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Two-dimensional thickness distribution measurement using near infrared spectroscopy

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We report on the development of a measuring method based on near infrared (NIR) spectroscopy, which is able to determine the thickness as well as the homogeneity of polyurethane lacquer coatings in two dimensions in the field of wind turbine blades. The typical thicknesses of these polyurethane lacquer coatings (50–350 µm) were investigated. NIR spectra were recorded in reflection mode. Quantitative analysis of the spectral data was carried out with partial least squares regression. Measurements were performed on a scanning device developed in-house at scanning speeds up to $0.05\,\text{m}^2\,\text{s}^{-1}$. It was shown that quantitative data with excellent precision (standard derivation below 10%) can be obtained.

Keywords: NIR spectroscopy, hyperspectral camera, principal component analysis, two-dimensional thickness measurement, polyurethane lacquer, scanning device, wind turbine blade, homogeneity
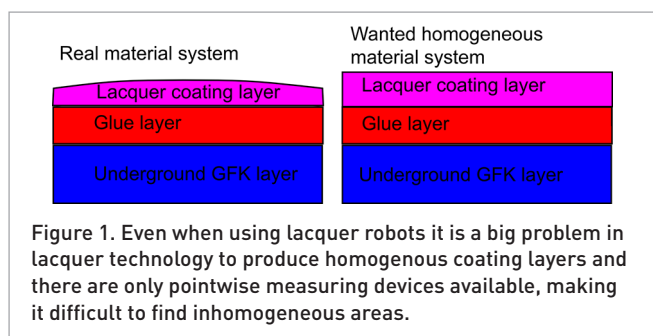
Introduction

Process analytical tools are used in a broad field of applications in the chemical industry to control the process state as well as the quality of the process result.[1] Such systems can be used to observe the surfaces of samples such as lacquer coatings on different substrates, for example on carbon fiber reinforced plastic (CFK) used for wind turbine blades. The properties of the coatings do not only depend on the composition of the formulation, but also on the homogeneity and thickness of the applied layer. Therefore, it is important to inspect both parameters of the coating layer at once. There are different analysis methods to obtain pointwise thickness information of a lacquer layer.

Currently, there is a lack of analysis methods which are able to observe two-dimensional thickness distributions of lacquer-coated surfaces. The homogeneity of the lacquer coating is important to create a surface with the same properties for the whole sample. There is a problem in lacquer technology with producing such high-quality lacquer coatings; an example is illustrated in Figure 1. By measuring different points on the surface, the probability of finding small inhomogeneous areas of the sample is quite low and can result in delivering low-quality products despite performing quality surveillance.

As explained, currently, there is a lack of analytical methods capable of providing precise homogeneity and thickness information of a lacquer coating of a two-dimensional plane. Therefore, the measurement of a large plane in a short time requires a method with high precision and high measuring speed. Furthermore, the use of this method in process control and quality control should be possible. Near infrared (NIR) spectroscopy is a powerful, contactless, non-destructive method that can be used for this application. Due to low absorption coefficients in the NIR region it is difficult to obtain high-quality spectral data. Furthermore, the analysis requires

Figure 1. Even when using lacquer robots it is a big problem in lacquer technology to produce homogenous coating layers and there are only pointwise measuring devices available, making it difficult to find inhomogeneous areas.

complex data processing algorithms due to the high data volume.

In this paper, we report on the development of a measuring method based on NIR reflection spectroscopy. Our approach is able to determine the homogeneity as well as the thickness of polyurethane lacquer coatings used for wind turbine blades in a two-dimensional approach by using a hyperspectral camera mounted on a vertical scanning device.

State of the art

There is a broad spectrum of different non-destructive technologies used to survey the surfaces of different materials.[2] Ultrasonic measurement devices are a popular technology for pointwise inspection of surfaces. The long history has created much experience with these techniques, and it is reliable and precise for thick coating layers. However, up to now there are no two-dimensional methods available based on ultrasonic technology.[3–5] Another approach uses thermographic techniques with active infrared pulses, which have shown good results for lacquer coatings by measuring the temperature curve over time.[6] Two-dimensional applications of this technique are currently a topic of research.[7,8] Eddy-current-based thickness-measurement devices are well understood and are especially used to inspect lacquer coatings on conductive substrates. Nowadays there are dedicated pointwise measuring eddy-current devices available.[9] For lacquer coatings on non-conductive substrates, microwave-based techniques are capable of precise measurements. This technique is effective for lacquer coatings on CFK-based substrates.[10] White-light interferometry is another powerful analytical method which has been used for at least a decade to determine the thicknesses of thin transparent dielectric coatings[11,12] or dispersive media.[13] The thickness of the sample is calculated from the specific interference pattern which is created by interfering light beams reflected from the surface of the coating and the substrate. Therefore, this method is not suitable for lacquer coatings that are not transparent in the spectral range of visible light. Furthermore, there is a new approach to measure the thickness of lacquer coatings with the aid of infrared spectroscopy using high-precision spectrometers. A principal component analysis is performed and the resulting data is compared to a reference set of spectral data of lacquer samples with different thicknesses.[14] This technique has already successfully been used for UV-cured acrylic coatings,[15] but not in two dimensions. The thickness of acrylic coatings is in the range of a few micrometres (5–20 μm) and is much lower than the typical thickness of the lacquer coatings used for the surfaces of wind turbine blades. The thickness of these coatings is in the range of several hundred micrometres (150–300 μm). In summary, there are different, reliable analysis methods which realise precise thickness measurement, but there is a lack of a two-dimensional analysis method for lacquer coatings used in the wind turbine blades technology.

Theoretical fundamentals

Infrared spectroscopy is a powerful analytical method and has been used for different applications in the past. One of the main reasons is that the characteristic absorption of a material can be used for identification and, with reference data, for quantitative analysis.[16] The absorption in the NIR region is much lower compared to the mid-infrared, resulting in a higher optical penetration depth. Therefore, it is possible to analyse thicker sample layers. The spectral data collected in NIR spectroscopy contains mainly overtones and combination modes. For polyurethane-based lacquer coatings, carbon–oxide double bonds, carbon–hydrogen-, nitrogen–carbon- and oxide–hydrogen-groups produce the characteristic absorption bands. This superposition of vibrations produces broad absorption bands which require complex statistical analysis algorithms to obtain precise results.[17]

The main characteristic absorption band used for thickness analysis of polyurethane lacquer coatings reaches from 1650 nm to 1720 nm in the NIR region, as shown in Figure 2. Infrared spectroscopy has not been used to provide a two-dimensional thickness distribution of lacquer coatings before. The introduction of hyperspectral cameras created the possibility of measuring the spectral data of a line with a spectrum at each pixel. Partial least squares (PLS) analysis algorithms assign a thickness to each pixel and spectrum, respectively. Combined with a scanning movement it becomes possible to obtain a two-dimensional thickness distribution in a fast and precise measurement.

Developed measuring device

The main component of the developed measurement system is a hyperspectral camera which is mounted on a mobile scanning device. This device can be moved horizontally to adjust the distance between sample and camera objective to 2.50 m. The vertical translation axis is used for scanning. The scanning speed can be regulated. The rotation axis is used to adjust the angle between the illumination system and the sample surface. A drawing of the developed scanning device is shown in Figure 3. The spectra were recorded with a KUSTA1.9MSI hyperspectral camera (LLA, Berlin, Germany). The instru-
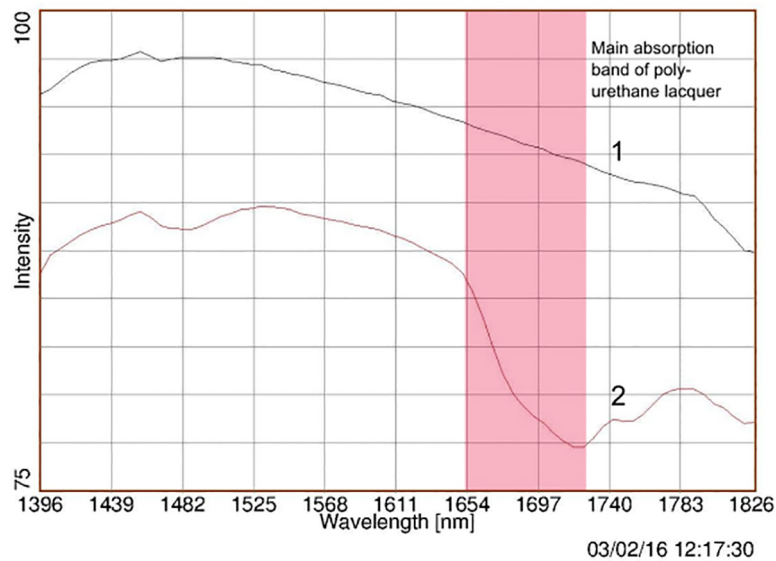
Figure 2. Infrared spectrum of the aluminium oxide substrate layer, (1), and the polyurethane lacquer coating, (2), applied on the underground layer. The main absorption band can be observed.

ment contains a concave grating and an InGaAs-based sensor array cooled to –8°C. This hyperspectral camera works as a line camera with 192 tracks per line and 256 pixels per track and was set to cover a spectral range of 1320–1900 nm with a spectral resolution of 8 nm. The SP-OLES30 objective lens (LOT-QuantumDesign GmbH, Darmstadt, Germany) with a focal length of 30 mm was used to focus onto the surface of the lacquer sample resulting in a 1 m width of the illuminated and observed line. Therefore, the observed area per pixel has a width of approximately 3.9 cm. This setup was mounted on a three-axis system to allow a scanning movement of the camera as well as a rotation of the illumination system. The

distance between the lacquer sample and the hyperspectral camera was set to 2.50 m resulting in an optical path length of 5.00 m due to the reflection geometry. The lacquer sample was illuminated by three 750 W gold-coated, quartz halogen flood-lights with a combined power of 2250 W arranged in specially developed reflectors to focus the light beam exactly on the observed line. The illumination system was developed by the Institute of Electromechanical and Electronic Design (IFTE, TU Dresden). The spectra were taken in reflection mode with an angle of 8° between illumination system and lacquer sample surface to avoid total reflection. The scanning speed of the instrument was set to 50 mm s^{-1} and 830 scans per second were performed.

Results and discussion

The developed measuring device can be seen in Figure 4. The photograph shows the device with active illumination system performing a measurement. In NIR spectroscopy, quantitative analysis of spectral data needs to be carried out by multi-variate calibration methods such as a PLS regression model.[18] This model has to be adapted to the spectral variation in the data and the parameter of interest, in this case the thickness of the applied coating layer.

Ten lacquer samples with different lacquer layers varying from 20 μm to 300 μm were prepared for calibration. To prove that the technique is able to deliver a two-dimensional thickness distribution over the complete sample surface, it was necessary to have macroscopic sample sizes, therefore the sample size was chosen to be 100 × 150 mm. For the creation of a precise calibration model the samples were split into two sets; one for calibration and the other for validation. The spectral range of the hyperspectral camera was limited to
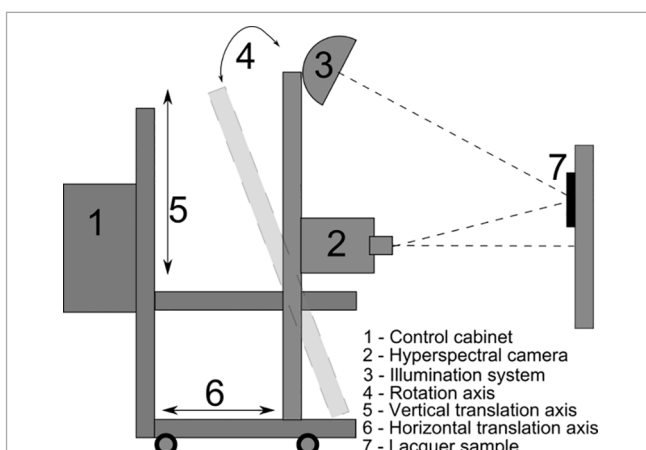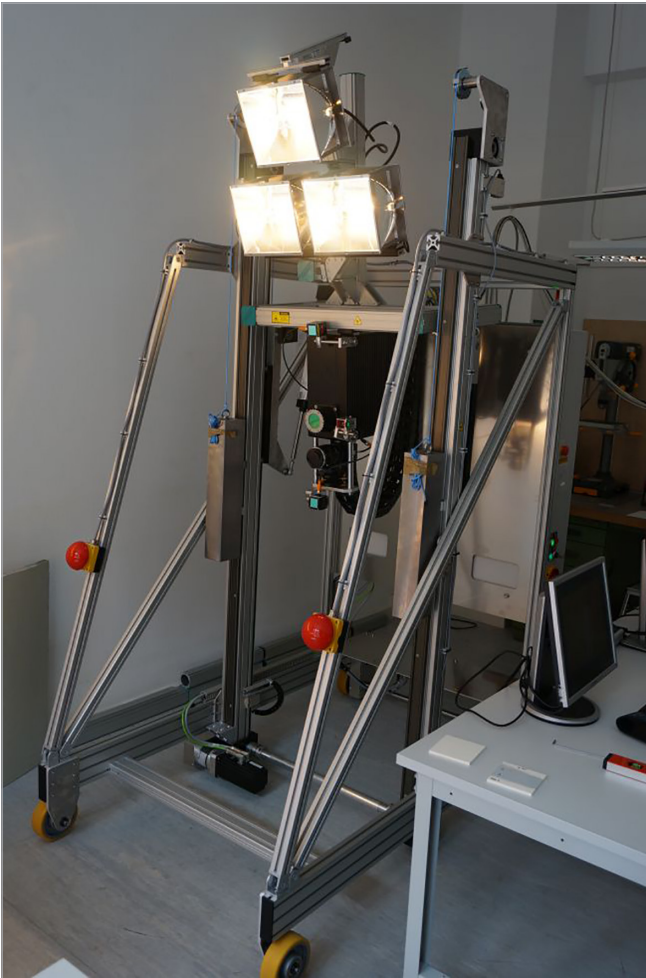

Figure 3. The developed scanning device is able to adjust the distance between sample and camera system, as well as the height of the camera system. The vertical axis is used for the scanning movement. The rotation axis enables the device to set the best angle between illumination system and sample surface for optimal spectral quality. The control cabinet is included in the mobile device.

Figure 4. Photograph of the developed mobile measuring device. The illumination system is active and the device is scanning.

Figure 5. PLS calibration for the thickness of polyurethane lacquer coating on a GFR substrate proves excellent matching.

1396–1826 nm to avoid noise and "bad pixels" which are more likely to occur in the spectral boundary area of the sensor. A pixel of the sensor is considered a bad pixel when it shows unacceptable behaviour, for example a suddenly changing value or the pixel's value being constantly zero or in saturation. The samples were mounted in front of the scanning device containing the hyperspectral camera and scanned. The spectral data for each pixel of the hyperspectral camera was analysed during the measurement with a PLS method including preprocessing. The preprocessing methods used, such as normalisation, first or second derivate, base line correction and linear or quadratic tilt, were tested and individually applied to the spectral data for ideal results. The correlation curve of the final calibration is shown in Figure 5. Due to the large amount of data, it was necessary to calculate the thickness value from the spectrum "on the fly" and the spectral data were not saved.

The control software of the hyperspectral camera hands the calculated thickness to the measuring computer which visualises the results. Therefore, the quality of the spectral data needs to be very high, especially with regard to bad pixels
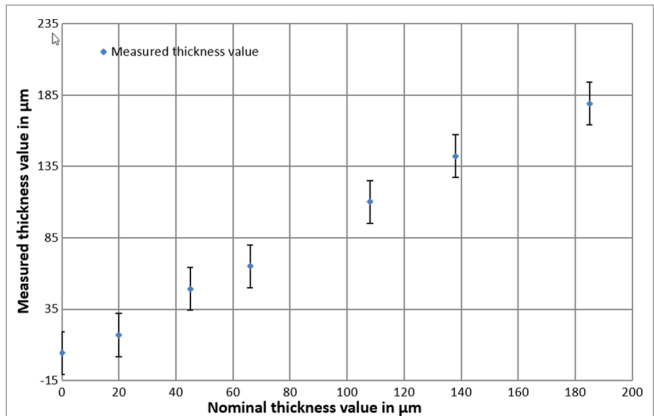
as well as signal-to-noise ratio. The number of bad pixels correlates directly with the exposure time; that is why the high power (2250 W) of the illumination system was needed to enable an exposure time of 1 ms per measurement. Three typical infrared spectra of the polyurethane lacquer with different thicknesses and normalised intensity used for the live analysis are shown in Figure 6. The dependence of the absorption strength of the sample thickness can be observed.

The performance of the developed model was tested by using two additional samples from the same manufacturer with different thicknesses within the thickness interval of the calibration sample set. The predicted thicknesses were compared to the actual thicknesses determined with microscopic cross-section measurements with the PAINTXPLORER 548 from ERICHSEN GmbH & Co. KG. As shown in Figure 7, it was obvious that the lacquer-coating thickness was not homogeneously distributed within each sample and the different thicknesses could be easily distinguished.
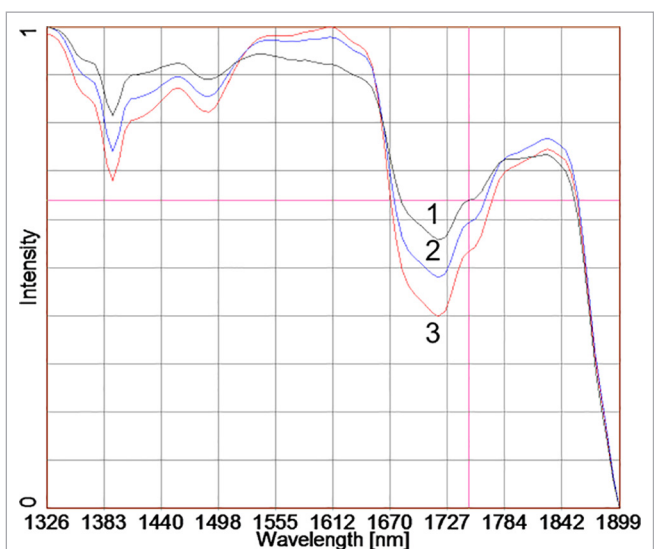

Figure 6. Three infrared spectra of polyurethane lacquer coating with different thicknesses. (1) 55 μm, (2) 167 μm, (3) 300 μm.
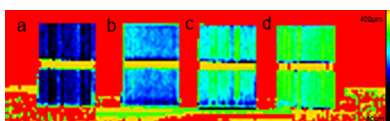
Figure 7. False-colour representation of lacquer-coated samples with different thicknesses in front of a gel coated plate (red area), (a) 100 µm, (b) 180 µm, (c) 270 µm, (d) 350 µm.

To show the practical use of the developed system, it was necessary to apply the calibration model on samples which are actually used in the industry. A sample from a wind turbine blade which had been used in the field was available. This sample was manufactured on a glass fibre reinforced (GFR) substrate layer and, as it had been lacquered by a varnishing machine, it was expected to be of high homogeneity. The actual thickness was identified with an ultrasonic measuring device to 175 µm. This sample was scanned and the analysis result is shown in Figure 8.

There is a stripe pattern observable in the figure which is an artefact from the hyperspectral camera. Due to the high exposure time, the different pixels of the camera produced slightly different intensity values.

A false-colour representation was used to visualise the analysis results. Even though the samples were professionally manufactured, it was obvious that the lacquer coating was not as homogeneous as expected. Therefore, a hyperspectral camera could be used to reveal the homogeneity and thicknesses of the lacquer coating for applications with high requirements for homogeneity.

Summary and conclusion

In this paper, it was demonstrated for the first time that it is possible to use a hyperspectral camera in a scanning device to measure the thickness of polyurethane lacquer coatings two-dimensionally. Samples with thicknesses ranging from 20 µm to 300 µm were studied. A multivariate chemometric method
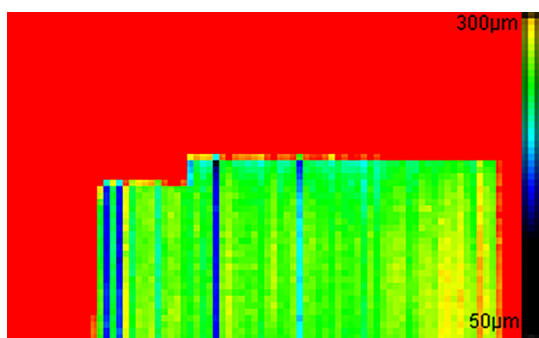

Figure 8. False-colour representation of wind turbine blade sample with lacquer-coating thickness of 175 µm on GRP ground layer in front of a gel coated plate (red area). The inhomogeneous thickness distribution is obvious; the left upper cut-out corner is due to the sample shape.

was used to calibrate the analysis algorithm. Analysis was carried out by an algorithm based on a PLS model. It could be shown that the results can be predicted with an error of approximately 10 µm. Spectral data were recorded with a high scanning speed of 55 mm s^{-1} and a linewidth of 1 m. A high correlation between the predicted NIR-based thicknesses and thicknesses measured by classic methods was obtained. In summary, NIR spectroscopy has been proven to be able to monitor polyurethane coating thickness two-dimensionally with high precision while delivering homogeneity information on the fly with a fast analysis speed. Consequently, this method could be effectively used for quality control in lacquer manufacturing technology for large surfaces.

Possible applications range from the aviation industry, to wind power plants, to the shipping and yacht industries. Another potential use could be monitoring the wearing process of the turbine blades. Changes in the chemical composition of the lacquer surface will directly be obtainable via NIR spectroscopy and could be monitored easily in the field in the future assuming that the development of hyperspectral camera systems progresses to produce smaller devices.

Currently, hyperspectral camera systems are big and need to be cooled. Anticipating smaller and more efficient hyperspectral camera systems, it is imaginable to create a hand-held mobile scanning device which would be a major objective to enable a very powerful and convenient way of on-site control of the quality of the lacquer layers. Therefore, it would be necessary to miniaturise the size of the scanned area to minimise the required illumination as well as the size of the hyperspectral camera. Such a device would create a broad field of possible usages of the developed measurement method.

Acknowledgements

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