All images source: Schäfter+Kirchhoff

Tracking down fractures

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

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Adhesive bonding is an established joining technique with many applications in for example aerospace, lightweight construction, and the automotive industry. It places high demands on materials, processes, and quality assurance, requiring extensive development and qualification procedures. Many process samples generated for testing are still evaluated manually by experts. The AdheScan provides a quantifiable, simplified and more accurate evaluation of adhesive failure surfaces.

The AdheScan inspection system is an advanced, user-friendly laboratory instrument for the evaluation of adhesive failure surface inspection assisted by machine learning algorithms. The system is designed to use expert knowledge in an objective and reproducible way. It is based on a specially designed image acquisition system combined with trainable machine learning algorithms. The goal is to provide a quantifiable, reproducible, and simplified evaluation of adhesive failure surfaces, combined with the ability to digitally store the data. Bonding professionals will finally have quantified, accurate data that allows for further systematic research and development.

AdheScan is a further development of a demonstrator, that was developed in cooperation with Fraunhofer IFAM (Department of Adhesion and Interface Research & Quality Assurance and Cyber-Physical Systems) in a project (SAMBA, 20Q1924A) that was publicly funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). The customization for this particular application and the implementation of the machine learning algorithm was made possible through close collaboration and knowledge sharing. The patent is pending.

State of the art evaluation

While adhesive bonding is a standard technique, it is essential to recognize that the bond quality cannot be evaluated in its entirety using nondestructive methods. The requirements for materials, processes and quality assurance for this joining method are therefore particularly high, as it is often used

◀ **Fig. 1** AdheScan is a complete inspection system for the machine learning assisted adhesive failure surface inspection. Shown here is the device in the preliminary housing.

in safety-relevant components. For this reason, extensive development and qualification procedures are required, during which a large number of process samples are produced for mechanical testing.

The samples shown in this article are all courtesy of Fraunhofer IFAM and were all manufactured by bonding a substrate to a stamp. They were then placed in a centrifuge until the adhesive fails.

An important indicator for evaluating the bond is to know when the bond fails. **Fig. 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 (cohesive failure CF, **Fig. 2b**) rather than at the interface (adhesive failure AF, **Fig. 2c**). Among others, another possibility is cohesive failure near the surface (SCF, **Fig. 2d**).

Once the samples are prepared an expert determines which parts of the sample can be assigned to which failure type. Currently, this is done manually by experts relying on a few standard procedures. One method is to visually inspect the two parts involved in the failure and estimate and note the area percentages. An image is then taken under 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.

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

Benefits for bonding experts

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 7 µm) and provides a high-resolution image at 11 µm 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 20 µm. A 3D representation of the sample is generated by combining the images with the height information. The standard system scans up to eight adhesive failure pairs (eight pairs of substrate and stamp) in less than 45 seconds and calculates the height information in approximately 20 seconds (**Fig. 3a**). A typical sample holder has several fracture pairs (**Fig. 3b**). A customized sample holder makes it possible to scan different types of samples.

The high-resolution image and the height information provide 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 one pair of samples, depending on the computer hardware.

What is a stereo line scan camera?

In a stereo line scan camera configuration the two line sensors are positioned parallel to the sample surface (**Fig. 4**). A difference in height (y) results in a difference in pixel position (x_1 on sensor 1 and x_2 on sensor 2). This so-called disparity $x_1 - x_2$ 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 provides height information for each

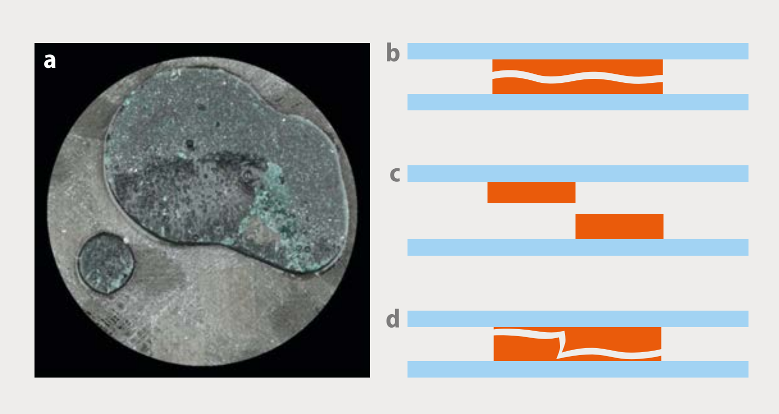

Fig. 2 High-resolution image of the stamp (a) and schematic drawing of common adhesive failure types. The sample exhibits both cohesive (b) and adhesive failure (c). Another common type is cohesive failure near the surface (SCF, d). The samples shown were provided by Fraunhofer IFAM.

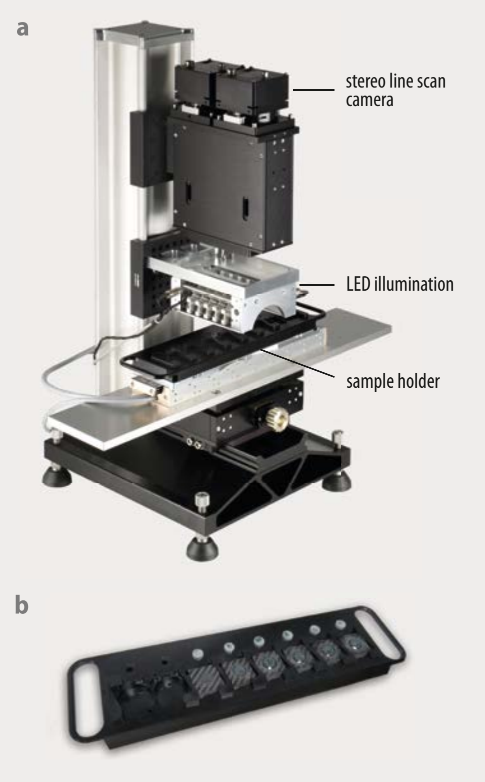

Fig. 3 The AdheScan was developed from this previous demonstrator (a) with the stereo line scan camera, LED illumination, and specialized sample holder. The sample holder has six fracture pairs (b).

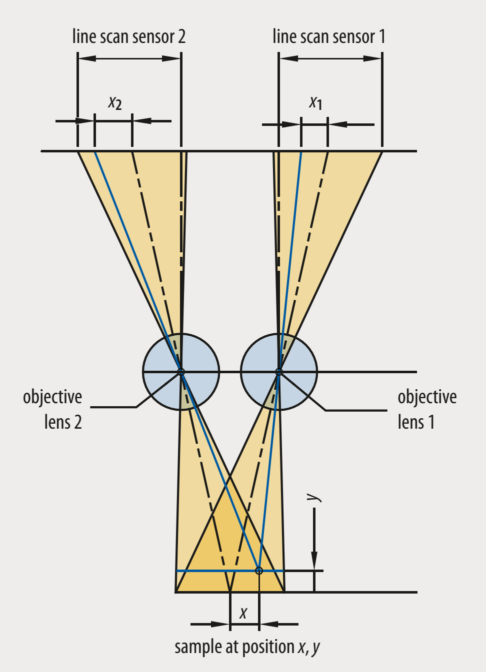

Fig. 4 In the stereo line scan camera configuration, a high-resolution image is captured with each line scan camera. The disparity $x_1 - x_2$ is then used to acquire the height evaluation for each sample.

sample point. 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.

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 region of interest 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 regions of interest and displayed in a 2 × 2 view. It shows the two high-resolution images of the two fracture halves – the substrate and the stamp – along with the corresponding height information. The software then supports the alignment of the images to each other. This is especially important because all four 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.

Fig. 5 shows a pair of substrate and stamp fractures after alignment: 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**), while (**c**) and (**f**) show the corresponding 3D images of both the substrate and the stamp.

The samples can now be annotated, which means the different fracture surface areas are marked. 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 described 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 **Fig. 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 then uses the pre-marked features to calculate the final results. Even with only a few markers, the algorithm can make a prediction for the entire image (**Fig. 7a–e**). The complete image is now divided into the corresponding fracture patterns according to the predefined labels, e. g. 25 % CF, 35 % AF and 40 % customized failure type. 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 to determine 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 train the algorithm. For verification, a portion of the training set is evaluated with the trained algorithm

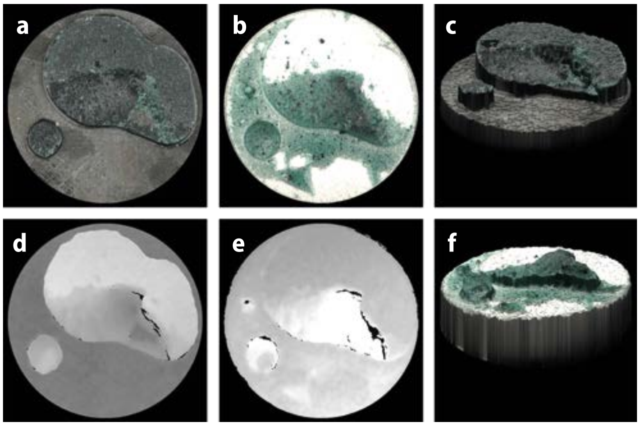

Fig. 5 High-resolution images of both substrate (a) and the stamp (b), height information for both substrate (d) and stamp (e) as well as the corresponding 3D images of both substrate (c) and stamp (f)

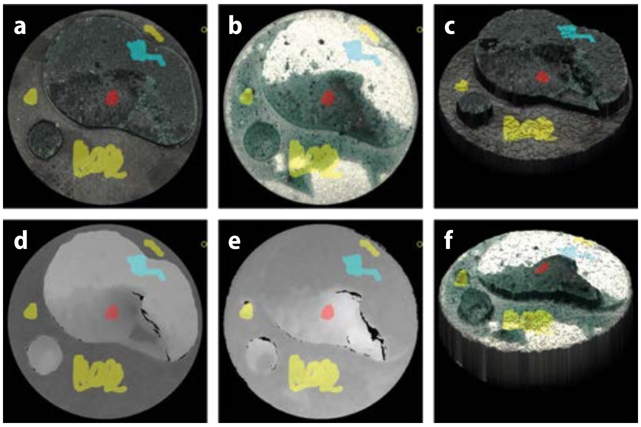

Fig. 6 In the annotation tool, the user marks the fracture classes for which the surface is easiest to identify either in the high-resolution image (a, b), or the height image (d, e). All other images are marked live for more accurate results.

and compared to the manually evaluated results. If the result is good, the training of the algorithm can be completed by releasing it and it can then be selected in process mode to use the machine-learning algorithm-assisted fracture inspection.

The system scans up to eight 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 900 × 900 pixels, the algorithm needs about four seconds to evaluate the sample. However, this depends on both the image size and the processor performance.

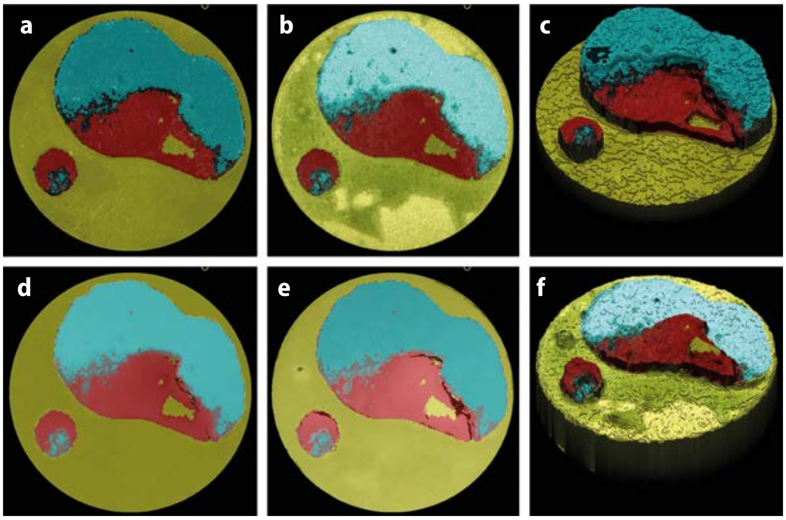

Fig. 7 Identified fracture types for both substrate (a, c, d) and stamp (b, e, f) in both high-resolution image (a, b), height image (d, e) and 3D image (c, f)

Conclusion

AdheScan finally provides valuable and reproducible data for bonding professionals as a basis for further research and development. Experts can mark the identifiable fracture patterns based on the high-resolution images and height information. The 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. In process mode, the large number of samples, e. g. in-process samples, can now be evaluated in an efficient, reproducible, and accurate manner.

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