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Enhancement of Pressure-Sensitive Adhesive by CO_2 Laser Treatment

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Pressure-sensitive adhesives (PSAs) are polymeric films that can be adhered to and detached from surfaces without leaving residue. Researchers are looking to enhance the bond strength between PSAs and different substrates. It can be achieved by tuning PSA's peeling, shear, and tack properties for every specific case. 'Very High Bond' (VHB) is a widely used PSA because of its high compliance suitable for stretchable and soft-matter devices. In this study, a simple and fast surface treatment approach to modify the adhesion of VHB by CO_2 laser engraving is reported. We characterized this surface treatment method for VHB with different substrates. Multiple laser settings were tested for each material combination to determine the conditions at which the surface adhesion would be the highest. Tests on mechanical properties, ablation directions, chemical composition, tackiness, surface viscosity, and peeling forces were conducted to understand the adhesion and viscoelasticity changes. A higher concentration of non-crosslinked materials was determined in the VHB structure after treatment than before. Thus, we reason that laser treatment changes the surface adhesion of the PSA by cleavage of the polymer network. This work provides a simple route for tuning peeling, shear, and tack forces of a popular VHB using common equipment.

1. Introduction

Pressure-sensitive adhesives (PSAs) are polymeric films that form noncovalent bonds to surfaces when pressed against a substrate. They are widely used for domestic purposes, industrial packaging, the medical industry, aerospace, and research.[1–5] This group of adhesives is well known for its convenience and affordable price. PSAs can be stuck to different surfaces without additional processing and detached without leaving residue.[3,6] One particularly popular PSA is "Very High Bond" (VHB, by 3M) because its elastic properties make it suitable for various soft and stretchable devices. For example, it has been used for wearable and microfluidic devices, including stretchable sensors and actuators in soft and medical robotics.[7–14]

PSAs adhere to surfaces because of van der Waals (VdW) forces. Viscoelastic dissipation near the interface further enhances adhesion.[1,6,15] Chemical composition is essential because it defines VdW forces and surface energy and because it affects viscoelasticity.[1,6,15] The adhesion force of PSAs is determined by peel strength, shear strength, and tackiness. The latter relates to the ability of the PSA to wet the contact substrate.[2,3] Researchers often seek to enhance the adhesion between a PSA and a substrate[5] to increase the durability of a device.[7] In addition, researchers are looking for precise adhesion control[4] and an approach to achieve the required peeling, shear, and tack properties of PSAs.[3] The chemical composition of acrylic PSAs and their surface can be modified with oxygen or nitrogen plasma and oligomers or aluminum nitride particles.[16–20] These approaches provide a way to enhance the adhesion with additional materials and processing steps but require specialized and well-equipped technical facilities. Here, a simple way to modify adhesion without additives is reported, which is compatible with rapid prototyping.

The proposed approach is based on a serendipitous discovery: treating VHB tape with a common CO_2 laser "cutter" can improve the adhesion.[7] Here, the proposed treatment method shows an improvement in adhesion by modifying the viscoelasticity of the surface layer without modifying the bulk material. Whereas most prior studies primarily test PSA adhesion on metals, the proposed surface treatment method is characterized on different substrates such as organic materials, inorganic materials, metal, and

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other PSA types, including VHB. For each of the material combinations, different laser settings are tested to empirically determine the conditions at which the surface adhesion would be the highest. To understand the change of adhesive properties, different mechanical properties, such as ablation directions, chemical composition, tackiness, surface viscosity, and peeling forces, are tested. This work provides a simple method to improve the adhesion of a popular VHB using a widely available laboratory machine without further chemical additives, thus enabling the realization of more effective connective layers in experimental soft robotics devices.

2. Results and Discussion

The surface treatment consists of engraving the surface of the VHB using a CO_2 laser with different combinations of engraving speed and power, which result in different applied doses (**Figure 1**a). There are two main consequences of the surface treatment: the formation of wrinkles and the development of a shiny appearance at higher applied doses (Figure 1b). We show that these surface changes alter the surface viscoelasticity and thereby improve adhesion.

2.1. Sample Preparation

Different substrates may benefit from different treatment parameters of the VHB surface. Hence, the adhesion of VHB to each of these different substrates is tested with different applied doses to determine the best treatment parameters for each substrate. Adhesion performance is assessed by relative peel force, shear force, and tack change. To determine an effect of a treatment method with a variety of substrates, the treated VHB is bonded and tested with the same VHB material (VHB 4905), VHB from a different family (VHB F9473P), organic material (polyethylenterephthalate [PET]), inorganic material (glass), and metal (steel) (**Figure 2**a). A VHB 4905 is chosen because it is the most currently used elastomer in the fabrication of soft devices, such as dielectric elastomer actuators and stretchable sensors.[21,22] Soft substrates, such as the two types of VHBs and PET, are chosen because of their use in soft-matter devices.[7,8] In some studies, the VHB from different families is used to form microfluidic channels. Thus, experiments are performed with VHB F9473P as a substrate layer to characterize the adhesion between materials with akin chemical structures. In conventional uses, VHB can also be stuck on rigid substrates. Thus, the peel strength on glass and steel is characterized. Different combinations of speed and power obtain the dose with a fixed number of pulses per inch. The dose is increased starting from a minimum applied dose of 117 mJ pulse^{-1} with a 50 mJ pulse^{-1} step size three times. All measurements are made with this condition. In addition, two higher dose parameters of 358 and 859 mJ pulse^{-1} are used to clarify the adhesion behavior under laser settings at which the material experiences shallow (385 mJ pulse^{-1}) and deep (859 mJ pulse^{-1}) wrinkle formations (Figure 1b).

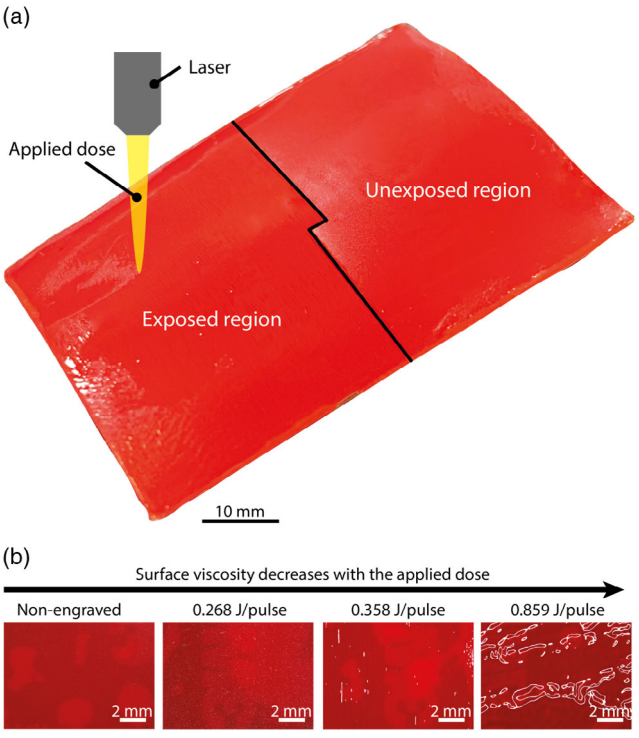

Figure 1. a) A schematic illustration of a surface treatment procedure using the engraving mode of a CO_2 laser cutter. b) Photographs of the treated VHB surface under different applied doses. The higher dose leads to the formation of wrinkles. The light regions in the nonengraved samples are due to the backing layer on the VHB.

2.2. Peeling Test

The laser-treated VHB is placed on a substrate following the standard peeling test protocol (see Experimental Section). The tests are conducted using 90° peeling test for rigid substrates (Figure 2a–i) and 180° peeling test for soft substrates (Figure 2a-ii). The adhesion under eight different treatment or engraving parameters from a regular nontreated sample (0 mJ pulse^{-1}) to a maximum dose of 859 mJ pulse^{-1} using six samples per dose is tested.

The treatment method affects the adhesion for all soft (Figure 2b–d) and rigid (Figure 2e,f) substrates. PET and VHB F9473P show an adhesion enhancement for some of the applied doses (Figure 2d,c). In the case of PET, the peeling force increases up to 85% under 215 mJ pulse^{-1} of the applied dose. The 43% increase in the maximum force for VHB F9473P is obtained at the same ablation parameters. The higher applied dose from 268 to 859 mJ pulse^{-1} in the case of both substrates decreases the relative peeling force. The VHB to VHB adhesion continuously decreases with increase in dose, resulting in a 49% decrease in the relative peeling force under 859 mJ pulse^{-1} (Figure 2b). In the case of glass and steel substrates, the treatment method does not increase the peeling force (Figure 2e,f).

2.3. Tack Test

The tackiness of VHB, i.e., its ability to adhere to a substrate, is characterized. The initial tackiness of the treated adhesive is measured using a loop tack test (see Experimental Section). In

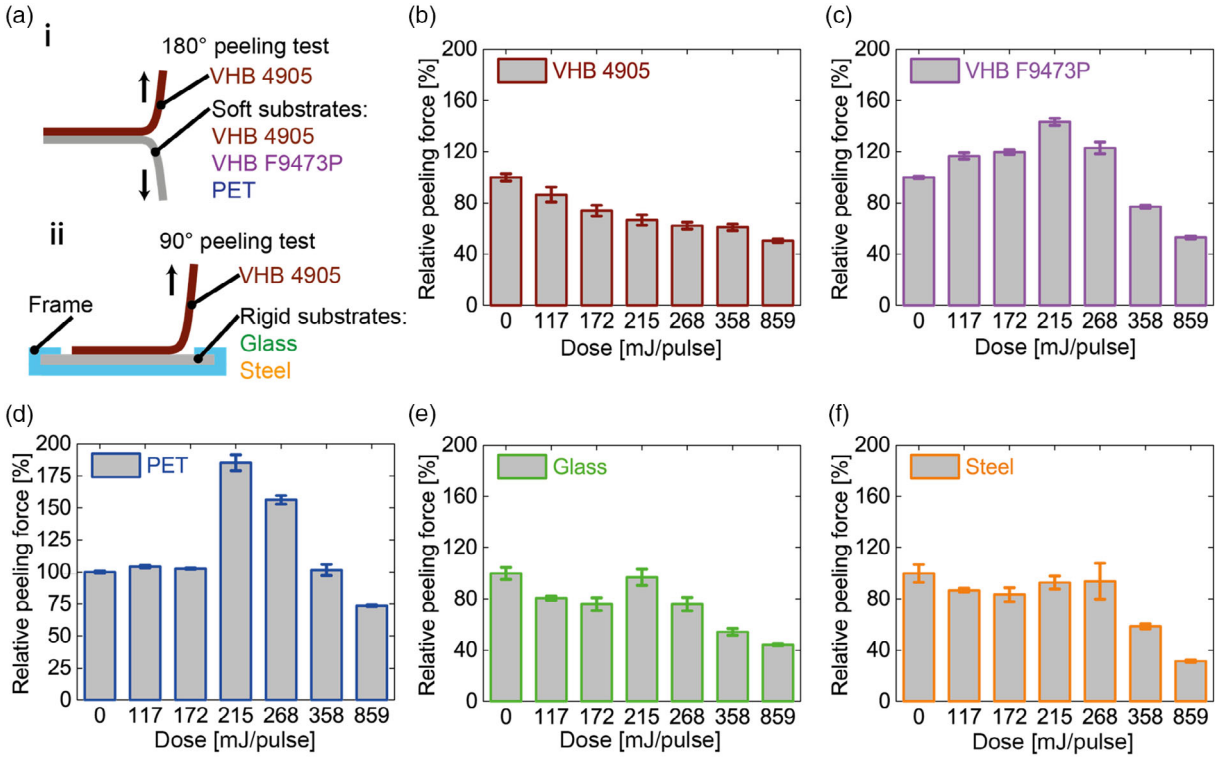

Figure 2. Peeling test results. a) The 180° peeling test is used for VHB 4905, VHB F9473P, and PET. The 90° peeling test is used for glass and steel substrates fixed in the rigid frame. b–f) The relative peeling force change for different substrates under applied dose from 0 to 859 mJ pulse^{-1} with the standard deviation resulted from six samples per dose.

the loop tack test, a loop made of treated VHB with an inextensible polymer layer on inner face is lowered at a constant speed to a stainless steel surface (see Figure S1, Supporting Information). Once the loop conforms to the substrate, the loop is raised from the substrate surface at the same constant speed as the previous step. The force required to pull the loop off the substrate is measured for six samples per dose. The tests are conducted for three rigid substrates: PET, glass, and steel.

The treated VHB shows higher tack force with all substrates for an optimal applied dose, which varies across substrates (**Figure 3**). For PET, the relative tack force increases from 113% to 125% between 172 and 358 mJ pulse^{-1}, but reduces to 72% at the maximum applied dose of 859 mJ pulse^{-1} (Figure 3a). For the glass substrate, the tack force drops from 100% to 80% between 0 and 172 mJ pulse^{-1} (Figure 3b). After that, it improves from 80% to 140% between 172 and 215 mJ pulse^{-1}. Then, it continuously decreases from 140% to 82% between 215 and 859 mJ pulse^{-1}. Tests with a steel substrate show adhesion enhancement from 145% to 125% on the dose range from 215 to 859 mJ pulse^{-1} with the highest relative tack force of 153% at 358 mJ pulse^{-1} (Figure 3c). Usually in PSA, tack and peel forces correlate similarly under certain

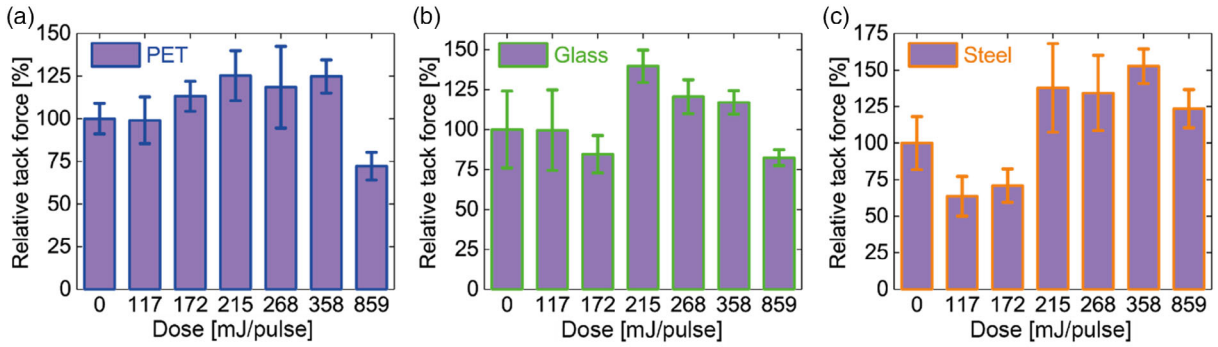

Figure 3. Relative tack force change for different substrates. Six samples are tested per each dose. a) There is a tack force increase of 25% at 358 mJ pulse^{-1} for PET. b) For a glass substrate, the maximum tack force enhancement of 40% is observed at the dose of 215 mJ pulse^{-1}. c) Adhesion with the steel substrate is enhanced by 53% at 358 mJ pulse^{-1}.

surface conditions. A correlation analysis of tack and peel force results is performed to determine how surface treatment method changes the relationship between tack and peel force at a certain dose (see Figure S3, Supporting Information). For this purpose, the relative tack and peel force data of laser-treated VHB are analyzed for three different substrate materials (PET, steel, and glass) under six doses (117, 172, 215, 268, 358, and 859 mJ pulse^{-1}). There is a high positive correlation between the relative tack and peel force change for glass and PET. Thus, the surface treatment influences the tack and peel forces on glass and PET substrates the same way at a certain dose. The negative correlation is observed only between relative tack force change of steel and relative peel force change of steel and glass. These results suggest that the treatment of VHB under a specific dose increases tack force, but by the price of the peeling force drop.

2.4. Shear Test and Viscosity Estimation

Static shear test is performed using a setup consisting of a stainless steel plate clamped vertically and a VHB sample with the weight bonded onto the stainless steel plate. The time to failure of the VHB sample is measured to estimate the shear capabilities and the surface viscosity of a VHB

$$t = \frac{L^2 \omega \eta}{2mgh} \tag{1}$$

where t is the time to failure, L is the length, ω is a width of the bonded sample, η is the viscosity, m is the mass attached to the sample, g is the gravity, and h is the thickness of the sample.

The relative time to failure remains almost the same in the range from 0 to 172 mJ pulse^{-1} (**Figure 4**a). At a dose of 215 mJ pulse^{-1}, the time to failure decreases by 75%, and at the dose of 358 mJ pulse^{-1}, the failure is almost instant. From these measurements, the viscosity change using Equation (1) is estimated. The viscosity changes from 27 kPa s for a regular VHB down to 82 Pa s for a VHB treated under 859 mJ pulse^{-1} (Figure 4b). Viscosity drastically drops down to 1.7 kPa s at 268 mJ pulse^{-1}, where the formation of liquid material on the surface of VHB (Figure 1b) can also be observed by a naked eye.

2.5. Surface Energy

Surface energy can contribute to the adhesion properties of PSAs. Thus, a contact angle experiment is performed using three reference liquids to investigate the surface energy of VHB samples treated under different doses (see Experimental Section).

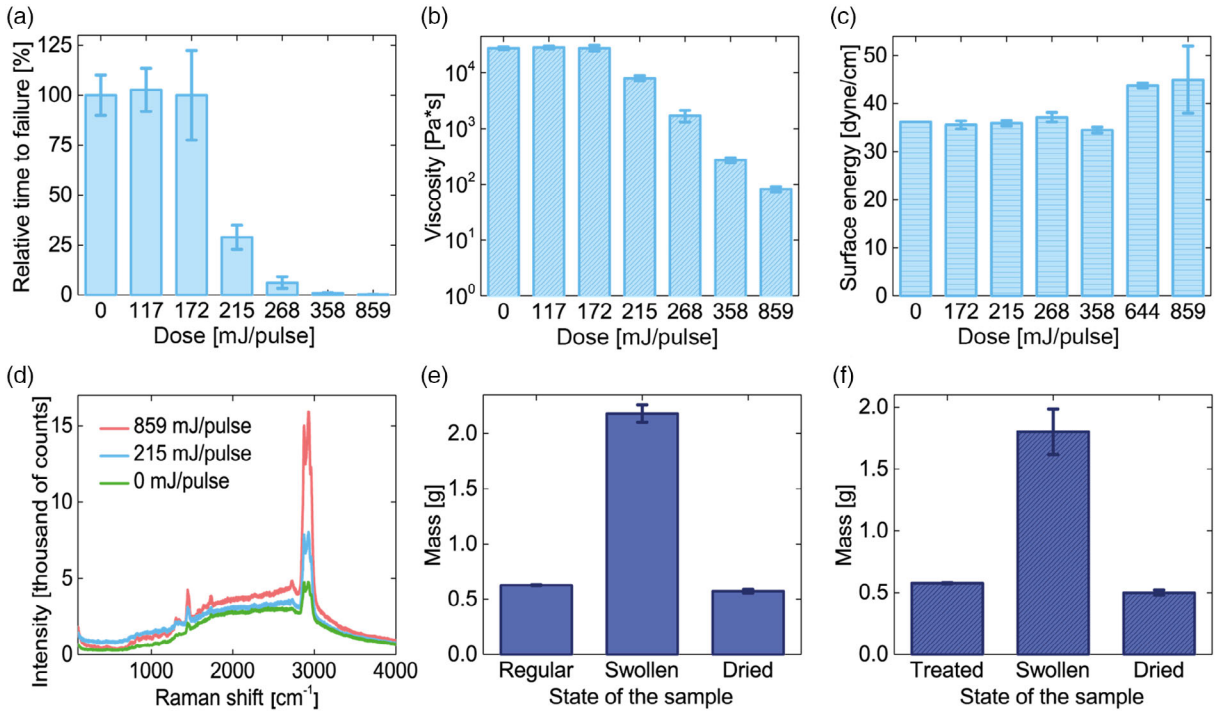

Figure 4. a) The relative time to failure remains the same in the range from 0 to 172 mJ pulse^{-1} and decreases by 75% at the dose of 215 mJ pulse^{-1}. At the dose of 358 mJ pulse^{-1}, the failure is almost instant. The data for b) the viscosity change from 27 kPa s for a regular VHB down to 82 Pa s for a VHB treated under 859 mJ pulse^{-1}. Viscosity experiences a drastic drop down to 1.7 kPa s at 268 mJ pulse^{-1}. c) The surface energy change on the interval from 0 to 358 mJ pulse^{-1} ranges from 34 to 47 dyne cm^{-1}. The formation of wrinkles beyond 400 mJ/pulse makes the measurement inaccurate with this technique. d) Raman spectroscopy shows a significant increase in the peaks from 2800 to 3000 cm^{-1} between regular and treated samples. This difference is explained by the increased concentration of C—H bonds in the sample due to laser treatment. Also, smaller peaks at 2700 and 1700 cm^{-1} suggest new functional groups. e,f) The initial weights of regular and treated samples, the weight right after the solvent bath, and in the dry state. Five samples were tested for each of the tests. After drying, the mass loss of 9 ± 3% for regular samples and 13 ± 3% for treated samples were observed.

This method has been used to estimate the surface energy of other acrylics (e.g., polymethylmethacrylate, PMMA).[2] The surface energy of the VHB ranges from 34 to 47 dyne cm^{-1} for the laser exposures used in this study (Figure 4c). The measurement is less accurate beyond 400 mJ $pulse^{-1}$ due to the formation of wrinkles. In addition, contact angle tests can be imprecise for PSAs due to the miscibility of low polarity testing liquids with the adhesive.[15] Nevertheless, these measurements suggest the surface energy does not appear to vary systematically with laser dose and variations at the very highest laser exposures should be ignored due to wrinkles.

2.6. Spectroscopy

As the surface energy experiments do not show a correlation between the adhesion enhancement and the surface energy, we explored the possibility of the chemical composition of the surface changing by using Fourier transform infrared (FTIR) and Raman spectroscopy. For PSAs, these two methods can detect heteronuclear functional groups, polar bonds, and homonuclear molecular bonds.[23] The composition of VHB is not provided by the manufacturer, but it is known to be an acrylic polymer. Using FTIR, no changes in chemical composition are observed as a result of laser exposure, with a sample's absorbance of infrared (IR) light at various wavelengths equal to 0.99 (see Figure S2, Supporting Information). However, FTIR is not particularly useful for simple alkyl stretches (C—H) likely found in the polymer as they are weak IR absorbers. Instead, they tend to be much more strongly active in the Raman spectra. Indeed, Raman spectroscopy (Figure 4d) showed differences between samples. It is possible to make a quantitative estimate from Raman spectroscopy as the peak intensity should be proportional to species concentration. Thus, the significant increase in the peaks 2800–3000 cm^{-1} suggests that the concentration of C—H bonds in the sample increased substantially due to laser treatment. Also, smaller peaks at 2700 and 1700 cm^{-1} suggest new functional groups (possibly oxidation).

2.7. Weight of Soluble Species

Some polymer networks, for example, silicones, tend to have unbound oligomeric species that migrate to the surface.[24] Such layers can affect the bonding of silicones to surfaces.[24] Thus, the amount of oligomers or other low molecular weight species in the VHB before and after laser exposure is measured; although the manufacturer does not provide the composition of the commercial starting material, it is reasoned that low molecular weight species could be present in the network including plasticizers or tackifiers. For this purpose, five pieces of regular (untreated) and laser-treated VHB are submerged in solvent (dimethylformamide [DMF]) for 24 h. The initial weights of the samples, the weight right after soaking in the solvent bath, and in the dry state are measured (Figure 4e–f). The weight of the regular sample changes from the initial state to the swollen state from 0.63 ± 0.004 to 2.18 ± 0.08 g. The increase in mass suggests DMF is a compatible solvent to swell the VHB network. After drying, the weight decreases to 0.57 ± 0.02 g, which corresponds to a mass loss of $9 \pm 3\%$. This confirms the presence of unbound, soluble species in the VHB network. The treated samples lost $13 \pm 3\%$ of their weight. This data suggests the laser treatment increases the amount of soluble, noncross-linked materials, presumably through cleavage of the cross-linked network.

2.8. Engraving Directions

The laser moves followed a determined pathway across the surface during treatment. To ensure the orientation of the laser pattern does not affect adhesion, different laser directions (vertical and horizontal) are tested to determine the influence of engraving orientation on the relative peeling force (**Figure 5**a). The peeling force difference varies by less than 5% (Figure 5b). Thus, the treatment orientation cannot be used to significantly tune the peeling force of the sample.

2.9. Waiting Time and Temperature of the Bonding

In comparison with treatment directions, the waiting time of sample bonding and the temperature at which they are bonded change the peeling force significantly. The influence of these adhesion conditions is tested in the aging study of nontreated PSAs and in contact with human tissue.[25,26] In the study, a sample of a treated VHB and a sheet of PET sheet are bonded and stored for 20 min or 5 days before testing. The results show an enhancement of 80% in peeling force after 5 days of waiting time (Figure 5c).

PSAs show sensitivity to temperature during bonding because the temperature influences the wettability of the adhesive. Wettability describes the ability of the adhesive to achieve complete contact and coverage of two surfaces bonded together. Lower temperatures increase the stiffness of the PSAs and, therefore, reduce the wettability. PSAs experience a decrease in elastic and viscous moduli with increased temperature.[27] To evaluate this parameter for a treated VHB, the experiments under different annealing temperatures of −18, 20, and 40 °C were performed using the regular peeling test protocol. The samples are stored under each one of the aforementioned temperatures, but the peeling test was performed at 20 °C. Relative to samples stored at 20 °C, the samples bonded at 40 °C show a 25% increase of the adhesion and 60% decrease of the adhesion after being bonded at −18 °C (Figure 5d).

2.10. Elongation at Break and Tensile Stress

The basic mechanical properties of treated VHB samples, such as elongation at break and tensile stress, are assessed to test if the treatment modifies the mechanical performance of the material. Elongation at break and tensile stress remain the same for both regular and treated samples (Figure 5e,f). This suggests that the laser only modifies a thin layer of the surface.

3. Conclusion

In this article, we report a treatment method of a PSA tape using a standard CO_2 laser "cutter," which improves the adhesion of a

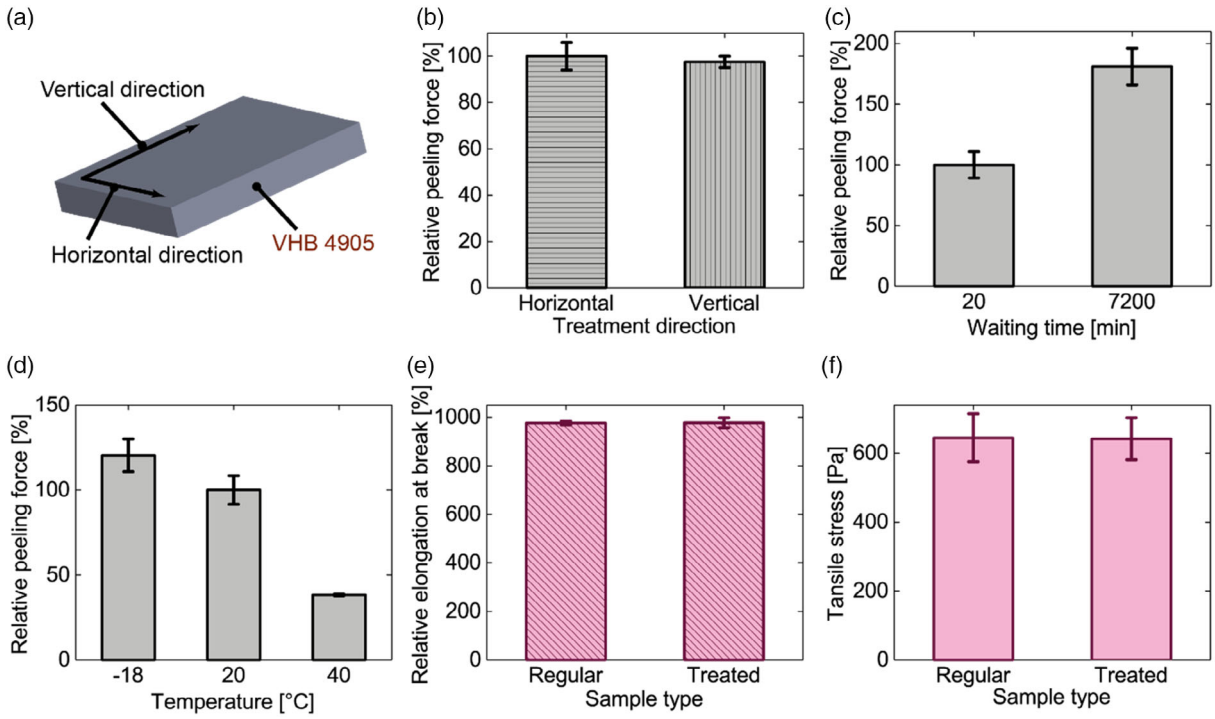

Figure 5. a) Schematic illustration of treatment direction of a VHB 4905 sample. b) Six samples of bonded treated VHB and PET are used in each of the following experiments. The VHB samples are treated under 215 mJ pulse^{-1} to achieve the maximal peeling force. The relative peeling force difference between horizontal and vertical directions is about 5%. c) The bonding times are 20 min and 5 days before testing. The results show an enhancement of 80% in peeling force after 5 days of waiting time. d) Waiting temperatures of −18, 20, and 40 °C under the regular peeling test protocol are used. The samples are stored under one of the aforementioned temperatures, but the peeling test is performed at a room temperature of 20 °C. The samples show a 25% increase of the adhesion being bonded at 40 °C and reduced by 60% adhesion being bonded at −18 °C. e,f) Elongation at break and tensile stress remain the same for both regular and treated samples.

tape with a variety of common substrates. As a representative material, VHB 4905 tape is employed because of its common use in soft-matter devices. The treatment method shows high adhesion enhancement for PET and VHB F9473P with an adhesion increase of 85% and 43% under 215 mJ pulse^{-1} of applied dose. The relative tack force is enhanced for PET, glass, and steel substrates by 25%, 40%, and 53%. Shear measurements suggest the surface viscosity falls from approximately 27 000 Pa s down to 82 Pa s with an increase in the dose. Raman spectroscopy of the VHB surfaces suggests that the concentration of C—H bonds in the sample increased substantially due to laser treatment. Also, the number of soluble species increased from $9 \pm 3\%$ for a regular VHB piece to $13 \pm 3\%$ for a laser treated sample. Finally, the mechanical properties of a treated sample are similar to a treated sample. Thus, the surface treatment method allows tuning of the surface adhesion properties of an adhesive, leaving the mechanical performance of a bulk material the same. This method can potentially be applied to other PSAs with similar compositions as VHB.

Taken in sum, the measurements reported here suggest that adhesion changes resulting from laser treatment are due to changes in the surface viscoelasticity due to cleavage of the network. Viscoelasticity is known to be the main parameter influencing the adhesion of a PSA.[1] This explanation is consistent with the change in surface viscosity of the polymer with laser treatment (Figure 4b), and the increase in the concentration of C—H bonds (Figure 4d) and mass of noncross-linked materials (Figure 4e,f).

In soft-matter devices, this treatment method allows adhesion tuning during fabrication process. We believe that, for layer by layer fabrication processes,[7,28] this tuning can lead to higher layer adhesion, thus longer life time of the devices. Moreover, adhesion tuning can be effective for the soft devices mounted on external substrates such as skin mountable sensors. Similarly, it could enhance the grasping force of soft grippers by increasing the tackiness of the external surface of the device. The method could selectively facilitate either an increase or a reduction in the adhesion. Therefore, it would enable disassembling of structural materials of soft devices that are mostly made irreversibly,[7,8] allowing to recycle them.

4. Experimental Section

Surface Treatment of VHB 4905 Samples: CO_2 laser cutter (Trotec, Speedy 400) with a wavelength of 10.6 μm and delivered power from 0 to 60 W is used to treat the surface of PSA (3M, VHB 4905) samples. The laser parameters, such as speed, power, and PPI, are controlled by the software (Trotec, Job Control). The dose for all experiments is defined by power and speed variations. Six dose values of 117, 172, 215 268, 358,

and 859 mJ pulse^{-1} correspond to a power of 9, 20, 22.5, 15, 15, and 20 W applied with a speed of 1952, 1775, 1598, 1429, 1065, and 355 mm s^{-1} accordingly. First, a wide piece of VHB (later support VHB layer) is bonded to the surface of a large PMMA layer with a thickness of 10 mm. This frame is used to hold the samples during the treatment in place inside the laser cutter. Then, a fresh piece of VHB covered with the regular red liner on one side is bonded from the liner side onto the PMMA frame with a VHB. At that moment, the frame consists of four layers from the bottom to the top: PMMA rigid frame, support VHB layer, red liner layer, and a VHB layer treated. Then, the samples are cut in stripes and engraved using the aforementioned treating parameters.

Peeling Test: The dimensions are set according to the standard ASTM D1876-08 standard test protocol for peel resistance of adhesives with a sample size of 207 mm in length and 25 mm in width. Then, the treated VHB layers are carefully placed onto one of the substrates used in the experiments avoiding bubble formation without applying pressure on the tape. After that, a weight of 150 g is placed onto the sample. The samples are kept in a fume hood under room temperature and constant humidity under the load before tests for a week. For the tests of adhesion under negative and high temperatures, the samples are placed in a freezer and hot plate at −18 and 40 °C, respectively, under the load for a week before testing them. The peeling tests are performed using a tensile machine (Instron, 5965) at a 254 mm min^{-1} speed controlled by software (Instron, Bluehill Universal). The data on Figure 2 indicate the relative values of peeling force starting from 100% at 0 dose for each of the substrate materials.

Tack Test: The loop tack test is chosen to study the tackiness of the VHB 4905 because it permits measuring the tack force directly using the ASTM D6195-03 standard method. This standard specifies the test conditions, including the specimen dimensions (125 mm in length and 25.4 mm in width), the material and size of the substrate (stainless steel plate of 25.4 mm × 25.4 mm), and the testing speed (300 mm min^{-1}).

Shear Test: The test is set based on the ASTM D3654 standard for shear adhesion of PSA tapes. This test requires support to hang the samples during the experiment and a standard roll with the necessary dimensions and weight to adhere the tape on the substrate. The roll is designed via Catia 2020 (Dassault Systèmes) and printed with ABS filament using Stratasys (Dimension Elite). The standard method requires a roller of 85 mm in diameter, and 45 mm in width, covered with rubber 6 mm in thickness, having a shore hardness of 80. The external side of the roll is covered with silicone Smooth-On, Econ 80 A using a molding process. The total mass of the designed roller is 2040 g. The sample of 12.5 mm in width adheres on the stainless steel plate with a length of 12.5 mm using the roll at a rate of 10 mm s^{-1}. Then, it is hung on the shear support. Between each test, the stainless steel surface is cleaned using acetone.

Tensile Test: The ASTM D3759 standard method for pressure-sensitive tapes is used to quantify the elongation at break and the maximum tensile stress of regular and engraved VHB samples. The tested area dimensions depend on the maximum elongation of the tested material. VHB is known to have an elongation of over 150%; thus, the standard method recommends the sample dimensions of 150 mm in length and 12 mm in width.

Surface Energy: The contact angle test based on the experimental protocol ASTM D7490-13 is used in this study. It consists of measuring the angle between the interface liquid/air and the interface substrate/air. Three reference liquids with different polar and dispersive surface tension components are used to determine the surface energy via Owens–Wendt–Rabel & Kaelble model. The method requires some hypodermic syringe of 1 mL with an N°27 stainless steel needle to deposit calibrated droplets of the referent liquids on the sample surface. The distilled water, the di-iodomethade, and the hexadecane are the reference liquids used during the experiments. The measurements are performed using the "Drop Shape Analysis" method from the Biomedical Imaging Group at EPFL using the ImageJ software. According to the standard D7490-13, the contact angles must be substantially identical to validate the measure. The mean of the six measures is calculated and implemented in the model.

Chemical Analysis with FTIR: The PerkinElmer Spectrum 3 FTIR spectrometer coupled with the PerkinElmer SpectrumIR software is used. Two types of VHB by five samples (45 × 25 × 0.5 mm) each were used: standard and engraved at a dose of 0.215 J pulse^{-1}. Each sample is placed at the center of the metallic circle on the machine. FTIR spectrum is recorded between 4000 and 650 cm^{-1}. Collected data are processed using PerkinElmer SpectrumIR software and MATLAB.

Chemical Analysis with Raman Spectroscopy: The LabRAM HR800 Raman spectrometer coupled with the HORIBA LabSpec 6 software is used. Three types of VHB (25 × 25 × 0.5 mm) each are used: standard, engraved at a dose of 0.215, and 0.859 J pulse^{-1}. All the samples are placed on a glass plate to sustain a flat shape. The flat shape of the sample is required in order to use the objective with a magnification of 100× and a working distance of 1 mm. It has the largest numerical aperture (high sensitivity) and the smallest depth of field. Raman spectrum is recorded between 100 and 4000 cm^{-1}. The intensity is collected from 0 to 16.000 counts. Collected data are processed using the HORIBA LabSpec 6 software and MATLAB.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

laser processing, pressure-sensitive adhesive, surface modification, surface treatment

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