# In-line quality assurance for ENDT of multi material adherend surfaces

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## ABSTRACT

To reduce $CO_2$-emissions lightweight structures needs to be implemented in all transport applications. At the same time, low-weight and high performance materials must provide safety and reliability, at economical prices. Extended Non-Destructive Testing (ENDT) contributes to safeguarding the performance of adhesively joined load-critical structures, permitting to steadily monitor adherent surfaces prior to bonding and to detect adhesion properties of bonded components.

In the present work, approaches exceeding the state-of-the-art of innovative ENDT techniques like robot-based Laser-Induced Breakdown Spectroscopy (LIBS) are presented. Furthermore, automated, AI-based image processing and evaluation methods for surface quality inspection are shown, aiming at overcoming today's limitations concerning handling, evaluation speed and reliability of results. First results of automated in-line surface quality assurance approaches for assessing multi material adherent surfaces are highlighted.

**Keywords:** ENDT, LIBS, image processing, adhesive bonding, DIN 2304

## 1. Introduction

Global demand to reduce $CO_2$-emissions will continue to increase drastically. To reach this demanding goal adhesive bonding is the key technology for joining light-weight and high performance materials. When it comes to adhesive bonding, a zero-fault production is needed, as modern adhesives are high-tech products. Some bonds will fail nonetheless; this is generally due to adhesive application errors. Here DIN 2304 [1] kicks in and lays down organisational matters relating to e.g. quality assurance. Together with that organizational quality assurance, technical quality assurance provides a safeguard against technical uncertainties in a process or for characterizing the quality of the final product. DIN 2304 should be understood as a user/application standard [2-3]. To implement the recommendations of that standard and to gain full advantage of idea behind DIN 2304 consequent process monitoring and quality assurance by in-line ENDT is necessary. To show the latest works in the field of automated surface quality assurance in the following two new approaches are described in detail.

## 2. Quality inspection by image processing and evaluation using AI

Imperfections on monopile surfaces used for offshore wind energy turbines negatively influence the effectiveness of the protective coatings significantly. To maximize the protective effect of coatings on steel structures, the condition of the surface to which the coating is applied is critical. Surface imperfections, such as edges and weld seams, are particularly important. It can be assumed that "60 to 85 percent of all premature failures can be attributed directly to inadequate surface preparation" [4].

EN ISO 8501-3 therefore defines surface preparation grades, such as "P2," which refers to "thorough preparation: most visible imperfections are remedied," and "P3," which refers to "extensive preparation: the surface is free from significant visible imperfections". [5] However, these categories are only described qualitatively, leaving room for interpretation. Even for highly trained staff like paint inspectors this does not always yield in clear and reproducible results, which is clearly a back draw of this standard. To overcome this, an automated digitalization and evaluation tool was invented together with partners at Fraunhofer IFAM.

The developed system uses a projected texture stereo vision system to generate a dense point cloud of the surface, which is then transformed into a 2D matrix and represented as a grayscale image using double precision numbers. The image data is normalized and divided into tiles of a given size. For each tile a number of features, ranging from simple predictors like the mean or median of the tile to complex ones derived from gray-level co-occurrence matrices, are calculated. These are used as input to a Random Forest model. Reference steel plates (200 mm x 400 mm) were manufactured with typical defects and the surface was analyzed by the newly developed vision system in parallel to an assessment by several well-trained paint inspectors. In addition, the annotations of the paint inspectors were used as input for the machine learning model. The typical workflow of the automated assessment is illustrated in Figure 1.

The applied random forest approach allows an estimation of the importance of the different features. It turned out, that not all features are of high importance for the construction of the prediction forest. Therefore, features of low importance were neglected. Out of over 100 features, 13 were selected for efficient prediction. The matrix of defect probabilities is then transformed into a defect map by thresholding. The experts' annotation corresponds well to the automatic analysis by the measurement system, and automated evaluation allows for reproducible classification of similar defects, leaving behind the influence of varying human performance and perception. The defect probability can be used as a guide for the comparison of different defects in different areas, significantly reducing overall inspection time. However, the experts' results cannot be considered a "ground truth" since the experts' results depend on their experience and their current perception of the defect. This becomes visible through very different evaluations when several experts review the same defect. The developed system is able to partially compensate for this subjectivity by learning from multiple experts. Nevertheless, the system is based on human experience and does not know "the truth" about which defects have a negative impact on the coating.

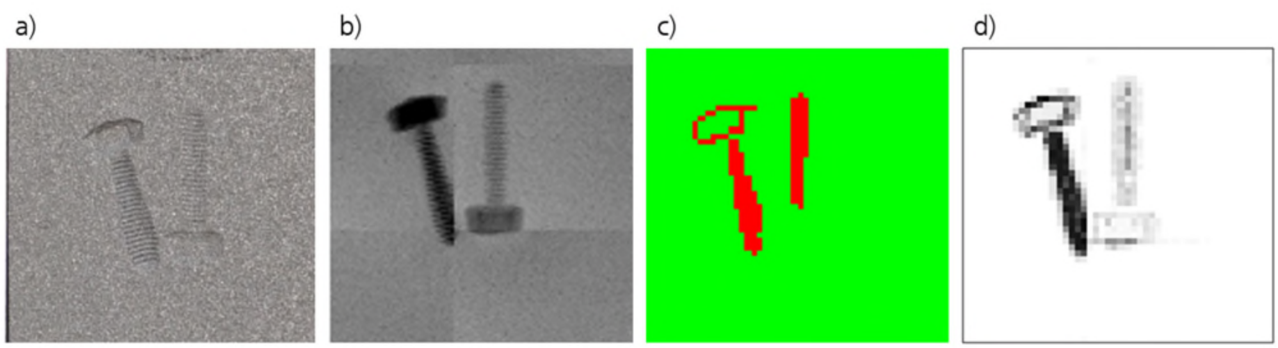


Figure 1: Process Overview from left to right: a) Photographic image of test samples with surface imperfections, b) Scan by the stereo vision system and subdivision in tiles, c) Surface assessment by paint inspectors, d) Calculation of defect probability using the random forest approach

## 3. Robot-assisted Laser-Induced Breakdown Spectroscopy for quality assurance

Nowadays, Laser-Induced Breakdown Spectroscopy (LIBS) is an established and widely used method to determine the chemical composition of surfaces. In the past, several studies like ENCOMB and ComBoNDT have shown LIBS is capability for the detection of even small amounts of residues of contaminants on surfaces, making it a suitable measurement tool for quality assurance in adhesive bonding [6-9]. Due to the high laser energies, size and weight of the components (e.g. laser, spectrometer), most LIBS systems are stationary lab setups. Therefore, the degree of automation and the part sizes suitable for inspection are limited. Together with the company LTB Lasertechnik, Berlin as project partner, Fraunhofer IFAM successfully developed a robot-mounted LIBS measuring head for automated LIBS-measurements using an industrial robot. In this setup, the LIBS technique is capable to serve as an in-line monitoring tool for adherent surfaces prior to bonding. The developed robot head is completely air-cooled and light weighted (7 kg) while at the same time providing excellent quality of plasma formation and spectrum acquisition. In addition, a security shutter is implemented directly on the laser unit and is controlled by interlock switches and a software.

The robot-mounted LIBS measuring unit was used during measurement in the IFAM lab. Here the task was to scan for release agent residue prior to bonding of CFRP parts. The LIBS unit can either be used as single robot application or in a collaborating setup with two or more robots. The current robot head uses a 1064 nm wavelength laser to create the plasma. Using lasers with shorter wavelength (532 nm or 266 nm) leads to a significant reduction in material ablation while remaining a good signal to noise ratio in the measurements on CFRP materials and is subject of current work in the field of robot-based LIBS.

To show the full potential of the robot-mounted LIBS a comparison with defined test specimen was done. Carbon fiber reinforced plastic (CFRP) specimens where artificially contaminated by dip-coating to set different levels of contamination. Frekote, a silicon based release agent was diluted with heptane to have control over the amount of Si applied to each sample. After dip-coating, X-ray Photoelectron Spectroscopy (XPS) was done to verify the “real” amount of Si on the surface of the samples representing the degree of contamination with release agent In Table 1 the results of the XPS analysis are listed. XPS results show that the Frekote solution with 4% Frekote was faulty as the Si amount is too little.

Table 1: Silicon content according to XPS for different levels of artificial contamination on CFRP specimen. (*) Si amount of 4% specimen is much lower than expected

| Frekote solution [%] | Si XPS [atom%] |
|---|---|
| reference | 0.3 |
| 1 | 1.1 |
| 2 | 2.0 |
| 3 | 5.5 |
| 4 | 2.8* |
| 7 | 8.0 |
| 10 | 11,4 |

With this set of samples the comparison between the stationary LIBS setup and the robot device was done. In Figure 2 the results of this comparison are summarized. The right picture shows the findings of the lab LIBS together with the XPS results. Sample 4% with too little Si is marked with as pink dot. All other points follow a linear correlation as expected. The left image shows the spectra acquired with the robot LIBS system. Again all samples shows the expected linear correlation in the intensity of the Silicon signal. And again, the too little amount of Si on sample 4% Frekote is clearly visible (arrow).

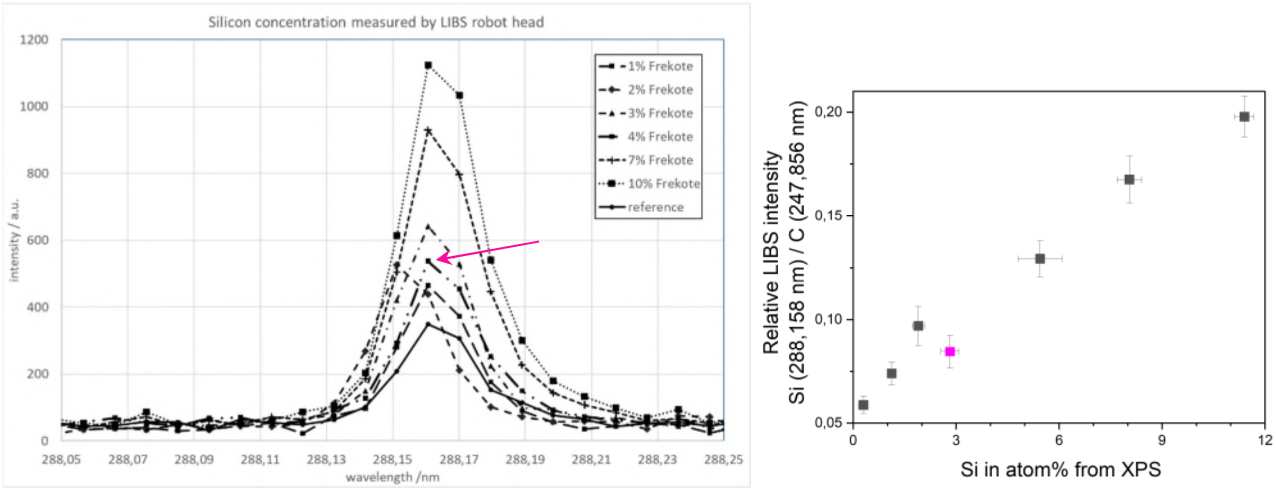


Figure 2: Comparison of measured LIBS data of Si-bases release agent on CFRP surfaces. Left spectra show data acquired with the robot LIBS head. Right reference data is shown which was acquired with the stationary LIBS setup (lab device).

This comparison demonstrates that the small and light-weighted robot-mounted LIBS device is capable to deliver the same results with the same accuracy as a state-of-the art lab LIBS system. It is possible to detect even small residues of Si-based release agents with a sensitivity of 1 at% which meets the high requirements of aircraft industry. With this knowledge, the LIBS method is a very powerful tool when it comes to automated in-line capable ENDT for large components in automated production lines on multi material surfaces.

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