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Avery Dennison

Develop self adhesive to stick on moist and icy substrates

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1. Abstract

Normal acrylic-based adhesives that stick to dry surfaces, do not stick to surfaces with a water film. The water decreases the Hamaker constant, which indicates the strength of the Van der Waals forces, by a factor 10. The time needed to squeeze out the water by applying pressure to a label on top of a wet surface, is too long for normal applications. Approaches to remove, use and penetrate the moisture layer are proposed. This work focuses on proposals for water removal and this case is analyzed theoretically and tested experimentally. Pores are needed to transport the water away from the gap between the substrate and the adhesive layer. We show experimentally that adhesives with pores (50 µm diameter, 1 mm spacing) have a larger pull-off force on wet surfaces after applying pressure than adhesives without pores. Theoretical calculations for a 20µm thick adhesive layer of 645 mm^2 surface area with 800 holes of 10µm diameter, show that the maximum volume of water retainable in the capillaries is $1.5 \cdot 10^{-12}$ m^3. This value is 500 times less than the volume of water squeezed out when the layer is reduced to 1µm. Therefore pores need to be made through both the adhesive and film layer where the water can evaporate or an absorbance layer is needed. Alternative strategies proposed to improve adhesion performance on moist icy surfaces include addition of polysaccharides, (poly)electrolytes, nanofibres, functionalized superhydrophobic and superhydrophilic patterns of the adhesive layer

2. Company profile

A merger with Dennison Manufacturing in 1990 created the new Avery Dennison. Today, Avery Dennison has more than 30,000 employees in 60 countries and $6 billion in sales.

Our vision 'Make every brand more inspiring and the world more intelligent' is all around labels and decoration technologies. Labels that you find virtually on most of the goods you find everyday in the supermarket. We foster creativity and the development of new ideas, products and processes to enable and provide solutions to help grow our customers' businesses.

Our technologies and capabilities are in the fields of self adhesive, web-based converting, high speed precision coating, printing, RFID, micro-replication, film extrusion and functional coatings

3. Problem description

Self adhesive materials are 'thick fluids' that bond to a substrate based on differential of surface tension which makes deformation of the adhesive possible. Upon debonding the stiffness of the adhesive and the energy dissipation play key roles (as is the adjacent printed layer).

Self adhesive labels are used in many areas because of its versatility to print, convert and easiness to apply the label to a product. Especially when labelling takes place under production environments below dew point, or when frozen substrates are labelled under ambient conditions the surface areas will be 'contaminated' with a layer of water making the bond difficult.

The consequence is that labels fall off, that they need to be labelled, or in the case of pharmaceuticals or bloodbags, manually dried before the label can be applied.

4. Problem solving strategy

The central problem in this case is that the moisture layer formed on icy and cold surfaces (5-10°C) hinders the effectiveness of the adhesion properties of the adhesive.

The scope of our strategy was limited to liquid water being condensed on the substrates surface. In case of icy surfaces, we suggested to use an anti-freeze agent in the adhesive layer, e.g. salts or diethylene glycol, to melt the ice to moisture and treat the issue in a similar way to the moisture problem.

The first step in assessing the problem is to analyze factors influencing adhesion. These include the roughness, humidity, moisture, surface tension, shape of the substrate, labelling temperature, and service temperature. In this case, water and the substrate – water – adhesive interface are the central factors. [UPM Raflatac (1)]

When these factors are known, improvements are suggested that could increase the adhering forces. A first brainstorm gave rise to three approaches: removing water, making use of the water and penetrating the water.

1. The first strategy is to design ways to remove water. In this approach it is important to know the amount of water that can be pressed out actively when the label is applied, and how much water can be transported via other means (e.g. capillary action). In addition, porous adhesive can facilitate improved water permeation and transportation. Bimodal-distribution of pore sizes may be desirable, in which larger pores allow water to channel fast and the smaller pores can continue to remove water when the height of moisture layer on the substrate reduces to the nanometer range. Enhanced water permeability is usually achieved by either physically blending hydrophilic additions or chemically incorporating in the backbone, hydrophilic hydroxyl groups by modifying the crosslinked low molecular weight acrylic oligomers with substantial quantities of hydroxyl containing monomers.[Osburn 1984 (2); Berejka, 1994 (3); Kellen and Taylor, 1988 (4)] Horizontal and vertical channels patterned onto the material, for instance, via chemical and surface patterning of the adhesive layer, can control the shape and location of liquid entrained during a coating process. In addition, patterned superhydro-

phobic coatings with optimized adhesive surface exposure to substrate may be of use. Zhang et al. illustrated on possible method to allow surface two-level patterning with two levels of opposite water affinities (Figure 1.) [Zhang 2007 (5)]. Furthermore, self-assembly of block copolymers, such as acrylic adhesives functionalized with hydrophilic ends of acrylic adhesives, can form water channels.

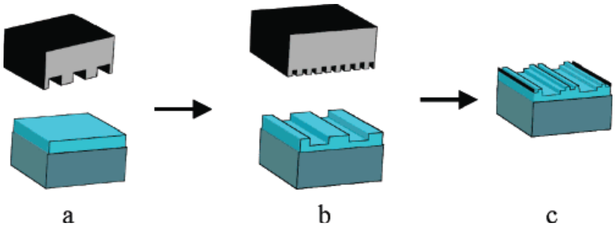

Figure 1. Sequential patterning: (a) a polymer film is coated onto a substrate, and a primary imprint is made by pressing the polymer with a hard mold at a temperature above the Tg of the polymer and at an elevated pressure; (b) a second mold is aligned to the primary imprint and pressed at below the Tg of the polymer and at an elevated pressure; (c) a two-level hierarchical structure is created on the polymer film. Courtesy to Langmuir [Zhang 2007 (5)].

2. When a liquid, in this case water, is found between two surfaces, a capillary bridge is formed that holds together the surfaces by F(b):

$$F(b) = 6\pi\mu R^2 \frac{1}{b}\frac{\delta b}{\delta t}$$

   Because the force is proportional to the viscosity, μ, by increasing μ, F can be increased. It is know that solutes like sugars or hydrophilic polymers such as polysaccharides and polyelectrolytes can increase that viscosity of water by order of magnitudes. Therefore one of the proposals is to add polysaccharides (starch) on the surface that would dissolve in the water layer present and would in turn increase adhesion.

3. Designing the adhesive to be able to penetrate the moisture layer is a possibility. Flocking of microfibres and nanofibres which are subjected to electric field, and due to like charge repulsion, nanofibres will stand vertically on the surfaces of their attached material and may be able to provide more penetration through the moisture layer compared to the nanofibrous structures on the surface of gecko's feet.

Due to the short time span, one approach (1, removing the water) is worked out theoretically.

Based on the calculations and subsequent suggestions, experiments are designed to test whether the proposed improvements show indeed the increase in adhesion.

5. Theoretical analysis

5.1 Why are moist surfaces more difficult to adhere to?

A number of reasons are proposed to explain the phenomena of reduced adhesion on a moist substrate compared to a dry substrate.

Firstly, assuming Van der Waals being the dominant adhesive force, the adhesive energy for two infinite half spaces is:

$$E = \frac{A}{12\pi D^2}$$

with D being the distance between the layers, A the Hamacker constant and E the Van der Waals energy. When comparing typical Hamacker constants in air and in water, it is found that in water A is about 10 times smaller then in air, due to dielectric screening. [Isrealachvili, 2011 (6)]

The water is simply preventing the adhesive layer and substrates layer to come into close contact. Due to the high viscosity of water, after pressing the adhesive film, the amount of water left in the interface falls under the viscous regime, as the moisture layer approaches micrometer thickness. In this regime very high pressures (much higher then the typical applied pressure) are needed to remove the remaining water from the film to the edges in a typical time used to apply an adhesive.

5.2 How much water is involved?

Characteristics of the moisture layer forming on the substrate play a crucial role in the strength of adhesion. Understanding the speed of formation of the moisture layer and the thickness of the moisture with respect to time is fundamental to solving the problem. Water layer formation depends on ambient humidity, temperature, heat transfer, and nature of the substrate. However, calculations based on thermodynamics suggested that within 2.5 minutes, the condensed water layer would be several millimeters. This was not in line with the value we found experimentally, by measuring the increase of weight of a tissue before and after wiping the surface of a 5°C stainless steel block with known area. In this case, the water film had a thickness of 3 μm.

5.3 What does the substrate look like?

Surface
Equally crucial is the understanding of the roughness of the surface of the substrate. In this case the roughness and the length scale of the surface is 5 μm (data supplied by Avery Dennison). In addition, the homogeneity of the substrate surface is important. For heterogeneous surface with micro protruding surfaces, the effective contact of water and the substrate is very small, thus water droplets have high mobility and slide off.

Bulk material
Conventional non-water permeable non-water soluble acrylic-based PSAs
Conventional non-patterned non-water-permeable Acrylic-Based PSAs display compensated adhesion due to water vapor accumulation at the adhesive and substrate interface. The rate of water permeability in a solid is a function of temperature, viscoelasticity, the size of the particles and the crosslink density of the adhesive. According to the classic model by Vanderhoff et al., the diffusion of water vapor in the adhesive moves through a layer of continuous polymer, either via capillary channels between the deformed spheres or through the polymer itself. This process is very slow [Vanderhoff et al. 1973 (7); Kajtna et al. 2008 (8)]. Water will generally not penetrate micro porous film due to the fact that the microscopic openings are too small (approximately 25 μm) to overcome the surface tension of water to permit water penetration. [Murphy, 2005 (9)]

Enhanced water permeable non-water soluble acrylic-based PSAs
Nonporous acrylic-based PSAs with enhanced water permeability have long been achieved by either physically blending hydrophilic additions or chemically incorporating in the backbone, hydrophilic hydroxyl groups by modifying the crosslinked low molecular weight acrylic oligomers with substantial quantities of hydroxyl containing monomers. [Shah et al. 1982 (10); Berejka. 1994 (3); Kellen and Taylor 1988 (4)]

Continuous non-porous 25μm thick coatings of an acrylic-based PSA including a type of alkyl acrylic copolymer PSA, which is similar to a typical type of materials used in Avery

Dennison with comparable coating thicknesses, exhibit water vapour transmission rates of greater than 1000 - 1600 g/m2/day at 40°C [Shah, 1982, 1985 (11)], an equivalent of 15 nm/s at 40°C for the upper boundary value stated here.

Porous acrylic-based PSA

In addition, one of our ideas included modifying porosity, which can be introduced to further enhance water transport, by crosslinking additions to form pores within the adhesive. This aspect is not discussed in this chapter as our focus of the approach is by patterning water transport channels within the adhesive instead of using porous adhesives.

5.4 Capillary action

Water that is condensed onto a cold surface can be excreted through pores that are applied through the adhesive layer and face material. There are several mechanisms that can be considered promoting the excretion of water in our system. One is by applying an external pressure, which is considered in the next paragraph. Secondly, capillary pressures can results in a net flow towards the pores. In this paragraph the capillary pressures are being evaluated.

The system is considered as a water droplet, of width R, that is confined between two planes, separated by distance d and having a contact angle (θ_1). In the upper plane a capillary, with a radius r, is connected to the confined droplet. The water from the droplet is allowed to creep up into the capillary. The water level in the capillary is described length L en the surface of the capillary has contact angle of θ_2 with water. Figure 2. shows a cartoon of the system.

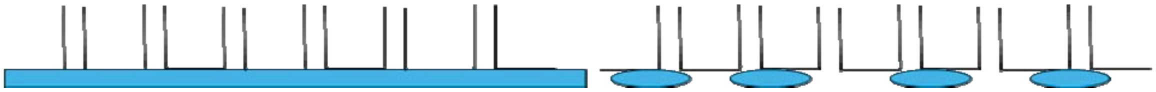

Figure 2. Schematic depiction of a water film between a substrate and a layer with pores.

Capillary pressure is expressed by the following formula:

$$\Delta P = \frac{2\gamma\cos\theta_1}{r} - \gamma\left(\frac{2\cos\theta_2}{d} - \frac{1}{R}\right) - \rho g L + \frac{2\gamma\sin\theta_2}{R}$$

For a continuous layer, R goes to infinity and so the fourth term can be neglected. However, if the condensed water layer consists of small droplets in the order of the size of the capillary all terms have to be taken into account.

The origin of the equation is from the balance between the capillary pressure acquired from all of the surfaces of water and the pressure of capillary related to its mass.

Four variables (L, P, r, R) in the upper equation make it quite nontrivial to analyze and concerning this, the following assumptions were made:

L is taken as the thickness of the adhesive layer. Hence it is the maximum height on which the flow should be taken. If the pressure P is positive when the water has reached the end of the capillaries, then the flow is directed inside the capillaries and contributes to decreasing the thickness of the water layer. The capillary size is taken between 10 µm and 50 µm (which complies with the experiment), and the size of the droplet is taken as no smaller than the radius of the capillary but not bigger than the spacing between two capillaries when they are placed in a lattice. The layer thickness d is expressed in the measures of the capillary thickness, r. From considering the example with the flat capillaries, one can estimate that r=d corresponds to the critical value of the thickness.

(Note that this explains why the use of parallel channels does not suffice to get rid of the water: due to this capillary pressure (r>d), water flows back from the channels to the water film between the substrate and the adhesive)

Further the demonstrations are made in order to investigate the connection of the sign of P depending on d, r, and R. For this purpose the contour plot is used (Figure 3.), which shows that for the relative thickness of the layer around the size of the droplet, all of the parameters of the system should be taken into account in order to estimate the optimal configuration which is necessary for the water to go inside the capillaries and the absence of the leftover water layer between. Two possible states are as follows: upon placing the adhesive, the water goes inside the capillary and when the sides of the droplet are touching the walls of the capillary, due to increased capillary pressure difference, the water goes in. The second unfavourable option is that the thickness of the water layer, d, gets smaller than r. Which of the above situations prevails, depends on the parameters of the system.

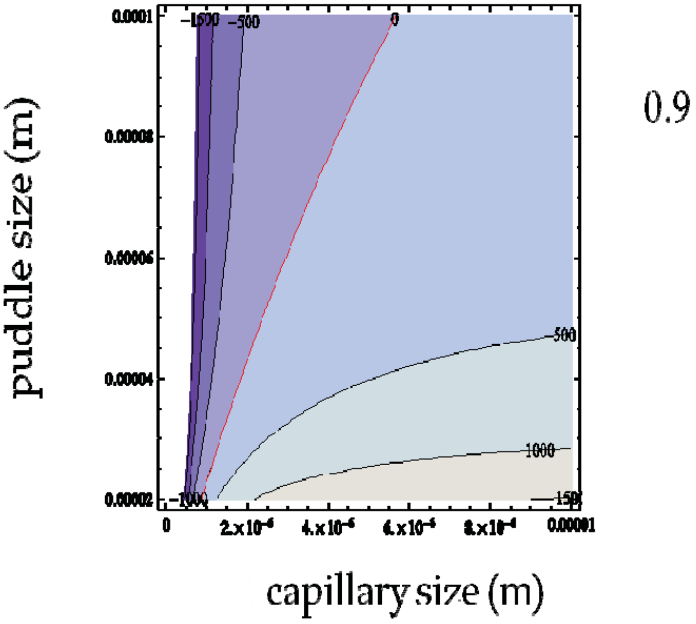

Figure 3. Level of the pressure depending on the capillary size and the size of the droplet. The red line is the level on which the pressure difference is 0, and the thickness of the water layer is related to the size of the capillary as 0.9.

Concluding, the capillary pressure plays a role for thin layers of water, but primarily when designing the capillary surface, the volume conservation should be taken into account and then the capillary affect should be considered.

5.5 Transport of water via pores

Many creatures in nature are capable of adhere to surfaces even under dry conditions. It is common that the type of surfaces to which these organisms stick are very extensive, ranging from stones to trunks in the trees. All of them rely on the principle of maximizing the effective contact area with the surface via secreting a liquid-like substance, patterning its own limbs or a mixture of those.

In the case of wet surfaces a counterintuitive phenomenon is found in nature, more specifically in the toes of tree frogs [Persson, 2007 (11)]. Their toe pad consists of a hexagonal-like network of channels which at the same time contain an inner (smaller) network of hexagonal pillars. This type of pattern in the contact area should reduce the adhesion between dry surfaces proportional to the voids left by designing such structure. Nevertheless, when water is added to the interface those channels and the space between pillars result in a effective drainage system that eases the squeeze out of the liquid.

Based on the principle of the toe pad of the tree frog we have designed a biologically inspired alternative. This idea is as simple as to pierce all the way through the adhesive with microscopic pores. We considered the adhesive fully perforated because it is required to expel the water out the interfaces permanently in order to maintain longstanding adhesion, something that is undesirable for the tree frog.

The transport of water via pores can be calculated using the modified Navier-Stoke equation for thin films [Landau, 1987 (13)]. Only the flow in the radial direction is evaluated:

$$\frac{12\mu}{h^3}\frac{\delta h}{\delta t}-\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta p}{\delta r}\right)=0$$

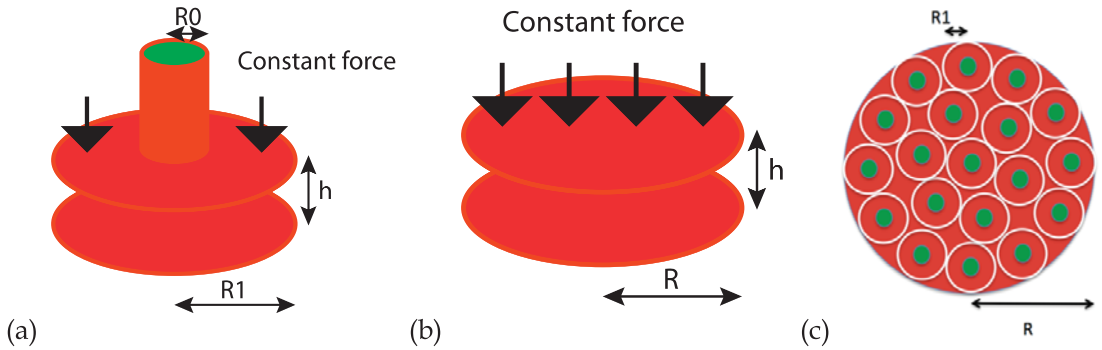

Figure 4. Schematic drawing of calculated geometry; water is squeezed out via the capillaries(a) or via the open sides (b). In (c), scheme showing the upside view relating both (a) and (b) system dimensions.

Here h is the thickness of the water layer, μ is the viscosity of the liquid (in this case water) and p is the pressure along the liquid. We can ignore the dependency of $\frac{\delta h}{\delta t}$ with r, by assuming that the plates involved are sturdy. In this manner it is possible to integrate it to obtain $\frac{\delta p}{\delta r}$:

$$\frac{\delta p}{\delta r}=\frac{6\mu}{h^3}\frac{\delta h}{\delta t}\left(r-\frac{R_1^2}{r}\right)$$

in which R_1 stands for the outer radius of the water layer. We have also used the fact that the pressure variation at the outer edge (far from the capillary) is negligible, so $\frac{\delta p}{\delta r}_{R1}=0$.

Integrating one more time results in

$$p-p_0=-\frac{6\mu}{h^3}\frac{\delta h}{\delta t}\left[R_1^2\ln\frac{r}{R_0}-(r^2-R_0^2)\right].$$

In which R_0 is the radius of the capillary and the boundary condition assumed is that the pressure at the capillary is p_0. In our assumption the net force applied on the system was constant so that the distribution of the pressure over the area is given by:

$$F_z = \int_{R_0}^{R_1}\int_{0}^{2\pi}(p-p_0)r\,dr\,d\theta = -\frac{12\pi\mu}{h^3}\frac{\delta h}{\delta t}D(R_0,R_1)$$

in which D is equal to:

$$D(R_0,R_1) = \frac{R_1^4}{2}\ln\frac{R_1}{R_0} - \left(\frac{R_1^2-R_0^2}{2}\right)^2 - R_1^2\frac{\left(R_1^2-R_0^2\right)}{4}.$$

From the previous equation is possible to find the rate at which the thickness of the water layer varies:

$$\frac{\delta h}{\delta t} = -\frac{F_z}{12\pi\mu D}h^3.$$

This equation allow us to calculate the rate at which water squeezes out through the capillaries when an applied force acts pushing both plates against each other. In our experiments we were able to perforate around 800 holes of nearly 10µm in 645 mm^2. Roughly, that situation is equivalent to have R_1 = 1 mm and R_0 = 25µm.

Similar calculations have been performed for the squeezing out of the water via the sides from two parallel plates, see Figure 4b. This resembles the situation for Avery Dennison, where a label without any pores is applied to a substrate. The time scaling behavior of this situation is similar to the previous calculations, but with different constants, depending on the geometry.

$$\frac{\delta h}{\delta t} = -\frac{2Fz}{3\pi\mu R^4}h^3.$$

Where R = the radius of the label, in the order of 1cm. The main difference between the squeezing of the water with and without capillaries is how the rate at which the water layer is drained out can be controlled not only by applying a greater force but also by tuning the ratio of $\frac{R_1}{R_0}$. We must be aware that by increasing the diameter of the capillaries reduces the net area of contact between the substrate and the polymer (reducing adhesion) therefore the optimum values for the ratio $\frac{R_1}{R_0}$ will be obtained when also the compromise adhesion are taking into account.

To give an indication of the time developments for both situations, a round label with a radius of 1 cm has been compared with and without capillaries. During a sturdy thumb press, a force of 50N can be applied, which corresponds to ca. 1Pa. For the label with capillaries only the situation between capillaries is calculated and to get a similar force over entire label, also a pressure of 1Pa has been applied in this situation. The results are shown in Figure 5. It is clear that for similar overall forces, it takes much longer for the label without capillaries to reach a 7µm decrease from a initial water film of 10µm, a thickness of the water film comparable to the roughness of the surface (5µm). It can thus be concluded that the capillaries help to reach thinner water layer under the label at normal pressing forces and typical label sizes.

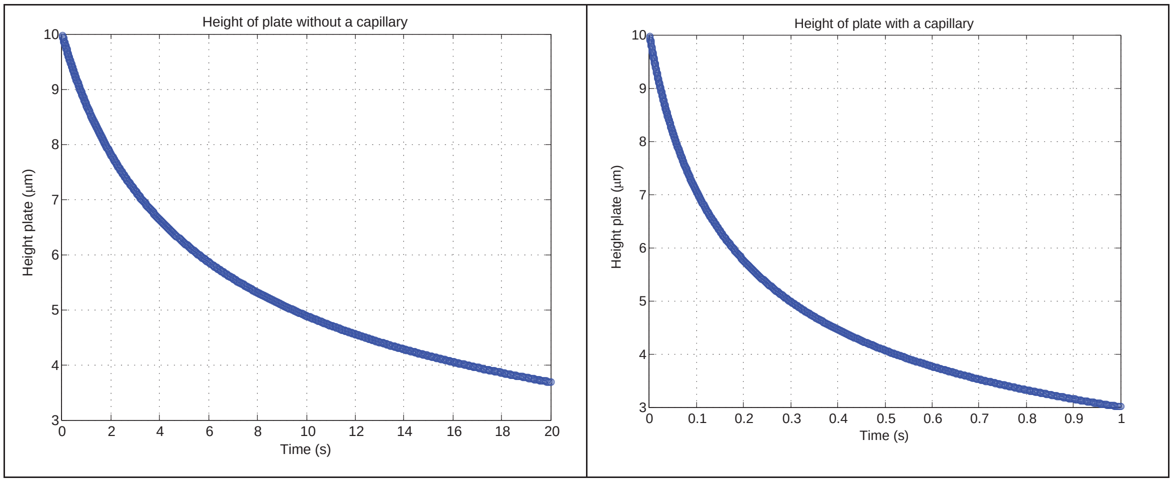

Figure 5. Time scales involved in pressing out water through open sides or capillaries.

It is also worth to notice that the total storage capacity for the capillaries is much smaller than the water that will be drained out. So for the case in which the adhesive layer has a thickness of 20µm, we encounter that in a pinned adhesive with the dimensions given previously, the maximum volume of water that can be stored in the capillaries is $1.5 \cdot 10^{-12}$ m^3. This value is 500 times less than the volume of water squeezed out when the layer is reduced in 1µm. Therefore the capillaries must either by made all the way to the free surface, where water is able to evaporate, or an absorbance layer must be used, to store the water.

6. Experiments

We have conducted experiments to check our theoretical findings concerning several adhesive layer modifications that could improve sticking to wet surfaces.

6.1 Materials and methods

Set-up

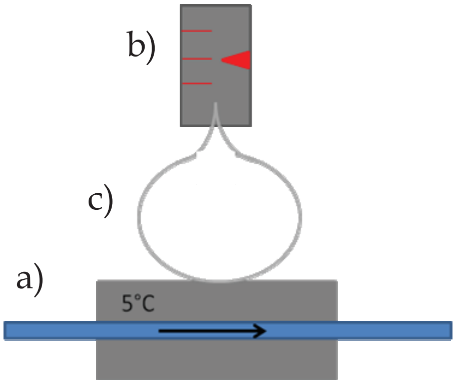

Figure 6. Schematic drawing of the experimental setup.

The experimental setup is presented in Figure 6. The lower, stationary part of the setup consists of a stainless steel stage (Figure 6a) constantly cooled by a water flow. The temperature of the block is kept at 5°C. The block is exposed to the environment of the lab, which is 20°C and 50% relative humidity. Since the temperature of the block is below the dew point, the surface of the block is covered by a layer of condensate. We have experimentally estimated the thickness of the water layer to be 3µm by measuring the increase of the weight of a tissue after wiping the stainless steel block.

The upper part of the setup can be moved in the vertical direction. It consists of a sensitive force measuring device (Figure 6b), to which a loop of adhesive tape can be attached (Figure 5c).

Samples with different surface modifications

The reference sample used was polypropylene face/general purpose acrylic emulsion/filmic liner. This is a common laminate used for labels, it is not specifically formulated to absorb water or such.

The types of surface modifications that we have applied to this adhesive are presented in Figure 7. Figure 7c and 7d show the top and the side view of the adhesive layer modified with groves in a square pattern. We have used two different pitches of 1 mm (sample name is 'Large grooves') and 200µm (sample name is 'Fine grooves').

In Figure 6c and 6d the top and the side view of the adhesive with through-holes is shown. The measured sample had an average hole diameter of 50µm and an average distance between holes of 1 mm. The holes are not arranged in a regular pattern. The sample with holes and no further modifications is called 'Holes'.

Figure 7e and 7f show the modifications of the sample with holes that we have used in the measurements. The former is covered with a hydrophobic layer on the part of the adhesive which comes in contact with the surface. The latter has an absorbing layer (paper) on top of the holes (sample name is 'Hole with absorbant'). This last sample also consists of a different adhesive layer.

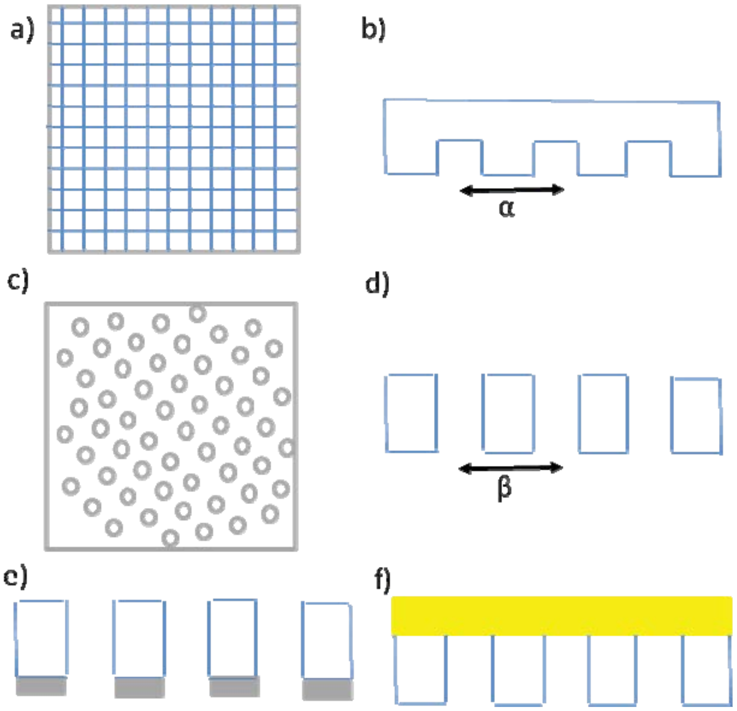

Figure 7. Schematics of adhesive modifications used in the experiments. a) and b) show the top and the side view of the samples with the groves in the adhesive layer, forming a square pattern. The pitch is denoted by a . c) and d) represent the samples with holes going all the way through the adhesive film, β is the average distance between the holes. e) shows an adhesive film similar to c) and d), but the part of the film which comes in contact with the substrate is covered by a water-repelling layer (gray rectangles). f) is similar to c) and d), but with an adsorbing layer on top (yellow rectangle).

Method

The experiment is conducted in the following way. A loop of adhesive tape (120*20 mm) is attached to the force sensor while the latter is retracted 100 mm above the surface of the stage. Then the force sensor is moved to 25.4 mm above the surface, such that the loop makes contact of approximately 26*20 mm^2 with the surface for the samples without absorbant. The adhesive tape loop can be left in contact with the surface for a certain amount of time, during which a pressure to the contact area can be applied. Then the force sensor is moved upwards and the maximum pull-off force is measured. After each test the stage is wiped with a tissue. After this drying, condensation is allowed to proceed for 2.5 minutes. It is assumed that this results in a reproducible film thickness. The sample is brought in contact with the stage before the first test. Before each measurement, the baseline is put to 0.

Three different tests are done: pull-off without waiting time (in duplo), pull-off with a delay time of 3 seconds and quickly pressing (< 1s) the sample (in duplo), and pull-off with a delay time of 100 s and 80 s of pressing. Pressing is done by applying a force of approximately 3 kg over an area of 18*24 mm (6.8 kPa).

6.2 Results and discussion

The maximum pull-off force for five samples and during the three test methods is shown in Figure 8.

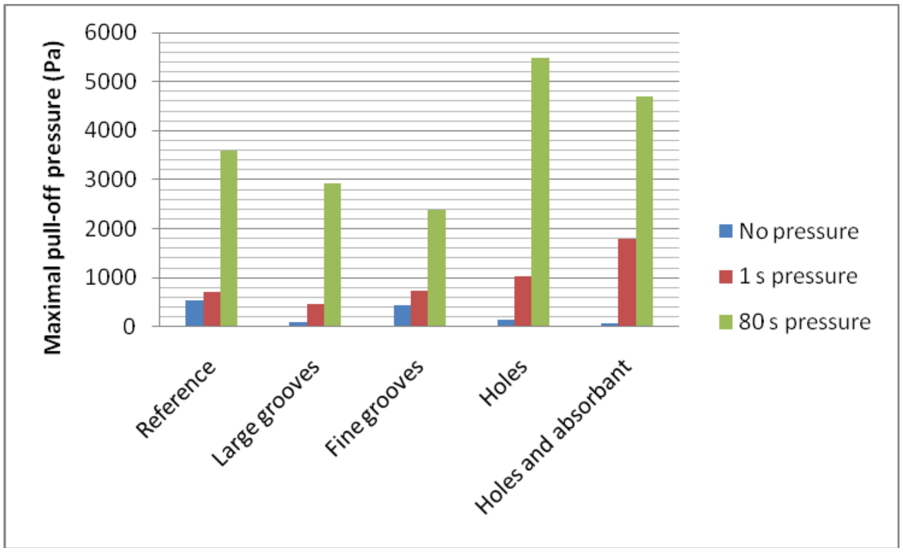

Figure 8. *Maximum pull-off force of the five samples during no delay time and no extra pressure (blue), 3 s delay time and less than 1s additional pressure (red) and 100 s delay time and 80s additional pressure (green).*

The sample to which the hydrophobic layer is applied, is left out. The hydrophobic layer stuck to the stage, thereby disrupting the condensation of a water film. Therefore, we could not measure this sample multiple times.

The grooves decrease the maximum pull-off force compared to the reference in all three cases. This is in line with our theory as discussed in Chapter 5.4; channels do not contribute to water transport outside of the label, and the dimensions are too small to hold all the water. The channels thus only effectively reduce the contact area.

The two samples with holes all the way through show a decrease in pull-off force when no extra pressure is applied. Apart from the difference in adhesive material, this can be due to reduction in contact area, since punching the holes manually (as we did) can increase the surface roughness. Also, the absorbant was very stiff, so the sample with the extra layer hardly touched the stage. The increase in stiffness can also explain the decrease in maximum pull-off force compared to the sample with holes and without the absorbant, since it may reduce the actual contact area. It is recommended to repeat the test with a non-absorbant layer with the same stiffness as the absorbant and with the same adhesive material.

After applying extra pressure, the samples with pores show increase in pull-off force, even after pressing shortly. This increase is considered to be significant. We can therefore say that we have the proof of principle that holes in adhesives show better adhesive properties to wet surfaces than adhesives without holes, or adhesives with channels.

Concerns of the absorption layer:
The absorption layer acts as a reservoir for water. Initially, moisture from the channels in contact with the absorption layer penetrates rapidly from the adhesive layer; however, the speed of transport of the moisture flow through the absorption layer is a variable which needs to couple to the water transfer rate from the channels to the absorption layer. If the former is not at least at an equal speed, higher moisture content will form near the absorption-adhesive interface. Eventually, when the moisture concentration in the channels drops, the driving force for moisture transport from the channels to the absorption layer reverses and moisture may transport back to the channels unless the channels can ensure unidirectional movement. At long times the moisture concentration profile in the adhesive layer should approach a pseudo-steady state profile.

7. Conclusions and outlook

The reasons for the lowered adhesion on surfaces with water condensation were contributed to weakened Van der Waals forces across water compared to air and the thin moisture layer preventing good contact between the adhesive and the subtract. Approaches to remove, use and penetrate the moisture layer were proposed. This work focused on proposals for water removal and the case was analyzed theoretically and tested experimentally. Characteristics of the moisture layer and factors influencing water condensation on the substrate were studied. The thickness of moisture formation for a typical duration of 150s was investigated and theoretical calculation indicated thickness in the range of several millimeters, which is in disagreement with the experimental result of 3 µm. The reasons for this disagreement should be further investigated. In addition, properties of the substrate were investigated for possible ways to influence adhesion. Surface roughness, surface homogeneity, water permeability, substrate porosity, optimum porous geometry such as horizontal or vertical channels and pores, and the capillary action and transport of water through vertical pores in an adhesive were studied. Theoretical calculations for a 20µm thick adhesive layer of 645 mm^2 surface area with 800 holes of 10µm diameter, showed that the maximum volume of water retainable in the capillaries is $1.5\,10^{-12}\,\text{m}^3$. This value is 500 times less than the volume of water squeeze when the layer is reduced to 1µm. Experimental data showed that adhesives with pores (50 µm diameter, 1 mm spacing) have a larger pull-off force on wet surfaces after applying pressure than adhesives without pores. Future work on the pores and the proposed alternative strategies, such as addition of polysaccharides, electrolytes, nanofibres, functionalized superhydrophobic and superhydrophilic patterns of the adhesive layer to improve adhesion performance on moist icy surfaces may be beneficial.

8. References

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