To perform the experiment, the weight was lifted to air for 3-5s supported only by the adhesion of the sample. We recorded whether the adhesion broke during this time window.

For each sample and weight, the experiment was performed nine times, three times with three separate discs.

After you have seen the experiment and the results, lets discuss what more info you would like to see if you were reviewing this science or grading this lab report.

Experiments



10:1 PDMS, 50 g weight, adhesion failed



30:1 PDMS, 100 g weight, adhesion held

Results:

Weight (g)	10:1	20:1	30:1
30	Yes	Yes	Yes
50	No (3/9)	Yes	Yes
100	No	No	Yes
200	No	No	No

If text is on light gray it means the experiment was not made. Added to table for clarity.

So we could say that 1 cm diameter disc of 10:1, 20:1 and 30:1 PDMS have enough adhesive ability to carry $40\pm 10\text{g}$, $75\pm 25\text{g}$ and $150\pm 50\text{g}$ respectively.

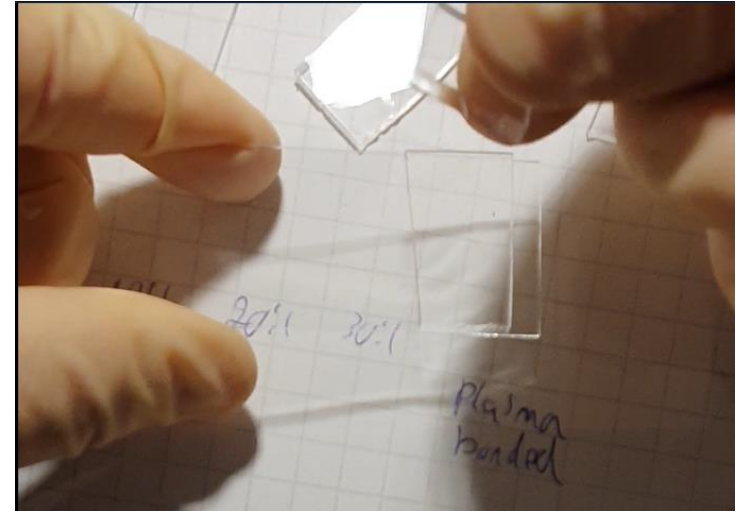
This can be translated to respective tolerance for tensile stresses of $\approx 1.2\text{ kPa}$, $\approx 2.3\text{ kPa}$ and $\approx 4.7\text{ kPa}$

Plasma bonded PDMS

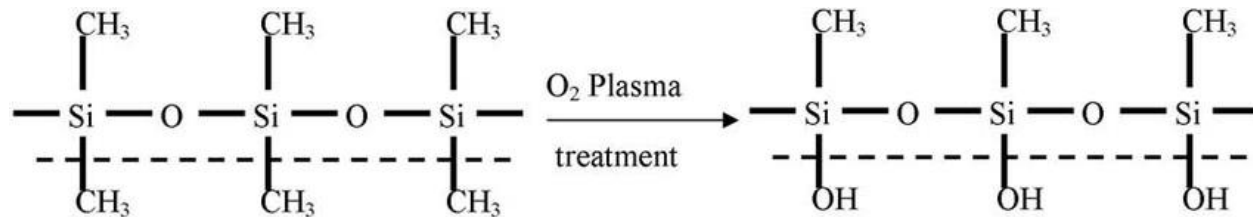
Bonus experiment: glass and PDMS surfaces were exposed to oxygen plasma, pressed together and heated to 70°C for 15 min. (process is called plasma bonding)

Now instead of Van der Waals bonds, covalent siloxane bonds form.

As a result, the bond cannot be separated by peeling. Instead, internal bonds of PDMS break before the siloxane bonds at the glass-PDMS interface.

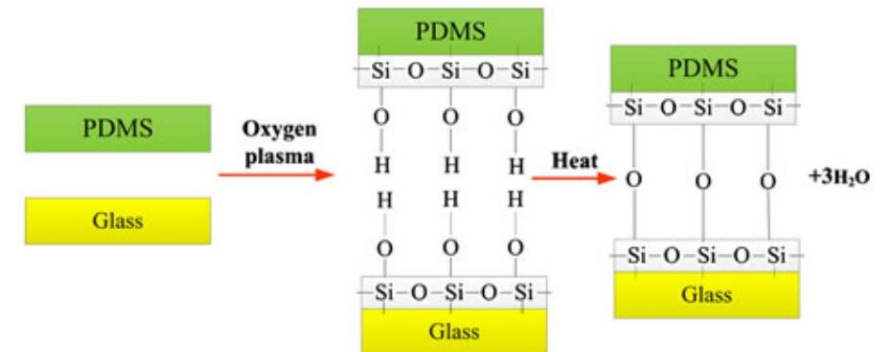


PDMS cohesion breaks before adhesion



PDMS surface

Oxidised surface



Experimental (short version)

A sample disc was pressed into contact between two polystyrene petri dish (Cellstar, Greiner Bio-one) surfaces.

The bottom petri dish contained the weight to be lifted (30 g – 200 g)

To perform the experiment, the weight was lifted to air for 3-5s supported only by the adhesion of the sample. We recorded whether the adhesion broke during this time window.

For each sample and weight, the experiment was performed nine times, three times with three separate discs.

Write into chat, what more information do you think would be important to include for the readers?

Should absolutely be included in experimental (and potentially improved in the experimental setup):

Cleanliness of samples and how they were or were not cleaned,

Distribution/balancing of the weight,

Centralization of the discs

Thickness of samples,

Which side of petri dishes was used (surface roughness can be different)

Brand and type of PDMS

Borderline: How the weight was measured (they were measured by a food scale with 1g accuracy and range from 3g to 10kg...but this is so commonplace that it can be left out. Might be safer to include if unsure.)

What doesn't matter and should not be elaborated: that coins were used as weights, samples were marked by stickers/pen.

Summary

Work of adhesion is the backbone of all types of adhesion.

Work of adhesion is based on surface energies, which are based on physical and chemical bonds (or lack thereof) at an interface.

Surface energies can be measured indirectly: there is some modeling/estimation involved

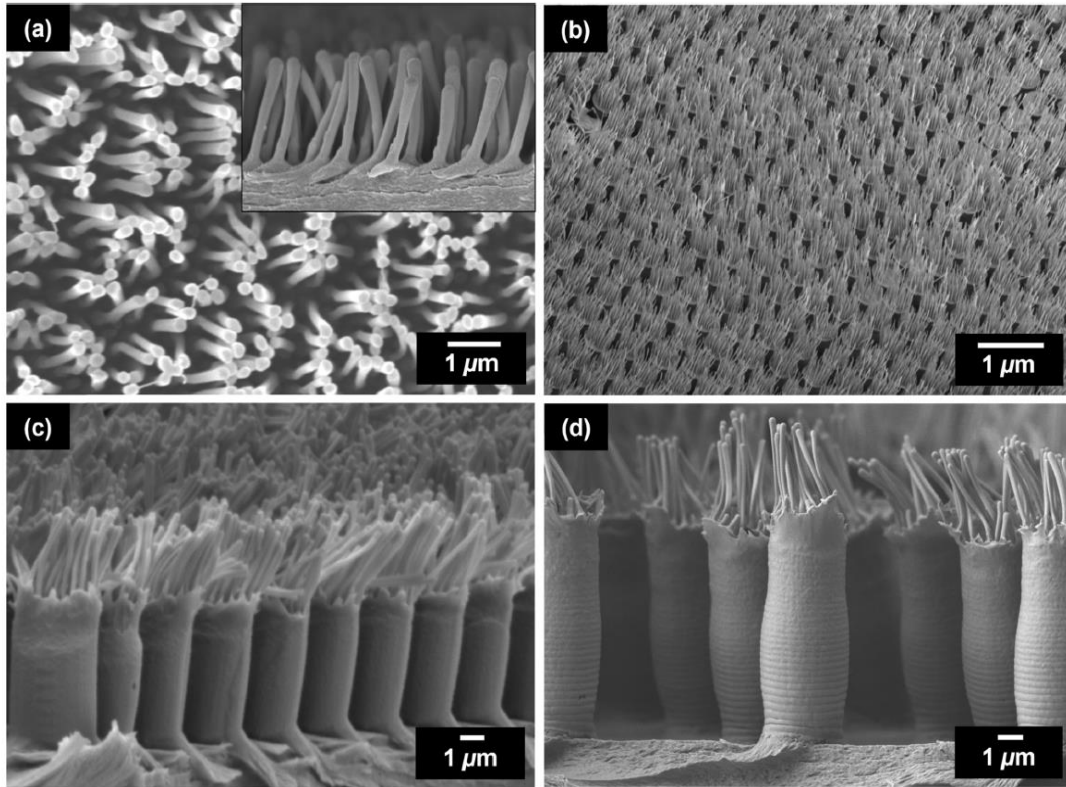
In practice, adhesion is complicated and is always the property of the whole system. Energy is not only dissipated in breaking a single interface but is instead dissipated also in the adhesive and in the substrate etc.

To make a good adhesive, it needs to wet (whether a glue or a PSA), to make bonds with many types of substrates and have strong internal bonds.

Roughness typically helps glues but hinders PSA:s.

Always strive to have clean samples in everything surface related you do 😊.

Gecko inspired dry adhesive



Gecko mimic structures...



...might allow you to climb vertical walls!