Microscopic delamination mechanics in the copper-rubber interface

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Abstract

Stretchable electronic devices improve the design freedom of electronic products. Metal-rubber interface delamination leads to early failure in the stretchable electronics. In this research, the influence of copper-roughness and peel-rate on the copper-rubber (TPU) interface delamination is investigated using T-Peel tests. Experimental results show that the work of separation increases for increased copper-roughness and peel-rate. Furthermore, longer rubber-fibrils are observed for higher copper-roughness through in-situ SEM imaging of the progressing delamination front.
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Chapter 1

Introduction

1.1 Background

Stretchable electronic devices improve the design freedom of electronic products. Some examples of the applications of stretchable electronics are smart clothing [1], sensitive skin for robots or prostheses [2], biomedical parameter monitoring [3], [4], [5], neural activity monitoring [6], [7], and intraocular retinal prostheses [8].

Typically, stretchable electronic devices are constructed out of small rigid semiconductor islands which are interconnected with thin metal conductor lines. These interconnects are located on top of, or encapsulated in, a highly compliant substrate (typically a rubber material). There is a large difference between the stretchability of rubber matrix (∼100%) and metal interconnects (< 1%). Therefore, high stretchability, i.e. the ability to withstand large deformations during usage without any loss of functionality, is difficult to achieve. One way to achieve the required stretchability is to use some mechanistic patterns [9], [10], [11], [12] all of which reduce the local stretch of the metal. The horseshoe shape interconnect is an example of these mechanistic patterns (Fig. 1.1a).

It has been shown recently that stretching-induced interface failure determines the amount of stretchability that can be achieved for a given interconnect design [13], [14], [15]. In-situ Scanning Electron Microscope (SEM) images of stretching-induced interface failure show that the forming, elongation and rupture of rubber fibrils play a large role in the interface delamination [16] (Fig. 1.1b). Thus, improving the interface integrity of such mechanistic interconnects can also improve the stretchability. To improve the interface, first a good understanding of the delamination mechanics is required.

Figure 1.1: (a) Typical horseshoe-shaped interconnect design; (b) in-situ SEM image of stretching-induced interface failure
1.2 Goal

In [13], it is shown that fibrilation has a dominant role in interface integrity. In this report, the effect of surface morphology and peel-rate on the fibrilation mechanics and interface integrity is investigated. In-situ observations of the progressing delamination front of peel test experiments are used to achieve this goal.

1.3 Project outline

The experimental methodology used to investigate the copper-rubber interface failure is explained in chapter 2. In chapter 3, three different peel test samples with different copper roughness values are peeled and their interface toughness is measured. The copper and rubber sides are investigated at the micro scale using SEM after peeling. In-situ Environmental Scanning Electron Microscope (ESEM) imaging of the progressing delamination front is performed to get insight in the fibrilation process for samples with different copper roughnesses. The same procedure is performed in chapter 4, but for different peel-rates. Finally, the report ends in chapter 5 with conclusions and recommendations.
Chapter 2

Experimental methodology

2.1 Peel test

In order to understand the mechanisms leading to interface failure of stretchable electronics, in this project, copper-rubber interface delamination is investigated by means of T-peel test experiments. The peel test is an established method of testing interface delamination properties [17]. In a peel test experiment, the two layers of an interface are separated at a specific angle while measuring the peel force and displacement (Fig. 2.1a).

![Diagram of a peel test experiment](image)

**Figure 2.1:** (a) Schematic of a peel test experiment; (b) Typical force-displacement curve

To study the effect of copper-roughness and peel-rate on the interface delamination, several peel test samples are created by Thomas Löher et al. of Technical University of Berlin. Peel tests of these samples are performed on two Kammrath-Weiss micro-tensile stages using a 100N load cell. Stage one is used for the slow peel-rates (i.e. 0.1, 1 and 10 μm/s) and stage two is used for the faster peel-rates (i.e. 1, 10 and 100 μm/s). All samples have the following common characteristics.

A copper-rubber sample consists of a thin 35 μm copper (TW-YE grade) film and a 50 μm TPU (Walopur, or Thermoplastic Polyurithane by epurex) film. The copper foil, used for peel test samples, is TW-YE grade foil which is an improved single side treated electro-deposited copper foil. With the inorganic YE protection on the shiny surface, the foil shows superior resistance to oxidation in warm and humid environments. The untreated shiny side has low roughness and the treated matte side has higher roughness. The treated side of the thin copper film and rubber film are bonded to each other. In order to obtain a stationary peel front, two samples are bonded back to back with a thin PTFE layer partially in between for the initial crack in the copper-rubber interface. After laminating, the PTFE layer can easily be removed and every loose end can be
mounted into the tensile stage to start a peel test. The final laminated sheet is cut into slender strokes which are the peel test samples. The samples are laminated at two different process temperatures i.e. 180°C and 200°C, creating effectively two different samples. For the 200°C samples, the roughness is varied pre-lamination by also laminating the rubber to the untreated shiny side of the TW-YE sheet and by laminating the rubber to a copper sheet which is treated with an extra roughening step.

Typical force-displacement curves from a peel test consist of an initiation regime, followed by a steady state peeling regime. From the steady state force plateau the work of separation (WOS) is defined as the peel energy \( U_e \) divided by the delaminated area \( A \)

\[
WOS = \frac{U_e}{A} \quad \text{(2.1)}
\]

where \( U_e \) is calculated as \( 2Fu \), where \( u \) is the displacement of the clamps. The total amount of mechanical energy that is supplied to the peel test sample \( U_e \), is transformed into internal energy \( U_i \) (elastically stored energy), surface energy \( U_a \), dissipated energy \( U_d \) (friction and plastic deformation) and kinetic energy \( U_k \).

\[
\frac{dU_e}{dA} = \frac{dU_i}{dA} + \frac{dU_a}{dA} + \frac{dU_d}{dA} + \frac{dU_k}{dA} \quad \text{(2.2)}
\]

If copper plasticity and rubber viscosity are taken into account, \( U_d \) is split into two terms. One term is energy dissipation due to plastic deformation of copper and the other one is energy dissipation due to rubber viscosity. Note that the measured energy consists of several parts, where for this research the interface toughness is the most interesting. The other contributions are considered as negligible.

### 2.2 Segmentation

The delamination takes place by initiation, growth and fracture of fibrils at the interface, a process called fibrillation. Therefore, zooming in on the copper-rubber interface, three different fracture mechanisms can be distinguished (Fig. 2.2); (i) Fracture can occur in the copper, (ii) in the rubber-fibril or (iii) at the interface of rubber-fibril and copper.

![Fibrillation process and different fracture mechanisms during peeling of a copper-rubber peel test sample](image)

Figure 2.2: Fibrillation process and different fracture mechanisms during peeling of a copper-rubber peel test sample

To know which of the three previously explained fracture mechanisms occurs more dominantly, the areas of both surfaces after peeling are investigated using the Scanning Electron Microscopy.
The area fraction of rubber left behind on the copper side \( (A_r) \) and area fraction of copper left behind on the rubber side \( (A_c) \) after delamination are determined by segmenting the SEM images of the peeled surfaces.

Back Scatter Electrons (BSE) are more sensitive to changes in material composition, therefore, BSE images will give superior contrast between rubber (dark) and copper (bright). This is nicely highlighted in figure 2.3 which shows two SEM images taken using two different detectors (i.e. SE and BSE) from the same field of view. Figure 2.3a clearly shows the location of the rubber, while in figure 2.3b the surface topography is more visible due to the use of the secondary electron (SE) detector.

![BSE detector](image1.png) ![SE detector](image2.png)

**Figure 2.3**: Two images of the same area, highlighting the influence of the detector on the SEM image

Besides choosing the proper detector for capturing the segmentation images also great care must be taken when selecting the E-beam properties, as illustrated by Fig. 2.4. This figure shows how the electron beam acceleration voltage can influence the image. A higher e-beam voltage results in deeper penetration of the back scattered electrons and consequently more bright areas in the image. The applied voltage and spot of the electron beam are set to 5kV and 3 respectively to take SEM images of the copper side. These beam settings are found to give the highest image quality without any rubber transparency effects.
The final SEM setting under discussion is the chamber pressure. A high vacuum generally gives higher image quality and this setting is preferred for the copper sides of the samples. But the rubber is a non-conductive material which will cause charging in SEM. In order to reduce the charging effect, the low vacuum (or ESEM) mode is used when taking images of the rubber side. In this case, the beam voltage is increased to reduce noise. Therefore, the applied voltage and spot of the electron beam are set to 15kV and 3.5 respectively to take SEM images of the rubber side. Note that, the previously discussed rubber transparency is not an issue when looking at the rubber side.

When a reliable SEM image is available, then it can be segmented. Histograms of the amount of pixels per gray value of the SEM images are used to determine the area fractions of copper and rubber on the peeled surfaces. The histogram of the SEM image of figure 2.5a is shown in figure 2.5b. The two peak points of the histogram correspond to the copper and rubber material. The threshold value for the segmentation is chosen around the valley point. This threshold value has to be carefully selected in such a way that the highlighted spots of the analyzed image after segmentation (figure 2.6) correspond to the occupied rubber area in the original SEM image (figure 2.5a). The influence of threshold value on the calculated area fraction ($A_r$) is shown in figure 2.5.
2.3 In-situ measurement inside SEM

Fibrillation is an important phenomenon in copper-rubber interface delamination. To get more insight in the fibril formation process, fibril length and its shape, in-situ measurements are performed inside the SEM in the low vacuum mode. The tensile stage is small enough to fit in the vacuum chamber of the SEM (Fig. 2.7).
For the imaging of the progressing delamination front, secondary electrons are used to be able to get more information about the shape of fibrils. The applied voltage and spot of the electron beam must be low enough not to influence the fibrillation process. On the other hand, they must be high enough to acquire good image quality in the low vacuum mode. Therefore, the voltage and spot of the beam are set to 15kV and 4 respectively.

Electron-beam of SEM can influence the fibrillation process. For a high E-beam voltage, high magnification image and a low peel rate, more energy is received by each fibril and the mentioned influence is accentuated. The E-beam effect on the fibrillation process can be checked by demagnifying after being focused on one area for some time. The areas to the left and right of the previously focused area should resemble the previously focused area.

The e-beam effect on the fibrillation process depends also on the peel-rate and the scan time. Therefore, the effect is checked after each series of images and if necessary the beam was adjusted and the images were recaptured.
Chapter 3

Influence of the copper-roughness on the copper-rubber interface delamination

The influence of copper-roughness on the copper-rubber interface integrity is investigated in this chapter. First, for each roughness type, the copper surface roughness is determined by means of surface profilometry. Then the WOS is measured for each roughness type from T-peel test experiments. Thereafter, SEM images of the peeled areas of both the copper and the rubber sides are compared. Finally, in-situ measurements inside the ESEM are performed to investigate the rubber fibrilation process as a function of copper-roughness.

3.1 Measuring copper-roughness

The TW-YE copper foil has two sides. The shiny side has low roughness and the matte side has higher roughness. Using an additional chemical roughening step on the copper foil creates two copper surfaces with new roughnesses. Only the side which was originally the rough side is laminated to the rubber. The Surface profiles, obtained with a Sensofar P1µ4200 confocal optical profilometer, of the smooth, smooth with additional chemical roughening and rough copper sides are shown in figure 3.1.
Surface roughness, often shortened to roughness, can be quantified by the vertical deviations of a surface from its ideal form [18]. There are many different roughness parameters in use. The most common ones are summarized in table 3.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$</td>
<td>Arithmetic average of absolute values</td>
<td>$\frac{1}{n} \sum</td>
</tr>
<tr>
<td>$R_q$</td>
<td>Root mean squared</td>
<td>$\sqrt{\frac{1}{n} \sum y_i^2}$</td>
</tr>
<tr>
<td>$R_v$</td>
<td>Maximum valley depth</td>
<td>$\min y_i$</td>
</tr>
<tr>
<td>$R_p$</td>
<td>Maximum peak height</td>
<td>$\max y_i$</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Maximum Height of the Profile</td>
<td>$R_p - R_v$</td>
</tr>
<tr>
<td>$R_z$</td>
<td>Peak to valley in-plane distance</td>
<td>$\frac{1}{n} \sum</td>
</tr>
</tbody>
</table>

Using the the most common used parameters for roughness, we have:

Table 3.2: Roughness parameters values for the different copper surface morphologies

<table>
<thead>
<tr>
<th>copper surface morphology</th>
<th>$R_a$</th>
<th>$R_q$</th>
<th>$R_v$</th>
<th>$R_p$</th>
<th>$R_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth copper</td>
<td>0.40</td>
<td>0.52</td>
<td>4.85</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Smooth copper (add. chemical roughening)</td>
<td>0.45</td>
<td>0.57</td>
<td>8.91</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Rough copper</td>
<td>1.92</td>
<td>2.46</td>
<td>21.11</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
It can be seen that the trend for the different roughness parameters is almost the same. $R_a$ is used afterwards in this report as the roughness parameter.

### 3.2 Work of separation

To compare the WOS for each roughness type, peel tests are performed for each type. But, the peel force for the “smooth” roughness was lower than 1 N making it impossible to be measured accurately. This low force also resulted in very large peeling radii, which also made it impossible to perform the in-situ measurements. Hence, this sample type is dropped from the evaluation.

Hereafter, the peel test sample with the additional chemical roughening treatment is called "rough" and "extra-rough" refers to the peel test sample with original rough copper side. Peel test samples are prepared as explained in chapter 2. The applied peel rate is set to 10 $\mu$m/s for all measurements. Force-displacement curves of the peel tests for the two different kinds of samples are shown in Fig. 3.2.

![Force-displacement curves of peel tests for two different copper roughness values](image)

Figure 3.2: Force displacement curves of peel tests for two different copper roughness values

The “rough” sample shows a clear drop in force, and therefore, also in WOS, when compared to the "extra-rough" samples. One possible explanation comes from the surface effects already mentioned in [13]. Increasing roughness yields (i) increased surface area, therefore more chemical bonding, (ii) increased mode mixity, due to more irregular surface morphology, (iii) and even increased mechanical interlocking. But another explanation may come from the delamination initiation mechanism in the interface which determines the shape and size of the fibrils which are formed at the peel front.

### 3.3 Peeled surface investigation

The delamination micro-mechanics are governed by three type of fracture; (i) rupture of the fibrils, (ii) failure at the interface, (iii) fracture of the copper. The last one can be analyzed by looking at the rubber side of the interface after peeling. More copper present on the rubber surface means that more copper fracture took place. SEM images of the peeled areas on the rubber side of the rough and extra-rough samples are shown in Fig. 3.3.
The surface morphology of the two rubber surfaces, shown in the figure 3.3 are totally different. The size of the copper particles left behind on the rubber side of the rough sample, is almost 10 times smaller than the extra-rough sample (look at the magnification of the images). But the $A_c$ value is almost the same for the two samples ($A_c \approx 0.03$). Due to some unexpected problems of the BSE detector of the SEM, the images are not reliable enough to investigate more about them and it is recommended to take more images.

Of the three types of fracture, mentioned in the previous section, the balance of the first two can be qualitatively analyzed by investigating the copper surface after peeling. More specifically, the amount of rubber left on the copper surface after peeling. The larger the area of the rubber ($A_r$), the more failure mode (i) took place instead of mode (ii), i.e. more fibril rupture and less interface failure. SEM images of the peeled areas on the copper side of the rough and extra-rough samples are shown in Fig. 3.4.

Figure 3.3: Comparison of rubber side after peeling the sample for different copper roughness

Figure 3.4: Comparison of copper side after peeling for different copper roughness

Considering the magnification of the images, it can be observed again that the surface morphol-
ogy of the two surfaces, shown in the figure 3.4 are totally different. Area fraction of the rubber left behind on the copper side of the rough and extra-rough samples is 0.63 and 0.34 respectively. This observation is in contradiction with the work of J.P.M. Hoefnagels et al. [13], which they observed more rubber left behind on the copper side of the sample with higher copper-roughness.

### 3.4 Fibril length

In addition to peel surface analysis, also real-time imaging of the progressing delamination front is performed to be able to see the fibrillation process in detail. Note that large fibril relaxation is observed upon stopping the peel test experiments, which would make it impossible to quantify the fibril length after peeling. Peel front images of rough and extra-rough samples are shown in figure 3.5, where copper is on the top side and rubber is bottom side of the images. The applied peel rate is set to 1 µm/s for all measurements.

![Image of fibrillation process](image)

**Figure 3.5:** Fibrilation process for two different copper roughnesses at two magnification factors.

It can be clearly observed that copper-roughness affects the rubber-fibril length. Fibrils are longer for extra-rough samples, compared to rough samples. To measure the fibril length, a movie is taken during peeling and the fibril is tracked until complete rupture. Then the fibril length, just before rupture, is measured. This procedure is repeated for 20 different fibrils of each sample. Quantitative comparison of the fibril lengths is summarized in figure 3.6. The fibrils of the rough
samples are approximately $12 \pm 3\mu m$ and the fibrils of the extra-rough samples are approximately $23 \pm 3\mu m$. Furthermore, the distance between the fibrils is more for extra-rough samples.

Figure 3.6: Quantitative comparison of the fibril length for the rough and extra-rough sample

### 3.5 Conclusions

- Peel test experiments showed that the WOS for extra-rough interfaces is higher than the WOS for rough interfaces.
- In-situ measurements of the progressing delamination front showed that the rubber-fibril length in copper-rubber interface delamination depends on the copper roughness. Extra-rough interfaces have longer fibrils compared to rough samples.
Chapter 4

Influence of peel-rate on copper-rubber interface delamination

To investigate the influence of peel-rate on the copper-rubber interface failure, T-peel tests are performed at four different peel-rates (0.1 µm/s, 1µm/s, 10 µm/s and 100µm/s). For each peel rate, the work of separation is determined. Whereafter, the peel surfaces of the copper and rubber sides are investigated with the SEM. Afterwards, in-situ measurements inside the SEM are performed to get more insight in the fibrillation process as a function of the peel-rate.

4.1 Work of separation

First the effect of the peel rate on the WOS is analyzed. Peel test experiments are performed at four speeds which are spread over a large span in rate. Force-displacement curves of the peel tests are shown in Fig. 4.1a. There is some scatter in the absolute force per measurement set, i.e. one tensile stage, one load cell, one sample, one day. Therefore, each set is normalized with the 10µm/s measurement of the set (Fig. 4.1b). Figure 4.1b shows an increasing trend in the maximum peel force for increasing in peel rates. This trend is also observed by Geij\text{\textael} et al. for Polyethylene-Polybutene peel system [19]. Within the range of strain rates, there is an approximately linearly increasing trend between the fracture toughness and the logarithm of the peel rate. Interestingly, the rate dependency is insensitive to the scatter in the peel-force. Furthermore, the rate dependency seems to be the same for both 180°C and 200°C samples, which clearly had a different peel-force. This indicates that the interface adhesion is not important for this rate effect, while the rubber material response is.
Viscoelastic materials dissipate more energy for higher strain rate. If the rubber, used in our peel test samples, is considered as a viscoelastic material, more dissipated energy would be expected for a higher peel rate. Therefore, the observed increasing trend in work of separation can be due to the dissipated energy induced by rubber viscosity. Another possible reason can be because of rate dependency of fracture strength of rubber.

Viscoelasticity mainly happens in the fibrils, while they are being formed and elongated. If the fibrils are strong enough, they will debond the interface or even fracture some copper asperities. But if the interface is stronger, then the fibril will fracture, leaving rubber on the copper surface. Therefore, the origin of this rate dependency effect can be further analyzed by looking at the two new surfaces created after peeling.

### 4.2 Peeled surface investigation

First the rubber surface, created by the peel test experiment, is examined. Figure 4.2 shows SEM images of the peeled areas on the rubber side for different peel rates. Small copper particles are visible on the rubber surface, highlighted in yellow.

![Figure 4.2: Comparison of copper (yellow color) left behind on the rubber side after peeling at three different peel rates](image)

To quantify $A_c$ better, five images were taken from each area, created with one peel-rate during one peel-test. For each peel-rate, the area fraction of copper, left behind the rubber side,
is calculated using the segmentation method described in chapter 2, with a threshold of 200. All values of $A_c$ are shown in figure 4.3 where can be seen that for a higher peel rate, $A_c$ increases.

![Figure 4.3: Quantitative comparison of the area fraction of copper ($A_c$) for various peel-rates](image)

A larger area fraction of copper on the rubber side means that more copper asperities fractured. Assuming that the strength of the asperities is normal distributed and that the fibril geometry is independent of the peel-rate, it can be concluded that an increase in $A_c$ means that stronger asperities also fractured. Consequently, the stresses in the interface must have been higher. Therefore, when the peel-rate increases, the strength of the fibrils also increases. Geißler et al. have presented and discussed a time-dependent cohesive model [19]. They have shown that the maximum traction of the traction separation law of the time-dependent cohesive zone model depends on the separation rate increasingly. Therefore, the interface strength is stronger for increasing peel rates, which is confirmed by the above observations.

The second surface, created by the peel-test under investigation, is the copper side. Figure 4.4 shows SEM images of the peeled areas of the copper side for different peel rates. On the copper surface, rubber patches were found, which are highlighted in red in figure 4.4.
The area fraction of rubber, left behind the copper side, is calculated for 10 SEM images for each peel-rate for the same peel-test and are compared in Fig. 4.5. The scatter in $A_r$ is too large to observe a clear trend. To be more conclusive about the effect of the peel-rate on the $A_r$, more measurements for more samples are recommended to see whether there is a trend or not.

For all investigated surfaces, $A_r$ was a significant part of the surface. This indicates that the rubber fracture has a significant role in the delamination process and can be partly responsible for the peel-rate effect. To investigate this further, the delamination process is investigated further by means of in-situ experiments.

Figure 4.5: Quantitative comparison of area fraction of rubber ($A_r$) for for various peel-rates
4.3 Fibril length

In-situ peel tests are performed inside the SEM as explained in chapter 2, where the goal was to visualize and quantify the fibrillation process. Figure 4.6 shows images of the progressing delamination front at three different peel rates, where the copper side is on the bottom side and the rubber is on the top side of the images. The experiments reveal that during peeling, rubber fibrils are formed, elongated and eventually either ruptured or debonded at the interface. The in-situ measurements are performed for three different peel-rates, i.e. 0.1, 1 and 10 µm/s. For the peel rate of 100 µm/s, due to image acquisition speed limitations, it was not possible to take accurate images during delamination.

The fibril length was determined in the same way as explained in chapter 3. A quantitative comparison of the fibril lengths is shown in figure 4.7, where can be seen that the fibril length does not depend significantly on the peel rate. Geißler et al. have shown that the critical separation of their TSL of their time-dependent cohesive zone model is nearly constant for different separation rates [19], which is correspond to the results in the figure 4.7.

4.4 Conclusions

- Peel-test experiments revealed that the WOS of the copper-rubber interfaces depends on the separation rate increasingly.
- From analysis of the amount of copper particles left behind on the rubber surface, it can be concluded that the interface strength of the copper-rubber interface depends on the peel-rate increasingly.
- The area fraction of rubber left behind on the copper surface after peeling is a significant part, indicating that rubber fibril fracture is also significant in the peel-rate dependency of the interface delamination.
- In-situ measurements of the progressing delamination front showed that the rubber-fibril length in the copper-rubber interface delamination does not depend on the peel-rate.
Figure 4.6: ESEM images of the progressing delamination front at two levels of magnification for three different peel-rates.
Figure 4.7: Quantitative comparison of fibril length for three peel rates
Chapter 5

Conclusions and recommendations

5.1 Conclusions

In this report, the influence of copper-roughness and peel-rate on the copper-rubber interface delamination was investigated by means of peel test.

Peel test experiments showed that the WOS for extra-rough interfaces is higher than WOS for rough interfaces. Furthermore, in-situ measurements of the progressing delamination front revealed the influence of copper-roughness on the rubber-fibril length in copper-rubber interface delamination. Extra-rough interfaces have longer fibrils compared to rough samples.

Peel test experiments showed that the WOS of the copper-rubber interfaces depends on the separation rate increasingly. In addition, from analysis of the amount of copper particles left behind on the rubber surface, it can be concluded that the interface strength of the copper-rubber interface depends on the peel-rate increasingly. The area fraction of the rubber left behind on the copper surface after peeling is a significant part, indicating that rubber fibril fracture is also significant in the peel-rate dependency of the interface delamination. Finally, in-situ measurements of the progressing delamination front showed that the rubber-fibril length in the copper-rubber interface delamination does not depend on the peel-rate.

5.2 Recommendations

- More SEM images from peeled areas of the rough and extra-rough samples can be used to get more accurate information for segmentation.
- Instead of using SEM, optical microscopy with a high magnification objective lens can be used. The advantage is that there is no E-beam effect anymore. Therefore, images and movies of highest peel-rate with high speed cameras can be taken, which is impossible in SEM.
- It would be interesting to see the fibrilation process during peeling from the side of the sample to get more information about fibril geometry.
- Segmentation of the copper side for different peel rates can be repeated for more samples to see whether there is a trend or not.
- Viscoelastic properties of the bulk rubber material can be investigated separately by means of Dynamic Mechanical Analysis (DMA) or tensile tests with different elongation rates.
- Due to the very small size of the rubber-fibrils (in the order of \(\mu m\)), their mechanical behavior is not necessarily the same as the bulk rubber. This size effect can be investigated.
Cohesive zone parameters of the interfaces are usually determined by fitting the numerical and experimental results. In this project, the trend of these parameters with respect to peel-rate was predicted experimentally and validated with numerical results of G. Geibler et al. Characterizing the cohesive zone parameters, directly from experimental results, can be investigated more.
Bibliography


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