AdheScan – adhesive failure surface inspection system

Adhesive failure surface inspection based on machine learning of high-resolution stereo images

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Fig. 1:

AdheScan – a complete inspection system for the machine learning assisted adhesive failure surface inspection. Shown is the device in the preliminary housing.

Adhesive bonding is an established joining technique e.g. in aerospace, lightweight construction and the automotive industry. It places particularly high demands on materials, processes, and quality assurance, requiring extensive development and qualification procedures. Many process samples are generated for testing, which are traditionally evaluated manually by experts. In addition to the time-consuming and subjective nature of the evaluation, not all useful information is taken into account.

The inspection system described here, called AdheScan, has been developed as a laboratory instrument for machine assisted evaluation of adhesive failure surface inspection. The system is designed to use expert knowledge in an objective and reproducible way. It is based on specially designed image acquisition in combination with trainable machine learning algorithms. The overall goal is a quantifiable, simplified and more accurate evaluation of adhesive failure surfaces, combined with the possibility of digital data storage. Bonding professionals will finally have quantified data that allows further systematic research and development. AdheScan was developed in cooperation with Fraunhofer IFAM (Department of Adhesion and Interface Research & Quality Assurance and Cyber-Physical Systems) in a project (SAMBA, 20Q1924A) publicly funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The patent is pending. The customization for this particular application and the implementation of the machine learning algorithm was made possible through close collaboration and knowledge sharing.

State of the art evaluation

Adhesive bonding is a standard technique, but it is important to keep in mind that it cannot be 100% non-destructively tested. This means that the materials, process and quality assurance requirements for this joining method are particularly high. For this reason, extensive development and qualification procedures are required, during which a large number of accompanying process samples are produced for mechanical testing. The samples shown in this article are all courtesy of Fraunhofer IFAM and are all manufactured by bonding a substrate to a stamp and then placed in a centrifuge until the adhesive fails to bond.

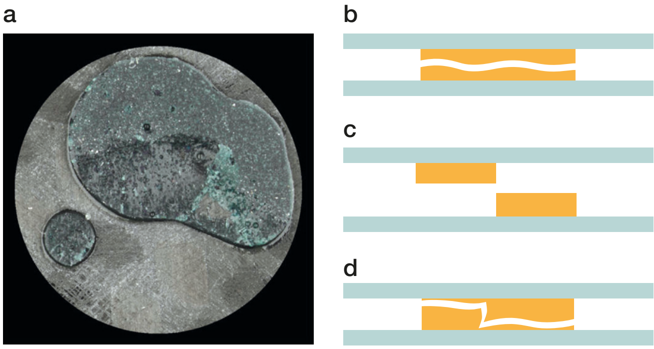

Figure 2:

High-resolution image of the stamp and schematic drawing of common adhesive failure types. The sample exhibits both cohesive (b) and adhesive failure (c). Another common type is cohesive failure near the surface (SCF, d). Samples courtesy of Fraunhofer IFAM.

Adhesive Bonding is a standard technique used in many industries to join a wide variety of materials. The requirements for process and quality assurance are generally extremely high, as it is often used in safety-related components. An important indicator for evaluating the bond is to know when the bond fails, i.e., at what force the bond breaks. Figure 2a shows a high-resolution image of a standard sample. The different failure types are defined according to DIN EN ISO 10365 – 2022 Adhesives - Designation of main failure patterns. Typically, the bond is optimized to break in the adhesive (so called cohesive failure CF, Fig. 2b) rather than at the interface (so called adhesive failure AF, Fig. 2c). Amongst others, another possibility is e.g. cohesive failure near the surface (SCF, Fig. 2d).

An expert then takes a look at the samples and determines which parts of the sample can be assigned to which failure type. Currently, this is done manually by experts relying on few standard procedures.

One technique is to visually inspect the two parts involved in the failure and estimate and note the area percentages. An image is then taken with a microscope and the values are documented manually.

Another option is to place a grid over the samples and then estimate the area percentage for each grid point, which increases reproducibility and makes the assessment a little less subjective. Overlaying the grid can be done with a film or an image of the sample. In both cases, the samples must be physically available for evaluation.

Another third option is to take an image with a microscope. While the reproducibility and accuracy are high, the evaluation is time consuming. Because the fracture pairs are not evaluated together, the fracture surfaces may be incorrectly assigned.

How do bonding experts profit from AdheScan

AdheScan provides reproducible, quantifiable results for common adhesive failure patterns. It uses two line scan cameras by Schäfter+Kirchhoff (type SK4k-U3DR7C, color, pixel size 7µm) and provides a high-resolution image (11µm optical resolution) of both surfaces of the fracture pairs. The cameras are used in a stereo configuration to provide additional valuable height information with a resolution of 20µm. Combining the images with the height information, a 3D representation of the sample is generated. The standard system scans up to 8 adhesive failure pairs (8 pairs of substrate and stamp) in under 45 seconds and calculates the height information in approximately 20 seconds. The complete AdheScan is depicted in Figure 3a. Figure

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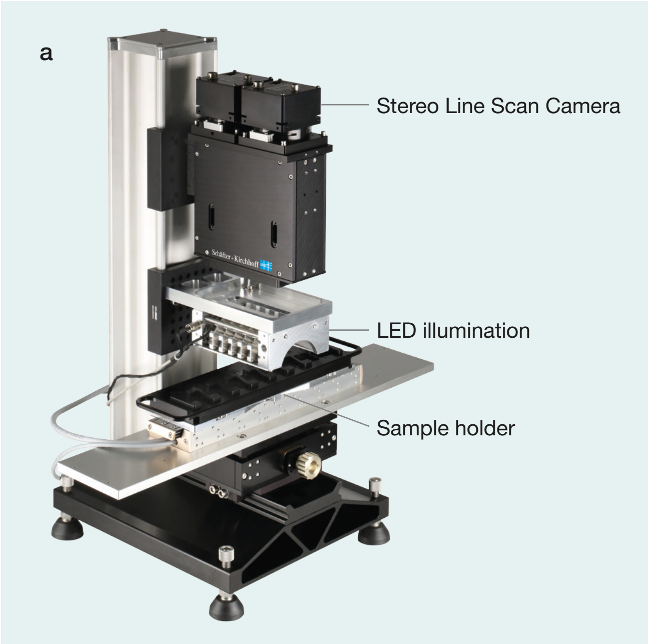


Figure 3a:

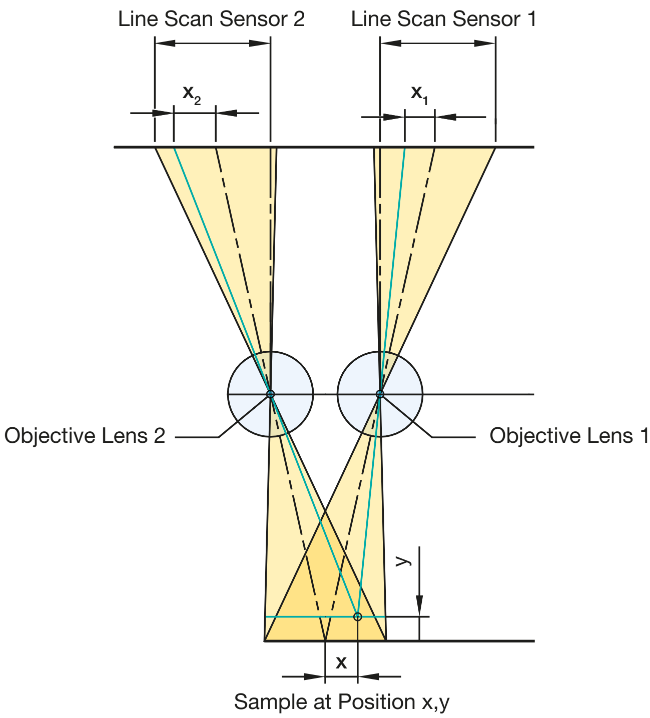
AdheScan with stereo line scan camera, LED illumination, specialized sample holder.

Figure 3b:

shows the sample holder. You can see the two fracture pairs.

3b shows a typical sample holder with 8 fracture pairs. It is also possible to scan different types of samples with the help of a specially adapted sample holder.

The high-resolution image and the height information are the basis for the subsequent evaluation using a machine learning algorithm. The software allows the user to easily train the machine learning algorithm to automatically evaluate samples in seconds. A well-trained algorithm has a processing time of only about 4 seconds for the evaluation of 1 pair of samples, depending on the computer hardware.



What is a Stereo Line Scan Camera?

A stereo line scan camera configuration is shown in Figure 4. The two line sensors are positioned parallel to the sample surface. A difference in height (y) results in a difference in pixel position (x1 on sensor 1 and x2 on sensor 2). This so-called disparity x1-x2 is the basis for the height evaluation of the image. A complete 2D image of the surface is acquired by moving the object under the two line scan cameras (e.g. from left to right). The disparity in the line scan signal for each position then leads to a height information for each sample point. Thus, a high-resolution 2D image of the surface and a height profile are measured simultaneously. The software then uses these two features to generate a 3D image for each sample.

Figure 4:

Schematic drawing of a stereo line scan camera configuration. A high-resolution image is acquired by each line scan camera.
The disparity x1-x2 is then used to acquire the height evaluation for each sample.

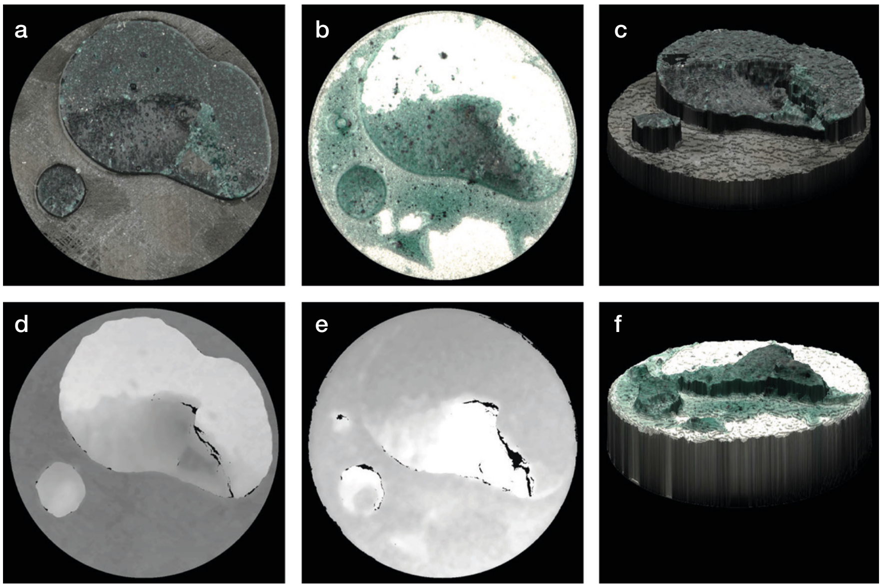


Figure 5:

High-resolution images of both substrate (a) and the stamp (b), height information for both substrate (d) and stamp (e) as well as the corresponding 3D images of both substrate (c) and stamp (f).

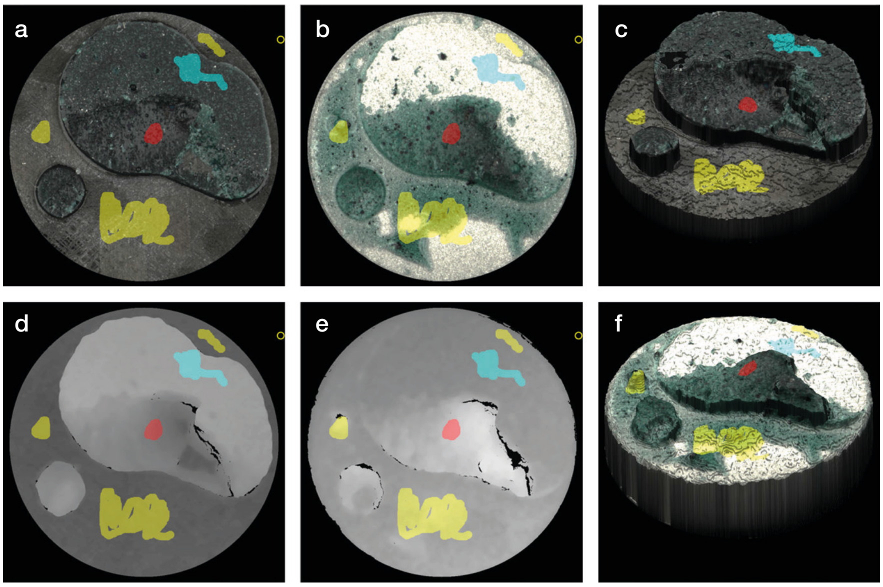


Figure 6:

Annotation tool. The user marks the fracture classes where the surface is easiest to identify in either both high-resolution image (a, b), height image (d, e). All other images are marked live for a more accurate results.

Surface Failure Inspection using AdheScan

The normal procedure for evaluating a set of samples with AdheScan includes several routines inspired by practical experience, e.g. a previously defined ROI set and the input of meta information such as the adhesive used and the substrate materials. A high-resolution image is acquired and an image with height information is calculated from the scanned images and stored.

Since the sensors scan the entire surface, the images are cropped according to the defined ROIs and displayed in a 2x2 view. The 2x2 view consists of the two images of the two halves of

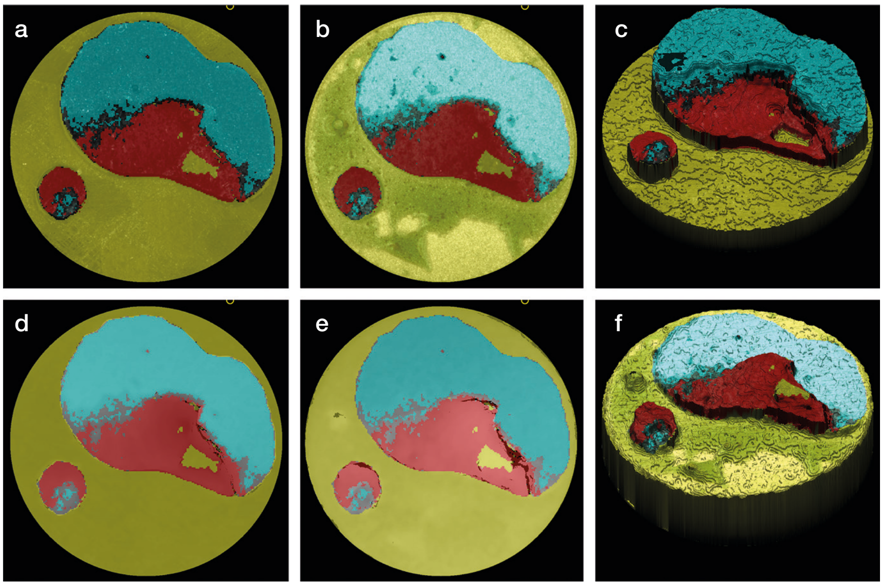


Figure 7:

Identified fracture types for both substrate (a, c, d) and stamp (b, e, f) in both high-resolution image (a, b), height image (d, e) and 3D image (c, f)

the fracture, the substrate and the stamp (the two fracture pairs) and the corresponding display of the height information. The software then allows the image to be rotated, as one partner may be rotated with respect to the other. This is especially important because all 4 images (high-resolution and height image) must be considered and evaluated together to achieve the highest possible accuracy. This is done via a dialog where the user can align the images with the help of a special visual representation. After alignment, the superimposed camera image is used to create a rotatable 3D image.

Figure 5 shows a pair of substrate and stamp fractures after rotation. The first row shows the high-resolution images of both the substrate (a) and the stamp (b), the second row shows the acquired height information for both the substrate (d) and the stamp (e), and figures 5c and 5f show the corresponding 3D images of both the substrate (c) and the stamp (f). Now, the samples can be annotated, which means marked with their fracture pattern. This can be done either manually using the Annotation tool or using a trained algorithm in Process mode.

The Annotation tool allows the image to be annotated according to user-defined label sets for the expected fracture surface patterns (e.g. adhesion fracture AF, cohesive fracture CF, etc.), which can be seen in Figure 6. The labeling of the sample is performed in parallel in both the height and high-resolution images and is displayed simultaneously in the 3D image. This allows the surface to be annotated based on the most convenient identification points. In this way, all significant features from all four images (both high-resolution and height images of the substrate and stamp) are considered and evaluated together during the marking process. This greatly increases accuracy, especially compared to manual evaluation where only one image of a sample is considered at a time.

An algorithm than uses the premarked features to calculate the final results. Even with only a few markers, the implemented algorithm can make a prediction for the entire image, as shown in Figure 7 a-e. The complete image is now divided into the corresponding fracture patterns according to the predefined labels, e.g. 70% CF, 20% AF and 10% undefined.

The software provides several in-depth features (such as histograms, heat maps, etc.) to evaluate the quality of the result. A threshold value can be defined. This determines whether the analyzed sample is considered a reject. All results are logged and all relevant data is stored in a database for easy retrieval of previous results.

The annotated images can then be selected as a sample set to be used for training the algorithm. Once the data set is selected, the algorithm can be trained. For verification, a portion of the training set is evaluated with the trained algorithm and compared to the manually evaluated results. If the result is good, the training of the algorithm can be completed by releasing it. This trained algorithm can now be selected in process mode to use the machine-assisted fracture inspection.

The system scans up to 8 adhesive failure sample pairs in under 45 seconds and calculates the height information in approximately 20 seconds. Depending on how well the features of both sides are visible in relation to each other, rotating and aligning the samples can take anywhere from 30 seconds to 2 minutes. When evaluating samples manually, the time may vary from user to user, depending on the desired accuracy and the number and identifiability of fracture patterns. In general, the evaluation can take between one and five minutes. In process mode, the trained algorithm takes over the evaluation of the images, after the user has aligned them properly. For a typical image size of 900x900 pixels, the algorithm needs about 4 seconds to evaluate the sample. However, this depends on both the image size and the processor performance. A prediction mode was developed for laboratory use when dealing with very frequently changing substrate/adhesive samples.

Conclusion

AdheScan finally provides valuable and reproducible data for bonding professionals as a basis for further research and development. Based on high-resolution images and height information, an expert can mark the identifiable fracture patterns. An algorithm is then trained using these annotations and further inspection is quick and easy. A prediction mode was developed for laboratory use when dealing with very frequently changing substrate/adhesive samples. The large number of samples required in this industry can now be evaluated in an efficient, reproducible and accurate manner.

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