New concepts for 100% inspection of coated and surface treated webs

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Motivation
Introduction Hyperspectral Imaging (HSI)

HSI for surface and thin film inspection
- Data evaluation by „hard & soft modeling“
- HSI for inspection of
  - Al₂O₃ coatings (slot die coating)
  - DLC coating @ steel
  - sheet resistance imaging

HSI for inline inspection of web properties
Introduction Hyperspectral Imaging (HSI)

- HSI = combination of spectroscopy and imaging
  - each pixel is characterized by the spectrum of the reflected/transmitted beam
  - capable for the UV-VIS-NIR spectral range

- analysis and evaluation of spatial differences of
  - chemistry
  - morphology
  - topology

"Hypercube" (raw data) → R, T = f(x, y, λ)
# Information content of HSI

## Monochrome

- **2^8 = 256 tonal values**

## RGB

- **(2^8)^3 = 16,7 Mio. colors**

## Hyperspectral

- **(2^8)^1000 tonal values**

## Image analysis

- Texture, topology, shape, structure

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Hyperspectral Imaging setup

- pushbroom imaging (line scan)
- camera / detector
- lighting
- lenses
- motion system
  (the moving web itself)
- software
  (data acquisition & evaluation)

imanto® pro
Lighting for reliable HSI measurements

<table>
<thead>
<tr>
<th>Position</th>
<th>2 cm</th>
<th>8 cm</th>
<th>15 cm</th>
<th>22 cm</th>
<th>28 cm</th>
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</thead>
<tbody>
<tr>
<td><strong>Power level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 V</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>8 V</td>
<td>7.4</td>
<td>7.4</td>
<td>7.2</td>
<td>7.2</td>
<td>7.5</td>
</tr>
<tr>
<td>12 V</td>
<td>29.1</td>
<td>28.1</td>
<td>28.0</td>
<td>28.0</td>
<td>29.0</td>
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</table>
Performance of coated web is influenced by:

1. stack composition
2. inclusions
3. cracks and scratches
4. (pin) holes
5. substrate defects
6. contaminations
7. material gradient
8. thickness gradient
Hyperspectral imaging for thin film inspection

Hard modeling approach

optical model:
CAUCHY: n, k
DRUDE: resistivity

reflectance (R)
transmittance (T)

optical model

Fresnel equations

transfer-matrix

\[
\begin{pmatrix}
M_{11} + k_2 k_3 M_{33} + (i(k_2 M_{23} - k_3 M_{13})) \\
M_{12} + k_2 k_3 M_{32} + (i(k_2 M_{22} + k_3 M_{12}))
\end{pmatrix}
\]
Hyperspectral imaging for thin film inspection

**EXAMPLE:** Al$_2$O$_3$ layer @ stainless steel*
- catalyst layer for CNT growth
- battery electrodes,
- roll-to-roll coating

**TASKS:**
- layer thickness monitoring of Al$_2$O$_3$ coating
- Evaluation of defects

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* F. Gruber, P. Wollmann, B. Schumm, W. Grählert, S. Kaskel; *J. Imaging, 2016, 2(12)*; doi: 10.3390/jimaging2020012

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Al₂O₃ layer monitoring

statistical modelling

reference: ellipsometry

Hyperspectral imaging
thin film inspection

setup a model

reference samples

hyperspectral measurement

measured hypercubes

pre-processing

ROI extraction

pre-processed mean spectra

PLS / PCR

PCR / PLS model

real layer thickness

ellipsometric measurement

measured hypercubes

pre-processing

pre-processed hypercube

PLS / PCR

prediction

new sample

hyperspectral measurement

measured hypercubes

pre-processing

pre-processed hypercube

PLS / PCR

thickness image

results spectroscopic ellipsometry

<table>
<thead>
<tr>
<th>parameter</th>
<th>thickness / nm</th>
<th>Aₙ</th>
<th>Bₙ</th>
<th>Cₙ</th>
<th>Aₖ</th>
<th>Bₖ</th>
<th>Cₖ</th>
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<tr>
<td></td>
<td>52.4 – 66.2</td>
<td>1.5827</td>
<td>0.0191</td>
<td>-0.0013</td>
<td>0.1359</td>
<td>0.3828</td>
<td>400</td>
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Hyperspectral imaging thin film inspection

- Al$_2$O$_3$ layer monitoring
- PCR and PLS modelling (regression)
- fast calculation in prediction → inline capability

<table>
<thead>
<tr>
<th>model</th>
<th>No. of latent variables</th>
<th>$R^2_C$</th>
<th>RMSEC</th>
<th>$R^2_{CV}$</th>
<th>RMSECV</th>
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</thead>
<tbody>
<tr>
<td>PLS</td>
<td>4</td>
<td>0.996</td>
<td>1.5</td>
<td>0.979</td>
<td>3.6</td>
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<tr>
<td>PCR</td>
<td>4</td>
<td>0.992</td>
<td>2.0</td>
<td>0.978</td>
<td>3.7</td>
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</tbody>
</table>

Soft modeling approach
Al$_2$O$_3$ layer monitoring

- result: thickness map
  (PLS model)

- CNT growth
- catalyst layer

- homogenous layer
- thin layer thickness
- coating defects and inhomogeneous layer

Al$_2$O$_3$ slot die coating
Hyperspectral imaging thin film inspection

- $\text{Al}_2\text{O}_3$ layer monitoring
- Calculation of quality control parameters

- $\text{CNT growth catalyst layer}$
- $\text{Al}_2\text{O}_3$
- Stainless steel

- $\text{Al}_2\text{O}_3$ slot die coating
Further examples for thin film imaging

Thin film imaging by hard modeling* of:
- layer thickness \((d)\)
- refraction index \((n)\) of layer
- absorption \((k)\) of layer

Diamor® thin film

DLC coating @ steel

* P. Wollmann, F. Gruber, W. Grählert; 2014, patent pending
Conductivity / sheet resistance imaging* by hard modeling

- spatial resolved sheet resistance
- Intrinsic material properties, (compared to 4-point measurement)

* P. Wollmann, E. Weißenborn, W. Grählert; 2015, patent pending
Prediction of water vapor transmission rate (WVTR) *

- WVTR ~ 10^{-2} \, g \, m^{-2} \, d^{-1}
- Soft modeling
- Feature extraction: PCR, wavelet transformation

HSI for inline inspection of web properties

Ca-test / HiBarSens®:

Measurement duration

WVTR (g/cm² * d):

- WVTR predicted by HSI
- WVTR reference (HiBarSens)

Barrier film

ZnSnOₓ

PET

* P. Wollmann, F. Gruber, W. Grählert; 2015, patent pending

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Conclusions

- spatial resolved evaluation of coated substrates (e.g. webs)
- contactless measurement principle
- Derivation of quality control parameters

- HSI technology for inline monitoring
  - thin film thickness, defects
  - sheet resistance of layers

- fast WVTR prediction of barrier webs
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Dipl.-Ing. Oliver Throl

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Thank you for your kind attention!

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