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Signal analysis in acoustic microscopy for non-destructive inspection of varnish layers on metal substrates

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Abstract - For preventing corrosion and for surface protection metallic objects are commonly finished with layers of varnish. The integrity of the varnish and potential defect propagation influence the durability of the metal and hence are a measure of the quality of the finishing. Scanning acoustic microscopy provides high axial and lateral resolution, a sufficient penetration depth and is non-destructive. The goal of this work was the development of a method for detection and evaluation of delaminations of varnish layers on metallic surfaces. Investigated were samples containing one or two layers of varnish. One group contained priming only whereas the second group contained varnish on top of the undercoat. The surface integrity of the finishing was destroyed by a scratch through all finishing layers. Defect aging was then modeled by exposing the samples to a corrosion-friendly atmosphere. Scanning acoustic microscopy combined with signal analysis was performed for investigating the connectivity between the finishing layers and the substrate. A robust numerical deconvolution technique has been adapted and optimized to enable the separation of strongly overlapping pulses. Echoes originated at the substrate and the finishing layers have been localized and layer thicknesses/distances were estimated. Delaminated spots of the finishing were successfully evaluated using the proposed method.

1 Introduction

In unprotected condition metallic surfaces preferably induce a chemical reaction with oxygen contained in the surrounding air. In the presence of water iron or steel is converted into iron-III-oxide. This oxidation process leads to an increase in mass and volume and causes tension in the metallic surface. The entire process damages the surface and the structure of metallic objects and is commonly known as corrosion. In order to protect metallic surfaces from the direct interaction with water and oxygen varnish layers are applied for surface-sealing. Important for a long-term protection is that the covering material is impermeable for water and oxygen and that it cannot be resolved by one or both of them. A varnish material should also be resistant to the exposure to sunlight, high temperature variations and mechanical forces.

The non-invasive inspection of varnish layers offers the opportunity of repeatedly investigating its preservation performance and thus monitoring the varnish reliability under various environmental conditions over an extended period of time. Not only the surface integrity but also the varnish adhesion to the substrate is of major interest. Under corrosion friendly conditions varnish compositions are commonly tested extensively. This procedure allows the investigation and development of new material compositions but also to test for reliability aspects under defined environmental application factors.

Scanning acoustic microscopy (SAM) offers a sufficient penetration depth, an excellent axial and lateral resolution and provides depth-specific information. The non-destructive operation of SAM measurements enables investigating one and the same specimen repeatedly over an extended period of time for monitoring the materials response to the exposure to varying environmental conditions. Ultrasonic imaging in the frequency range above 50 MHz is capable of detecting adhering conditions between varnish layers and the carrying substrate. The major challenge for evaluating adhesion properties and detecting delaminated spots is the separation of the ultrasonic pulses which are reflected at the varnish, primer and the substrate. These boundaries only provide sufficient reflectivity when the acoustic material properties show significant differences. Overlapping pulses and a low signal to noise ratio (SNR) exacerbate the detection of adjacent boundaries. To overcome these difficulties a stable and robust computational algorithm is required for automated

detection of delaminations and evaluation of defect propagation.

For boundary separation in ultrasonic testing deconvolution of measured echo signals may be applied. This approach assumes that the impulse response $s(t)$ of the test-sample is described as a sum of discrete delta functions, which is convolved with the impulse response of the probing equipment $h(t)$. For a linearly behaving system signal theory predicts that the measured ultrasonic echo signal $e(t)$ can be derived from the convolution of the impulse responses of the sample and the measurement device supplemented with noise $n(t)$. Under the condition of linearity the structural composition of the sample can then be obtained from the $e(t)$ with known $h(t)$ and measured $n(t)$ using an appropriate deconvolution algorithm. However, solving the inverse problem as described above becomes increasingly difficult with the noise amplitude of the setup. The application of a simple deconvolution algorithm does not provide stable and meaningful results. Therefore, a more complex method needs to be applied. Previous published studies investigated a variety of numerical deconvolution techniques. Non-adaptive procedures were investigated by Hayward et al. 1989. Sin et al. 1992 also performed a comparison between various deconvolution techniques and found that Wiener filtering in combination with extrapolating the obtained spectrum showed the best performance. McRae et al. 1990 investigated adhesive joints in composites using Wiener filtering and spectral extrapolation. This combination was further developed by Honavar et al. 2004 who extended the deconvolution algorithm by applying several frequency windows which resulted in an improved robustness and a significantly increased SNR. The group of Honarvar applied the extended deconvolution technique to signals obtained from simulations but also to signals measured using an ultrasonic set-up. The data analysis showed that the computational effort of the method developed was acceptable.

The study described in this article applied scanning acoustic microscopy in the range between 75 MHz and 120 MHz. Signals acquired were processed off-line using an improvement of the numerical deconvolution technique in combination with Wiener filtering as described by Honavar et al. 2004. Acoustic pulses obtained from the interface between the varnish and the substrate, have been separated. Defects were classified in terms of the altitude of the finishing layer above the surface of the metallic substrate and the size of the delaminated spot.

2 Materials and Methods

2.1 Scanning Acoustic microscopy

Scanning acoustic microscopy is a powerful tool for non-destructive inspection of optically opaque materials for deriving depth-specific information in combination with a lateral resolution in the μm -range. A fast scanning Evolution II (SAM TEC GmbH, Aalen, Germany) scanning acoustic microscope equipped with a 100 MHz central frequency transducer with a focal distance of 10 mm was applied. Scanning was performed with an increment of $4\ \mu\text{m}$ in the lateral x- and y-directions. During the experiments the transducer tip and the specimen investigated were immersed in distilled water at room temperature, which served as the coupling medium for the wave propagation. Received signals were digitized with a sampling frequency of 500 MHz and a resolution of 10 bit by the acoustic microscopes A/D-converter and stored at the internal hard drive. Data files containing unprocessed rf-signals were then transferred to a desktop computer for off-line analysis.

2.2 Sample description

Investigated were steel samples with two different kinds of coating as illustrated in figure 1. The first group contained a priming coat of $25\ \mu\text{m}$. The primer consisted of a water-borne 2-component polyurethane varnish. The second group of samples had a finishing coat of thickness $25\ \mu\text{m}$ on top of the priming layer. For finishing a solvent-borne 2-component polyurethane finishing varnish was used. All samples were cured according to the manufacturer instructions. Polyurethane varnish forms a solid film which results in a durable finishing that is non-permeable for water and oxygen (Musselman et al. 2007). For investigating defect propagation a scratch through all finishing layers was introduced into the surface of each sample. Corrosion of the substrate material at the defect and the propagation into the sample was accelerated by exposure to a brine-spray-test. All samples were prepared and tested under industrial manufacturing conditions at BAYER MaterialScience (BAYER AG, Leverkusen, Germany) prior to acoustic inspection by SAM.

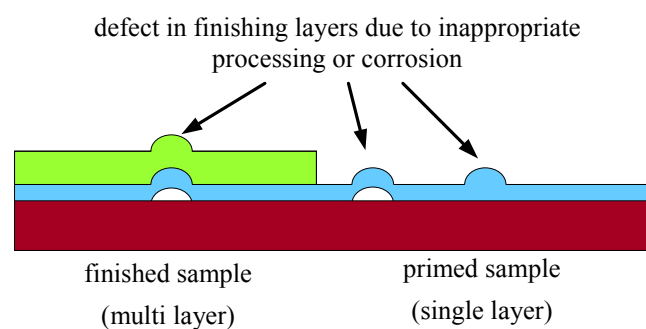


Figure 1: Illustration of sample composition. Single layer samples were treated with a water-borne polyurethane primer. Multilayer samples contained an additional finishing layer on top of the primer.

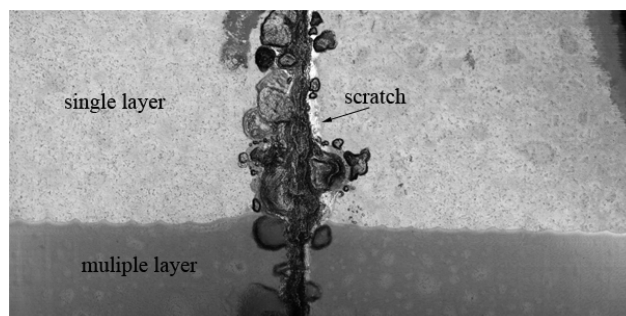


Figure 2: C-scan image of a sample with single and multi-layer coating. The scratch was introduced prior to brine-spray-testing for corrosion acceleration.

2.3 Data processing

Signal processing was performed using a custom-made MATLAB (The Mathworks, Natick, USA) software developed at the Q-BAM laboratory. In the first step a C-scan intensity image was computed from recorded rf-data by estimating the maximum amplitudes of the Hilbert-transformed of each signal as shown in figure 2. In the second step of the signal analysis numerical deconvolution of the rf signals was performed. The deconvolution algorithm used in this study is based on the method proposed by Honarvar et al. 2004. This method applies a Wiener filter using a reference signal which incorporates the systems transfer properties and a “noise-dedesensitizing factor” Q . Q^2 is commonly set to $10^{-2} |H(\omega)|_{\text{max}}^2$, where $H(\omega)$ is the spectral transfer function of the measurement equipment. This transfer function was assessed by recording a pulse reflected from a stainless steel reflector and is shown in figure 3. The deconvolved spectrum obtained by Wiener filtering was further improved by applying autoregressive spectral extrapolation. The application of the spectral extrapolation algorithm assumes that the autoregressive process can be modelled from a spectral range of the input signal which has a high signal-to-noise ratio. For performing a reliable and robust autoregressive spectral extrapolation the maximum-entropy spectral algorithm of Burg as described by McRae et al. 1990 was used.

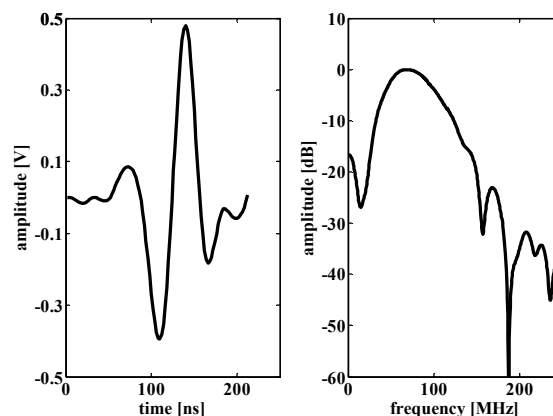


Figure 3: Left: Reference signal recorded from a plain steel reflector. Right: Spectral transfer-function of the equipment. Transfer properties were applied for estimating the boundary locations inside the sample by deconvolution of the rf-signals recorded with the acoustic microscope.

Spectral extrapolation was repeated for 10 different frequency ranges within the -10 dB range of the reference spectrum for each signal contained in the two-dimensional scan recorded with the acoustic microscope. The order of the autoregressive model was set to 15. Extrapolation results were averaged prior to performing inverse Fourier transformation for converting signals into time domain. Results obtained from the inverse Fourier transform contained peaks which correspond to the position of the boundaries in the sample. From the deconvolved signals the pulse polarity and position can be derived. In cases of strong pulse-overlapping and a high noise level in the underlying signal the deconvolved signals may show a distortion of the delta peaks making it difficult to assign the peaks to a boundary inside the sample. For improving the robustness of the method the absolute values of the resulting time domain signals were computed and convolution with a narrow rectangular window (width : 10 ns) was performed. From the processed signals local maxima were estimated and assigned to the boundaries of the underlying specimen according to the order of their position. Delaminated regions in the sample were detected based on the altitude-position of the entrance echo and the echo originated at the substrate material.

3 Results and Discussion

Results obtained by numerical deconvolution at different varnish thickness and delamination conditions are shown in the figures 4 to 7. The top graph in each figure contains the unprocessed rf-signal recorded with the acoustic microscope. The bottom graphs show the processed signals after applying the numerical deconvolution algorithm and post-processing. Peaks in the deconvolved signals correspond to boundaries inside the sample. Results obtained from a non-delaminated single-layer sample can be seen in figure 4. Peaks in the deconvolved signal of fig.4 are separated by 20 ns which corresponds to a layer thickness of 25 μm . The signal displayed in figure 4 was recorded at the position marked "A" in the C-scan image provided in figure 8. An observed delaminated spot of a sample containing a priming coat only is analyzed in figure 5. The signal was recorded at position "B" in figure 8. The peak separation in the bottom graph of figure 5 was estimated to be 52 ns. Accounting for the sound propagation in the primer material (20 ns) the propagation time in the water underneath the varnish is calculated to be 32 ns. This time delay corresponds to a 24 μm layer of water between the varnish and the substrate. The sound velocity of the 2-component polyurethane varnish was 2500 m/s and 1500 m/s for the distilled water, respectively. Figure 6 displays the rf signal and its deconvolution in presence of a multi-layer finishing of the steel substrate. The position of the data acquisition of this rf signal corresponds to the position marked "C" in figure 8. In the processed signal a peak separation of 38 ns was observed. A value of 2500 m/s was used for the sound velocities of both varnish layers. The time delay estimated from the deconvolved signal corresponds to a full thickness of the finishing coats of 47.5 μm . The accumulated thickness of both varnish layers is approximately 50 μm , therefore no delamination appears to present in the analyzed spot. Figure 7 shows the deconvolution result when analyzing a cross section through a single- and multi layer finishing of the

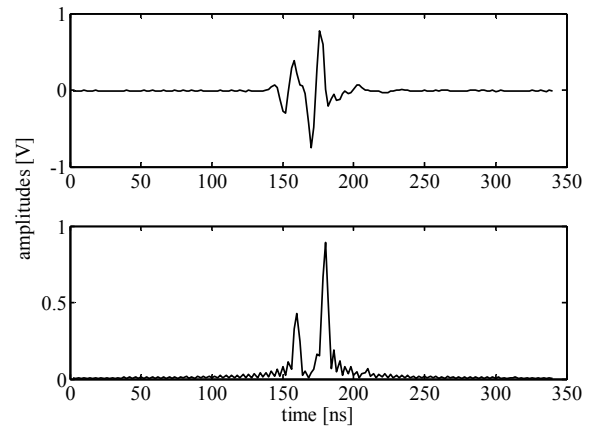


Figure 4: Rf signal and analysis result of a single layer coating (fig 8-A). The primer material at this position was not delaminated. Top: rf ultrasonic signal with strongly overlapping pulses; Bottom: deconvolved and smoothed signal. Peak separation corresponds to the boundaries inside the sample.

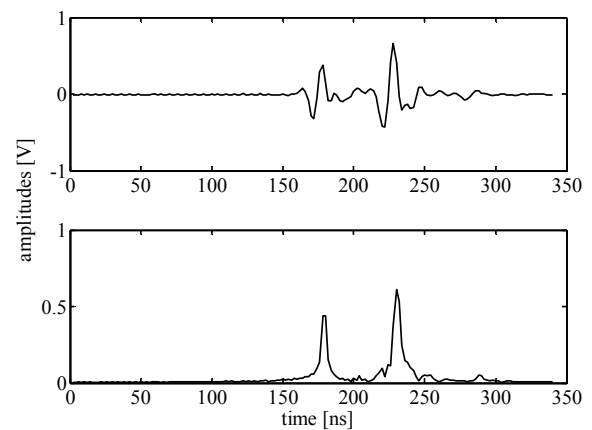


Figure 5: Rf signal and analysis result of a single layer coating (fig 8-B). The primer material at this position was delaminated. Top: rf ultrasonic signal; Bottom: deconvolved and smoothed signal. Peak separation corresponds to the boundaries inside the sample.

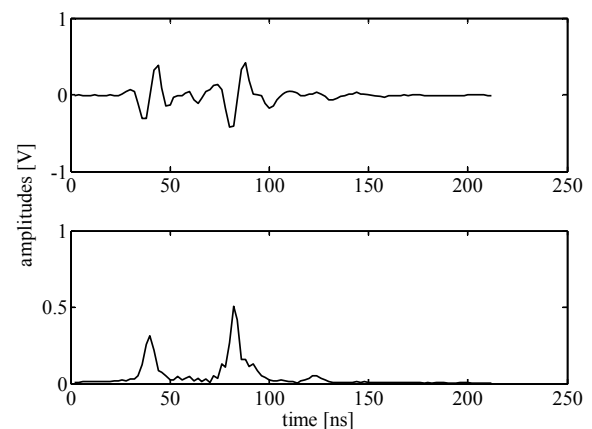


Figure 6: Rf signal and analysis result of a multi layer coating (fig 8-C). Both materials at this position were not delaminated. Top: rf ultrasonic signal with clearly separated pulses; Bottom: deconvolved and smoothed signal. Peak separation corresponds to the boundaries inside the sample.

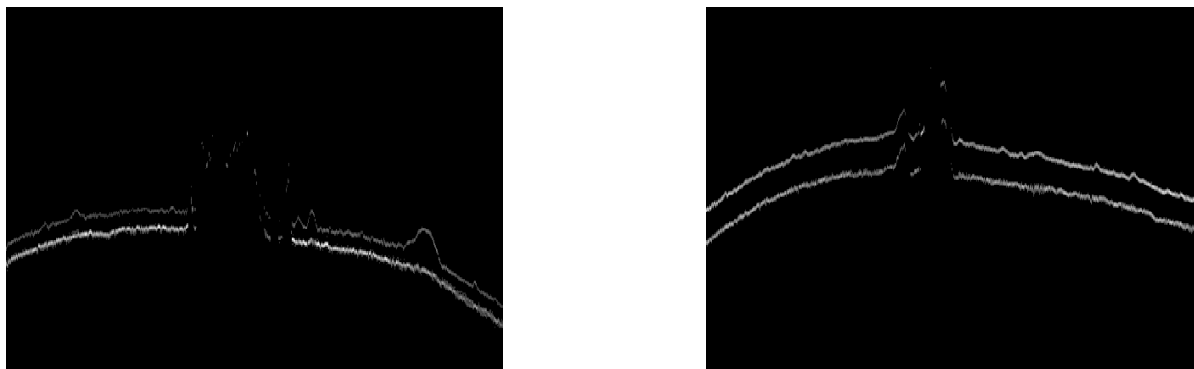


Figure 7: Results of deconvoluting ultrasonic B-scans. Both images show a cross section through a sample. Left: Boundary positions of a cross section through a single layer coating (fig 8-D). Right: Boundary positions in a cross section through a multi layer finishing (fig. 8-E). The irregular peak positions in the center correspond to the scratch, as seen in figure 8.

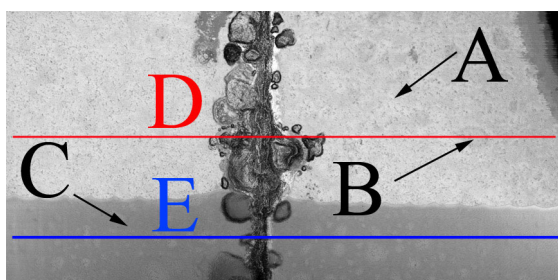


Figure 8: C-scan image of sample surface. Markers correspond to the positions where rf signals were recorded according to the figures 4 – 6, 8, 9. A: single layer non-delaminated; B: single layer delaminated; C: multi-layer non-delaminated; D: B-scan single layer; E: B-scan multi layer.

steel substrate. In the left hand side image a delamination of the primer coating can be seen. It should be noted that the distance between positions of the top echo and the substrate echo is approximately twice as high in the results obtained from the multi layer finishing (right hand side image) compared to the single layer finishing. Due to similar acoustic properties of the two varnish materials the boundary between the primer and the finishing coat cannot be detected. Figure 9 contains a distance map computed from a sample containing both single- and multi layer finishing. Delaminated regions can easily be detected.

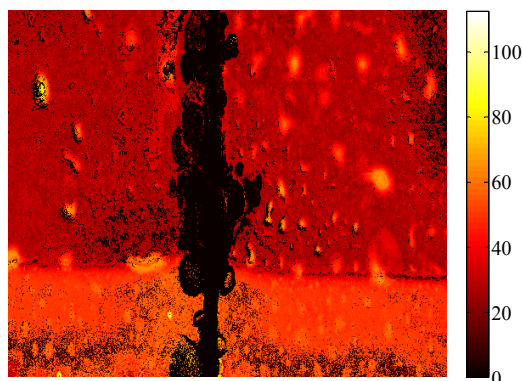


Figure 9: Distance map of the two echo positions. The scale bar denotes the peak separation in ns. The contrast in this image is provided by higher peak separation in delaminated spots.

The contrast in figure 9 arises from the peak separation which is higher in regions containing a delamination.

5 Conclusion

A numerical deconvolution method proposed by Honarvar et al. 2004 was improved and provides a robust and computational efficient solution for pulse separation. Even in cases of strongly overlapping pulses satisfying results were obtained. The method was successfully applied for quantitatively assessing delaminations in finishing layers on solid substrates.

Acknowledgments

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