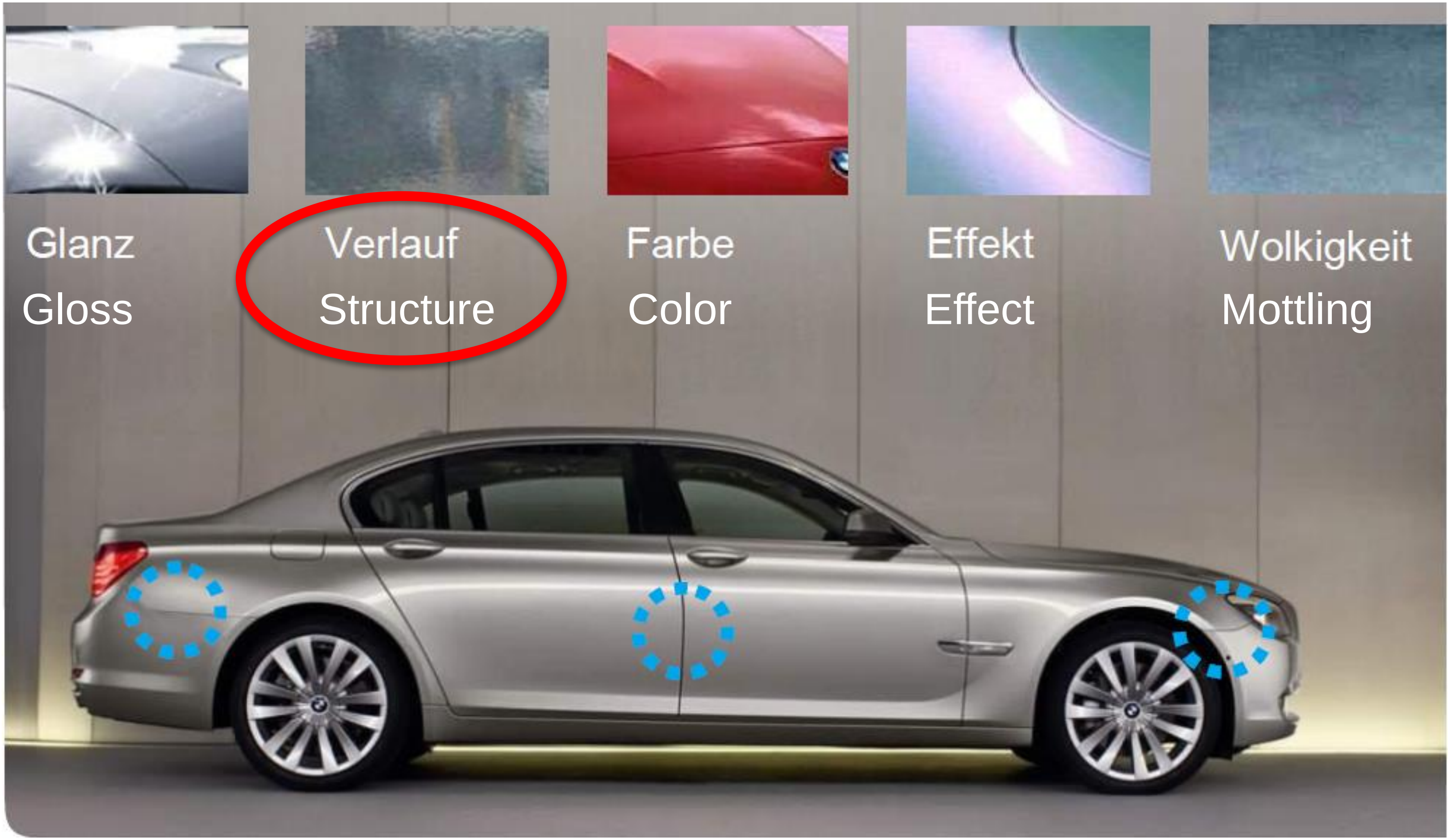
Origins of the Formation of Surface Structures on Coating Films

Matthias Schneider, Christian Hager[1)], Ulrich Strohbeck, Oliver Tiedje

Department of Coating Systems and Painting Technology,
Fraunhofer Institute for Manufacturing Engineering and Automation IPA,
Stuttgart, Germany

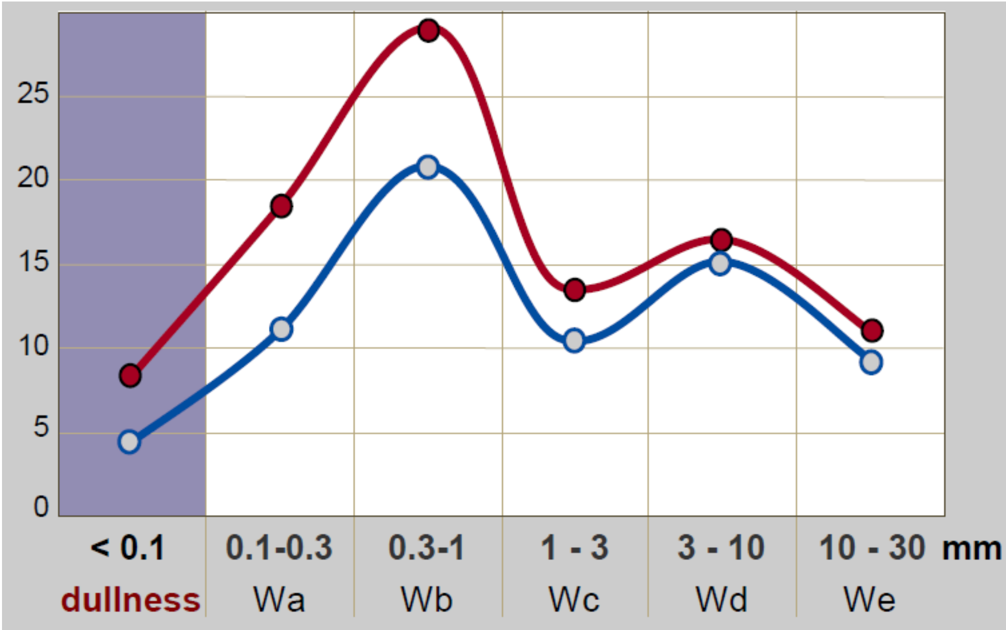
[1)] also Graduate School of Excellence advanced Manufacturing Engineering (GSaME),
University of Stuttgart

Components of paint film appearance



Source: BYK

Classification of surface structure in wavelength bands Wa – We



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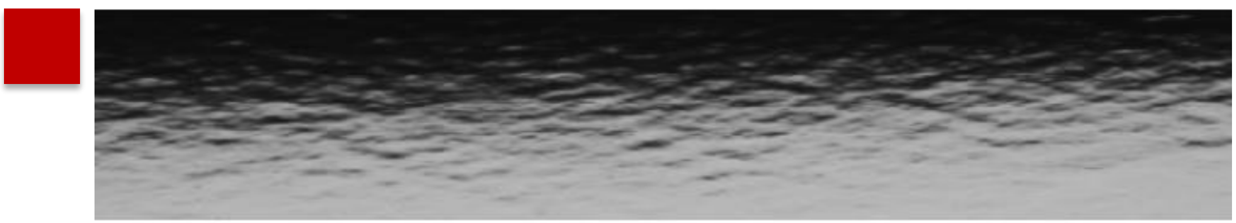
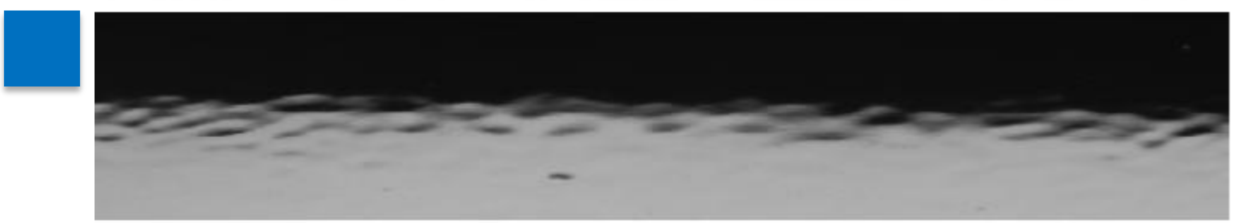




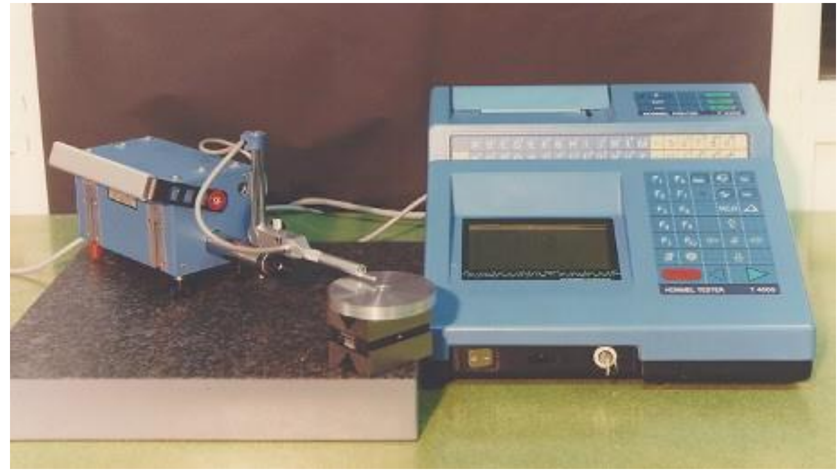
- Different characteristics of wavelength distribution result in varying visual impressions
- Typical wavelength of orange peel: 1-10 mm

Measurement and evaluation: *wave-scan* (BYK), profilometry

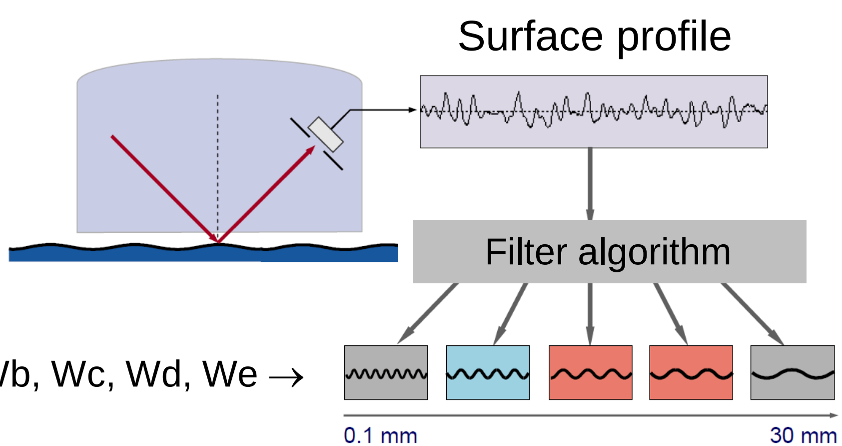
1. wave-scan

wave-scan dual (BYK-Gardner)

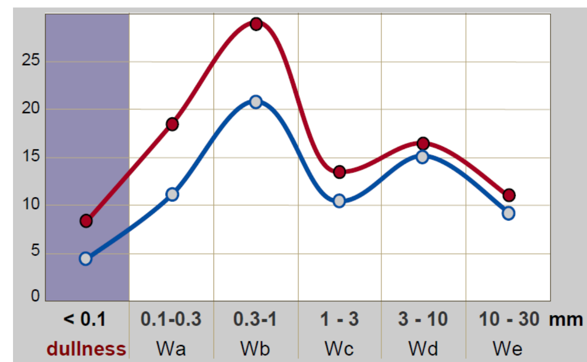
2. Profilometry (optical/tactile)



Tactile measuring device



Wavelength bands Wa, Wb, Wc, Wd, We →



Source: BYK

Appearance Assessment on Large Surfaces – Other Areas of Application

Examples: Coatings on airplanes, railway vehicles, buses, etc.

Coating on rail-way vehicle

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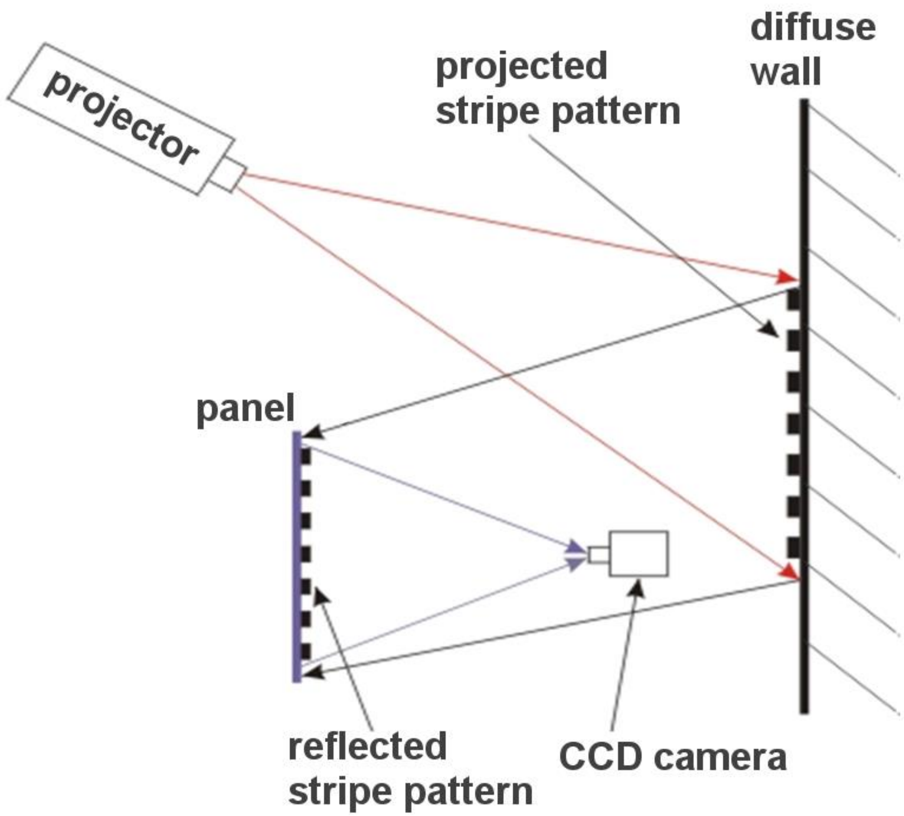
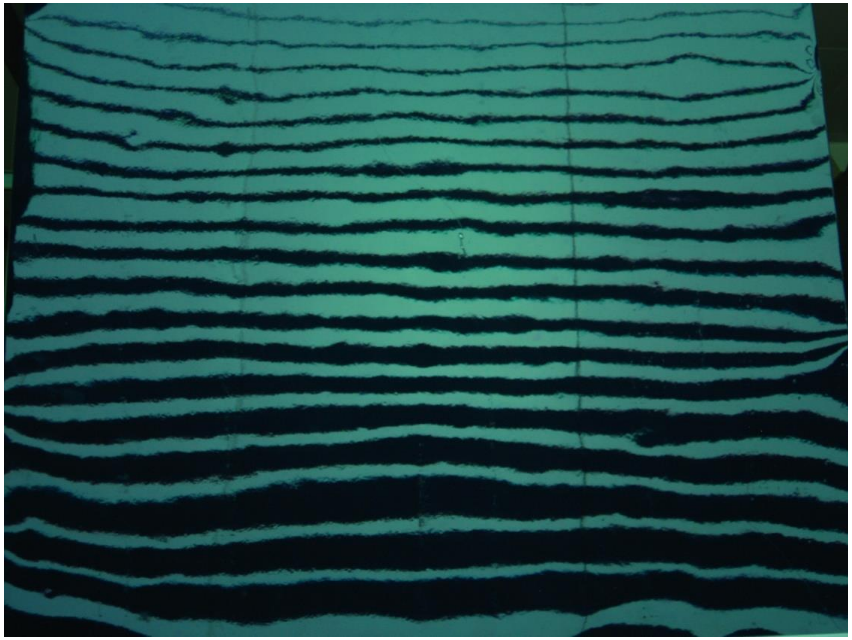
Detection of Ultra-longwave Structures by Deflectometry





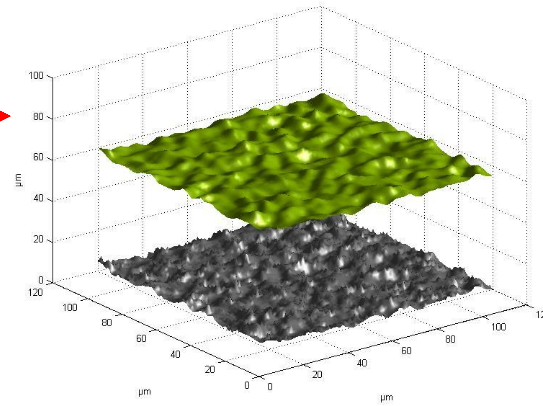
Reflected stripe pattern (panel ca. 1 × 1 m²)

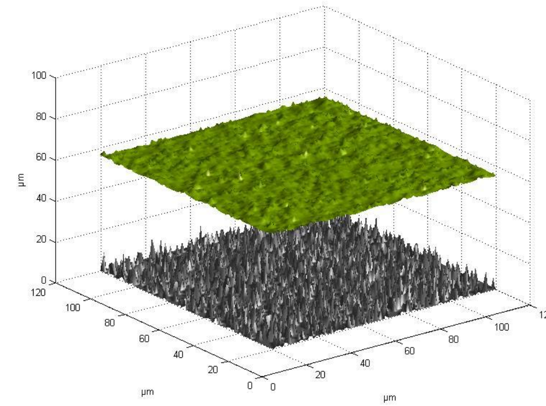
Paint film leveling and waviness

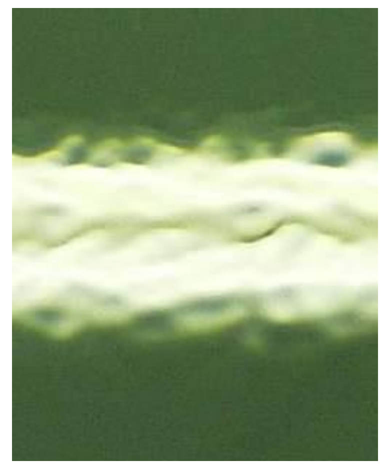
Influences on paint film structure in practice

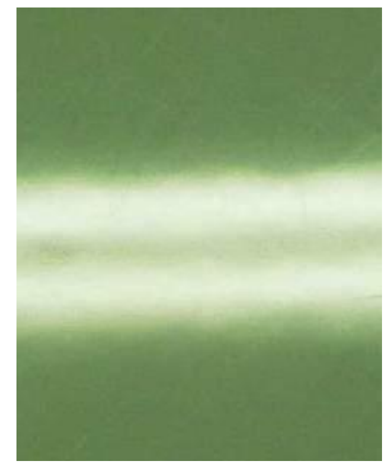
Different paint film structures result from, e.g.

- horizontal/vertical position
- different substrate structures →
- differing paint and application parameters







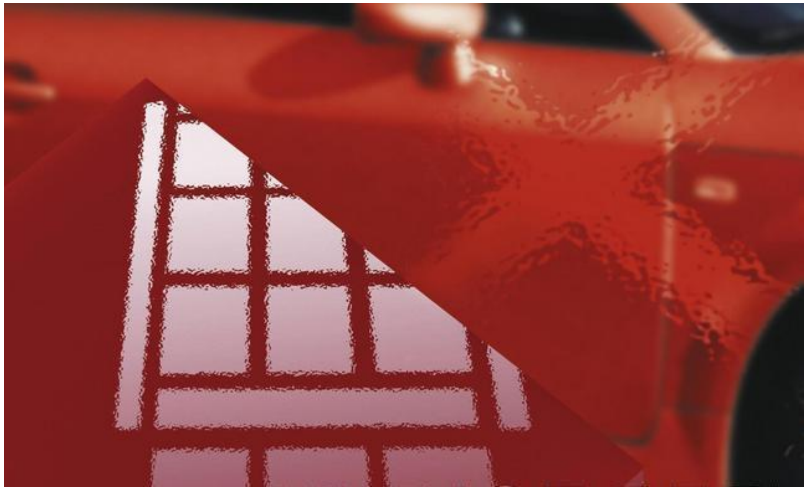


What is the practical importance of paint film leveling?

- Poor leveling hinders innovations, e.g.:
  - Light-weight / multi-substrate constructions
  - Primerless process / coating thickness reduction
    $\rightarrow$ stronger mapping (“telegraphing”) of substrate structure
  - Powder coating
  - …

Mechanisms for the formation of surface structures on paint films

1. **Structure formation by superposition of paint droplets**
2. **Leveling caused by surface tension driven paint flow**
3. **Influence of gravity on vertical leveling**
4. **Flow-induced structure formation on wavy substrates (vertical)**
5. **Structure formation by film shrinkage due to solvent evaporation**

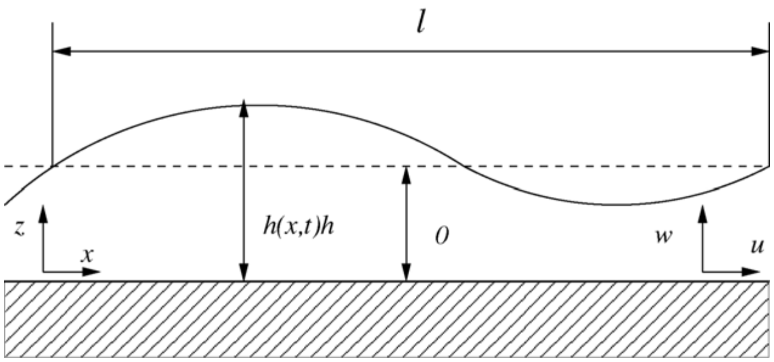


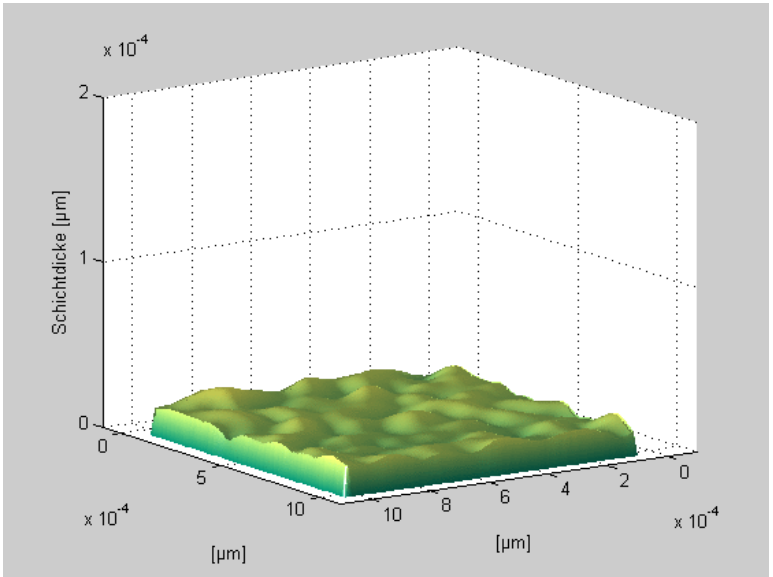
Source: BYK

Approach: New numerical model based on Lubrication theory

Lubrication **theory**

- Time-dependent solution of the ***Navier-Stokes equation*** for ***free-surface thin-film*** flow taking into account surface tension, viscosity, solvent concentration and gravity
- Numerical solving of the differential equations in three dimensions
- All mechanisms of paint film structure formation are included in the new simulation model





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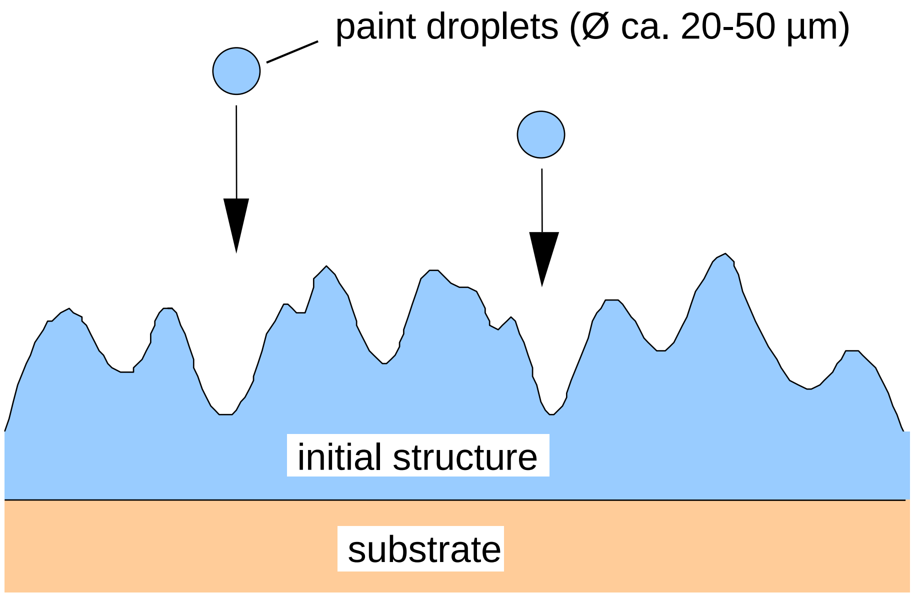
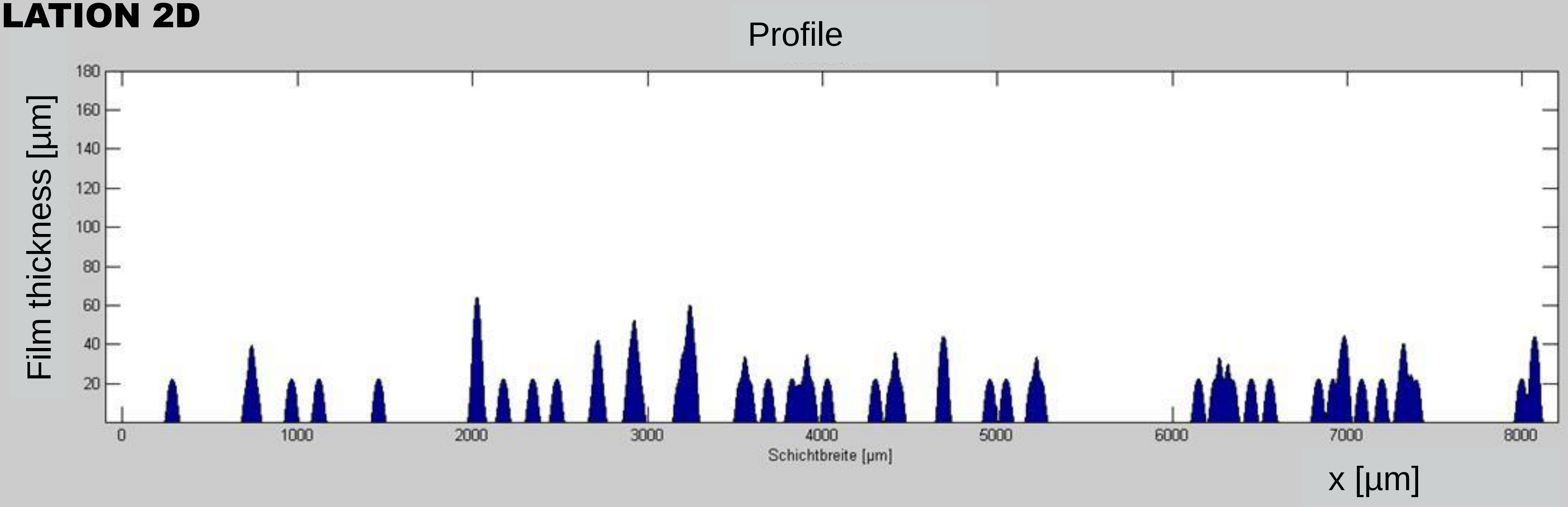
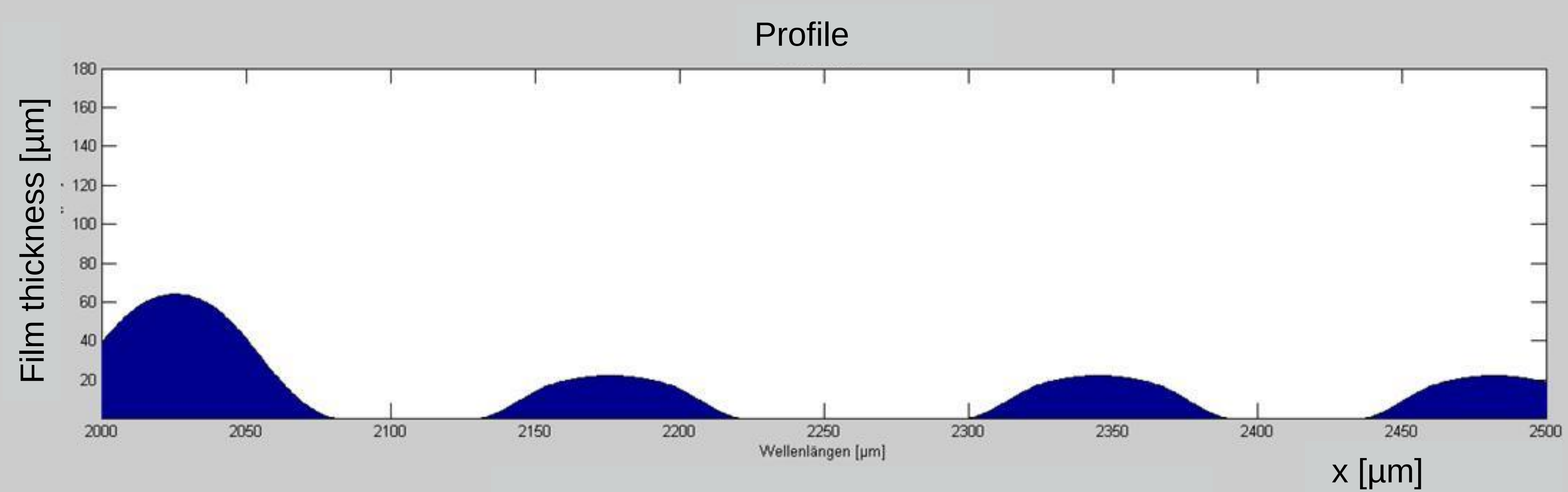
Structure formation by superposition of paint droplets

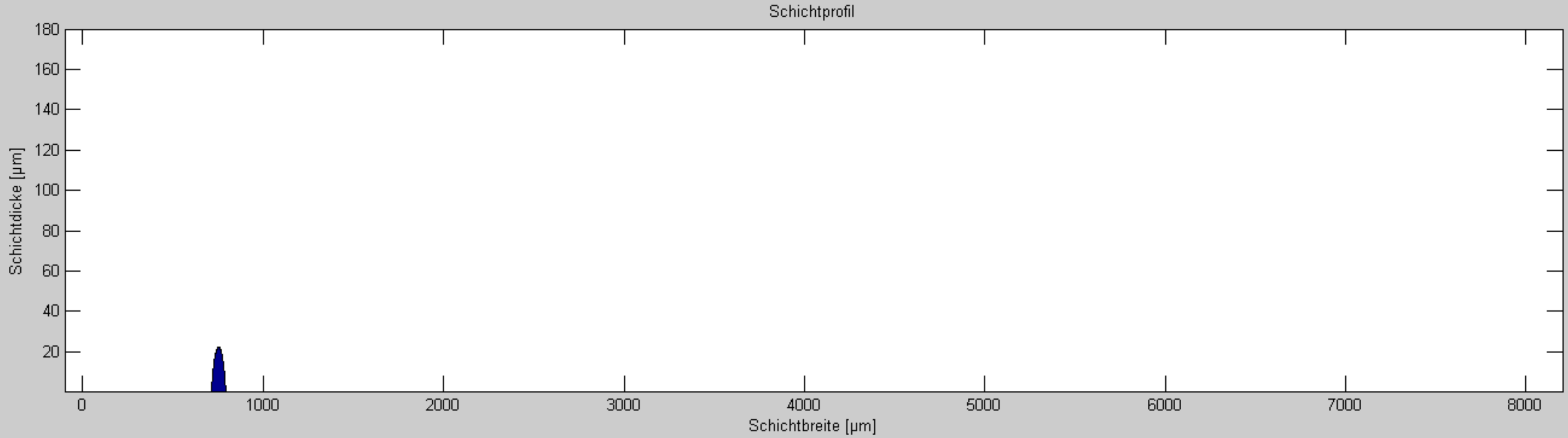


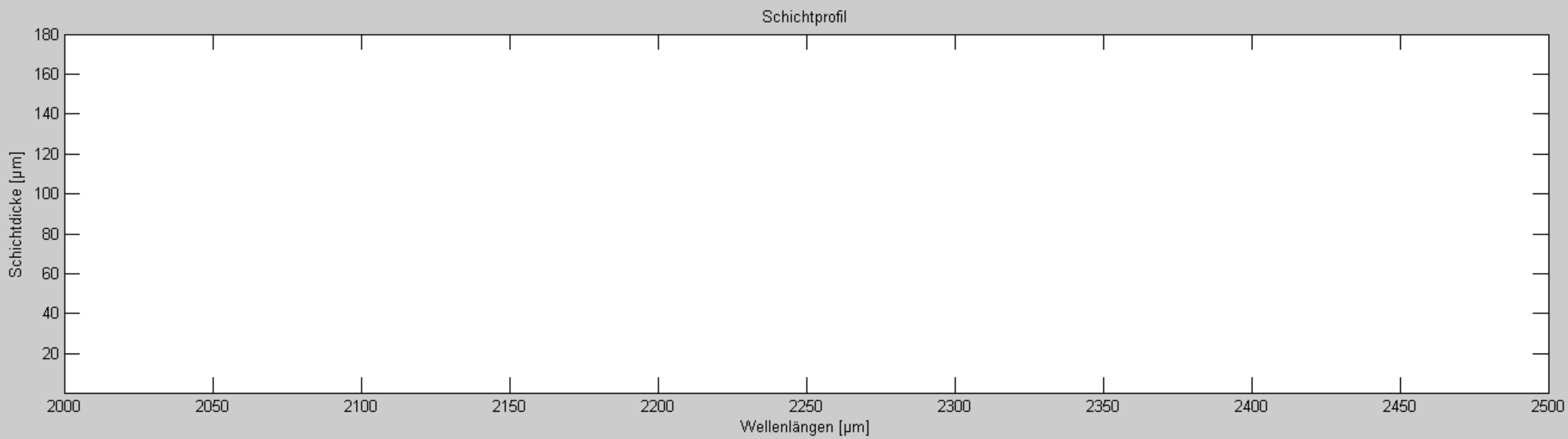
- **Stochastic superposition** of droplets on substrate surface
- **First published:** S. Tanno and S. Ohtani: Mechanism of Paint-Film Formation in Spray Coating, Intl. Chem. Eng. 19, 306 (1979)
- **Modeling** by *shot-noise* model
- ***Structure generation*** also in long-wavelength range $\lambda > 1$ mm ($\rightarrow$ much larger than droplet diameter)

SIMULATION 2D









Die mittlere Schichtdicke beträgt: 0.15336 µm
Die Rauheit beträgt: 1.6643 µm
Die Beschichtungszeit beträgt: 0 s
Die Anzahl der aufgetroffenen Lacktropfen beträgt: 1 Lacktropfen
Die Ablüftzeit beträgt: 0 s; in Minuten: 0 min; in Stunden: 0 h; in Tagen: 0 Tage
Die Schrittzeit während der Beschichtungsprozesses beträgt: 0.008 s
Die Schrittzeit während der Ablüftphase beträgt: 8 s

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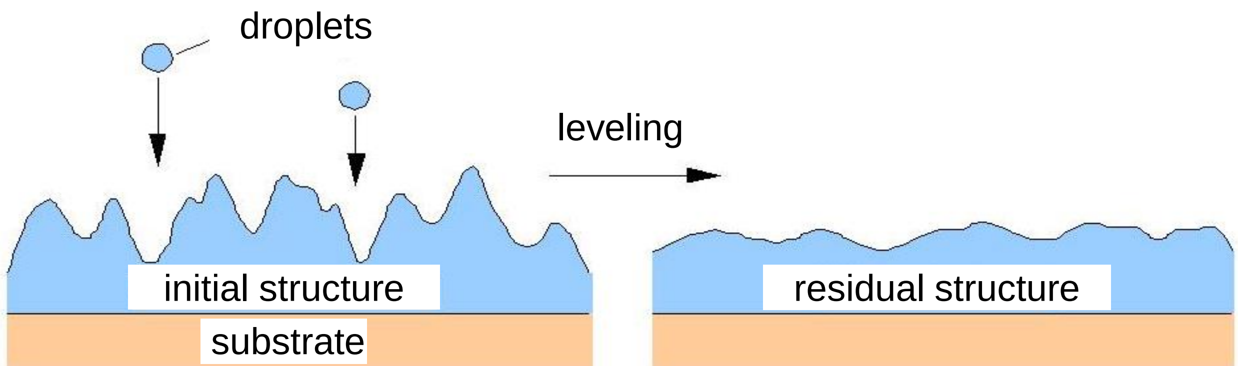
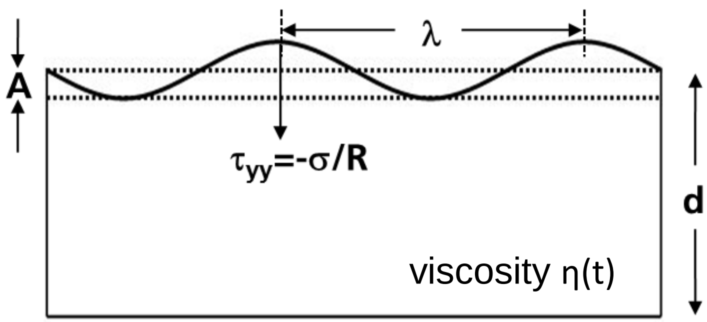
Horizontal leveling according to Orchard (2D)





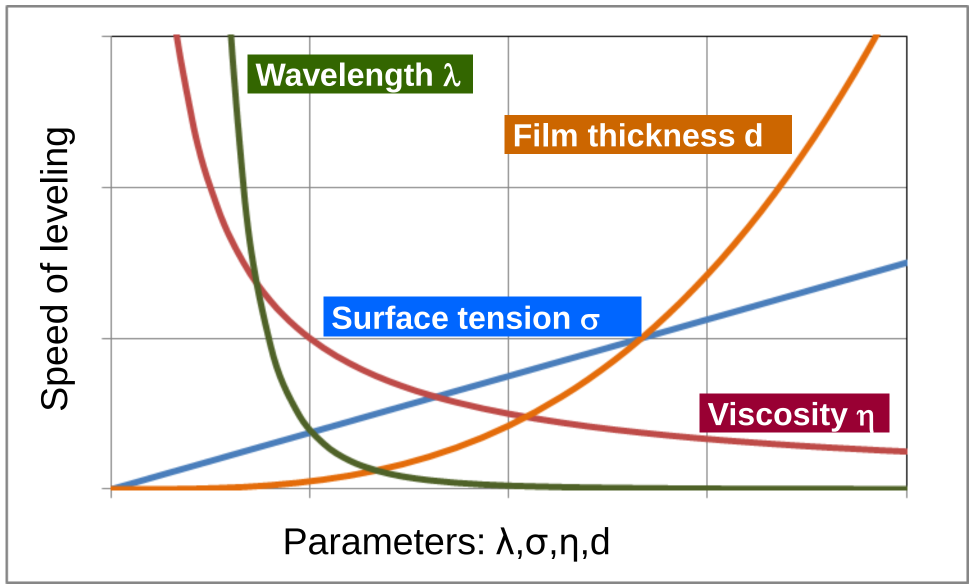
$$A(t) = A_0 e^{(-\nu \cdot t)}$$

$$\nu = \frac{16\pi^4}{3} \cdot \frac{\sigma}{\eta} \cdot \frac{d^3}{\lambda^4}$$

$$I_\eta = \int_0^\infty \frac{1}{\eta(t)} dt$$

ν speed of leveling

- Analytical solution of the Navier-Stokes equation (2D)
- **Surface tension σ** is the driving force for leveling
- **Viscosity η(t)** is limiting factor regarding leveling
- Layer thickness and wavelength have strong influence (3rd and 4th power)



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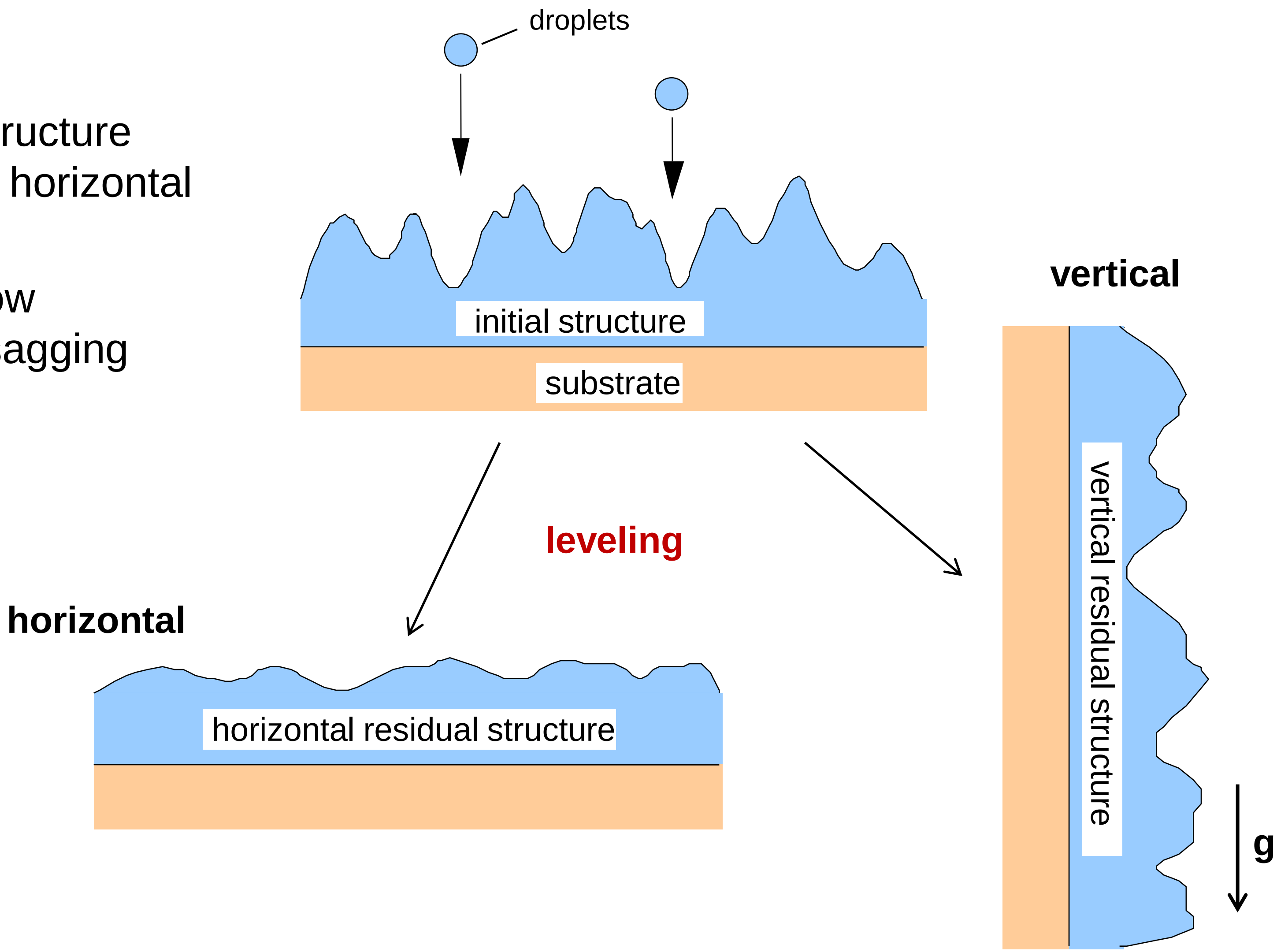
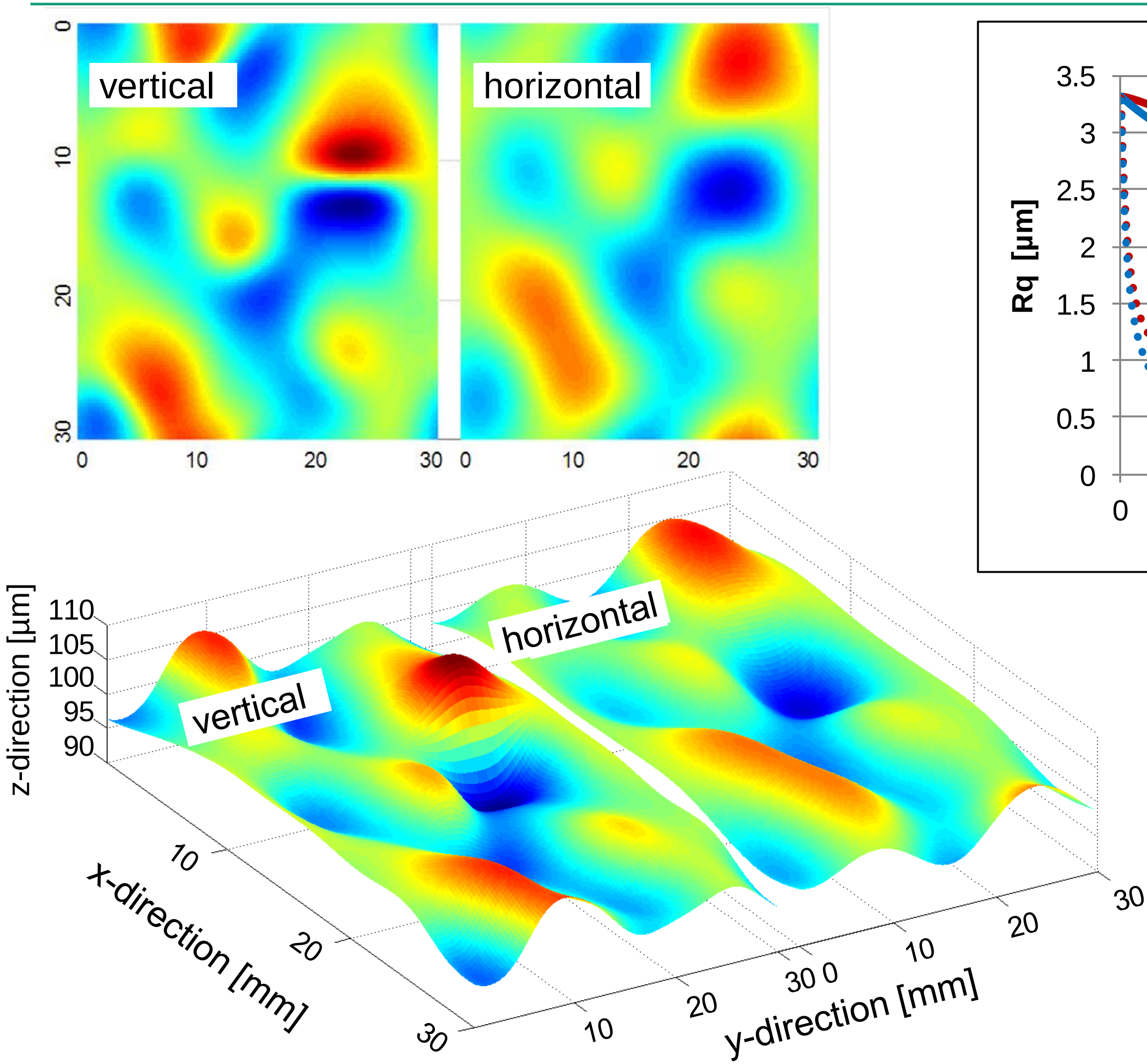
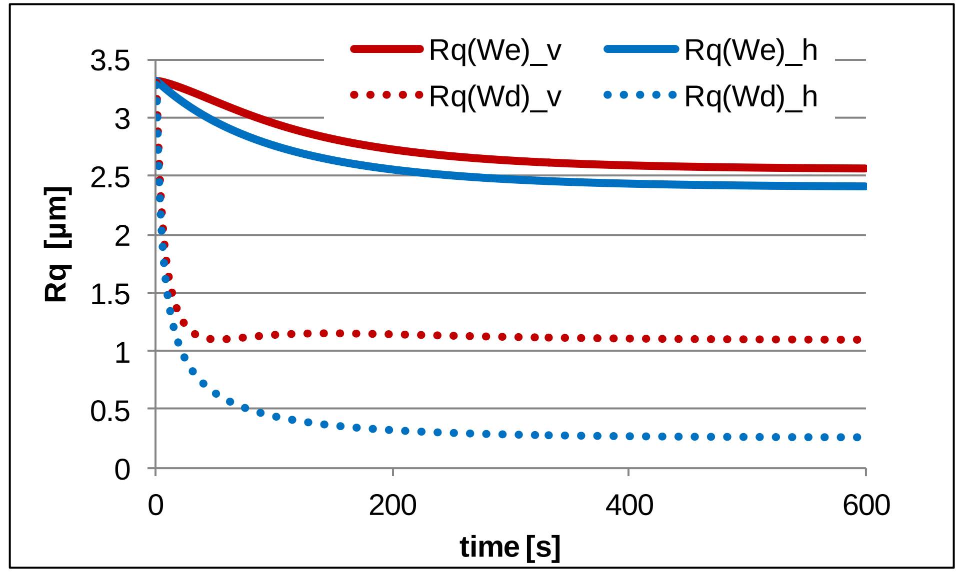
Influence of gravity on vertical leveling

- Vertical residual structure generally exceeds horizontal structure
- **Gravity** causes flow instabilities up to sagging



Influence of gravity on vertical leveling





Significant differences of structure formation in the wavelength ranges **Wd** and **We**

Mechanisms for the formation of surface structures on paint films

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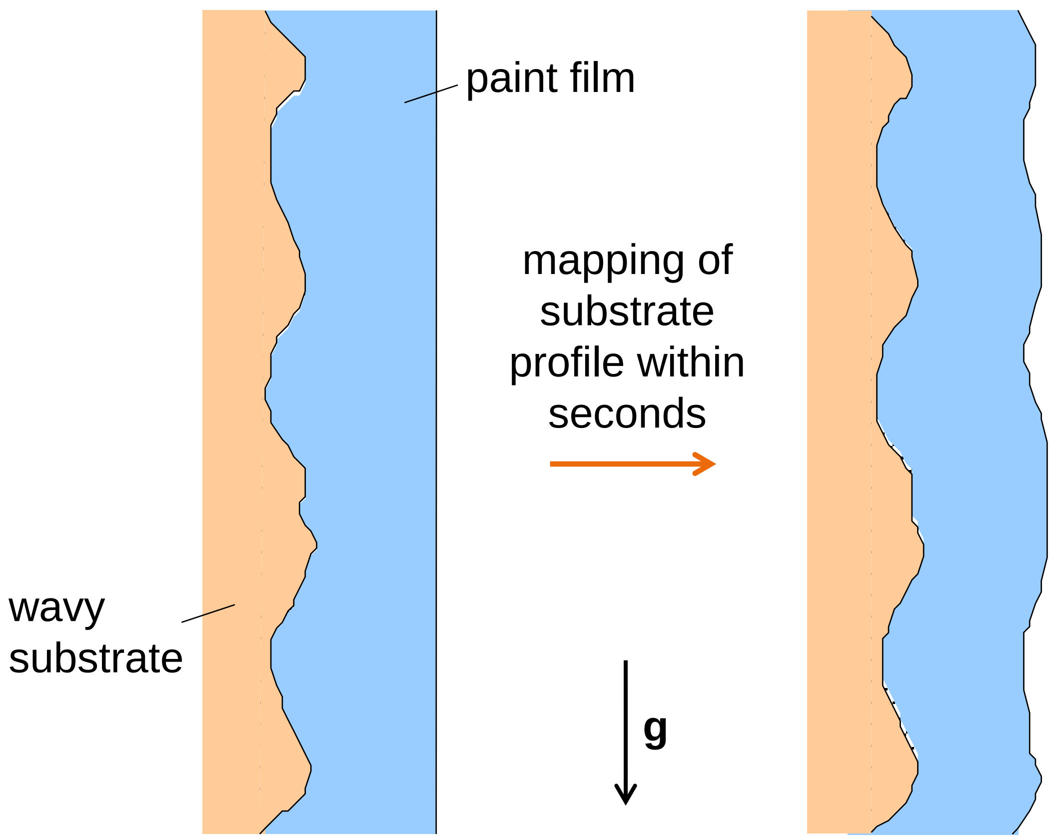
Flow-induced structure formation on wavy substrates (vertical)



- K. A. Smith, R. J. Barsotti und G. C. Bell (1989): **Flow-Induced Surface Roughness** of High Solids Finishes on Vertical Substrates
- **Strong mapping** of structure in Wd and We band $\lambda > 3$ mm (mapping ratio nearly 1:1)
- **Important factor** for structure formation in multi-layer coatings

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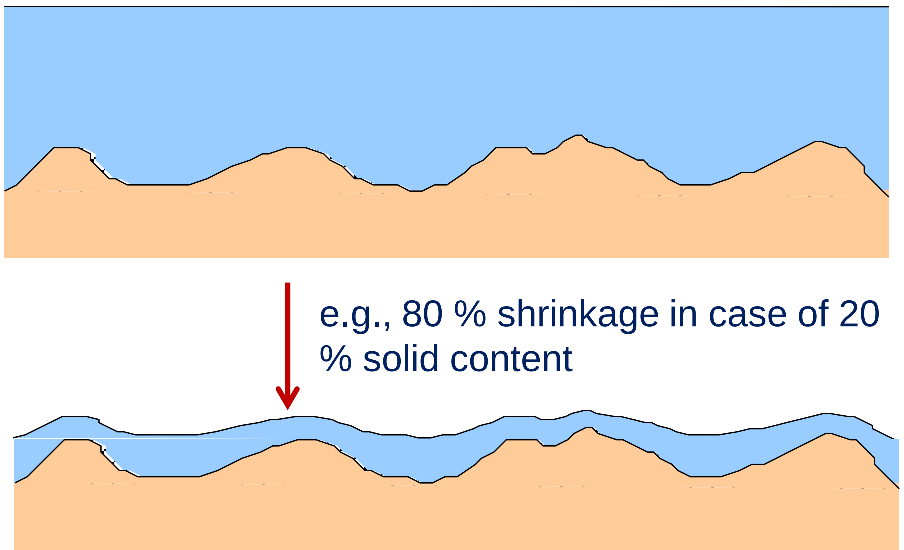
Structure formation by film shrinkage due to solvent evaporation



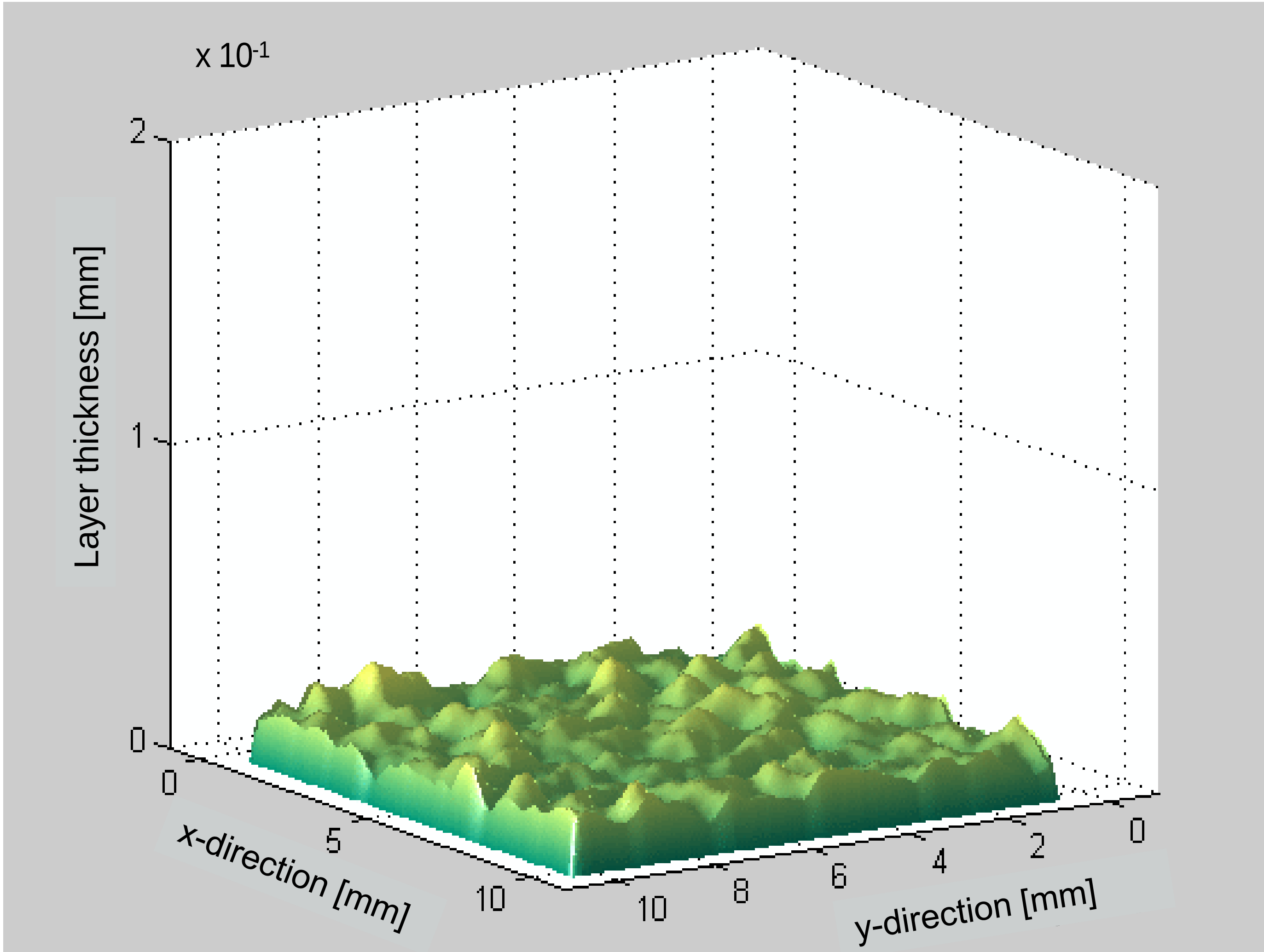
- ***Shrinkage*** ~ solvent content $c_{solv}^{vol} = (1- c_{solid}^{vol})$ of paint
- In case without flow:

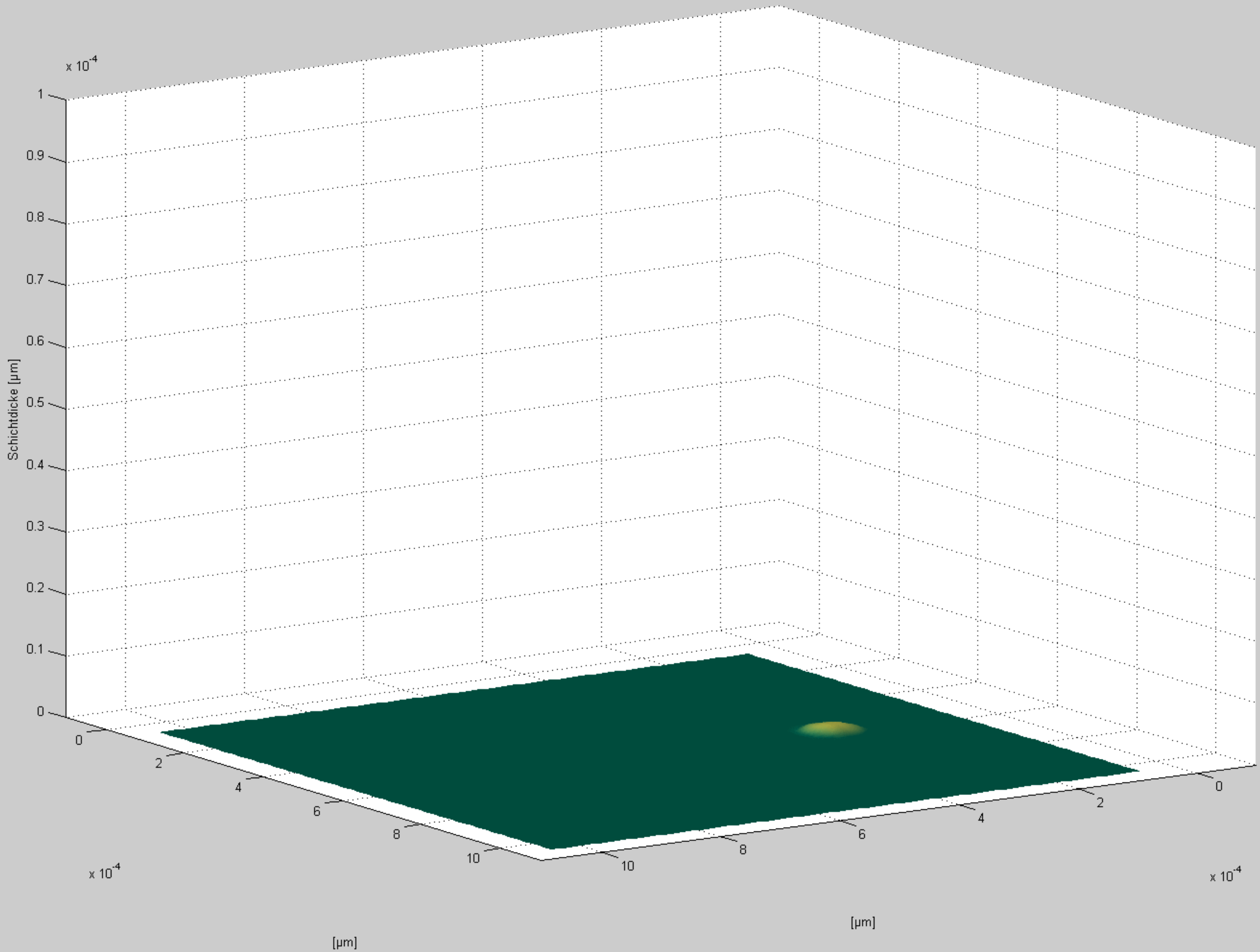
$$S_{paint} = (1 - c_{solid}^{vol}) \cdot S_{substrate}$$

- ***High solids*** show lower level of shrinkage structures
- Especially during ***baking*** structure formation by shrinkage is fully effective because the leveling of the generated structures is drastically limited due to the high viscosity of the paint film
- Effect on all wavelength ranges (also Wa and Wb)

Example of a 3D simulation

Simulation 3D

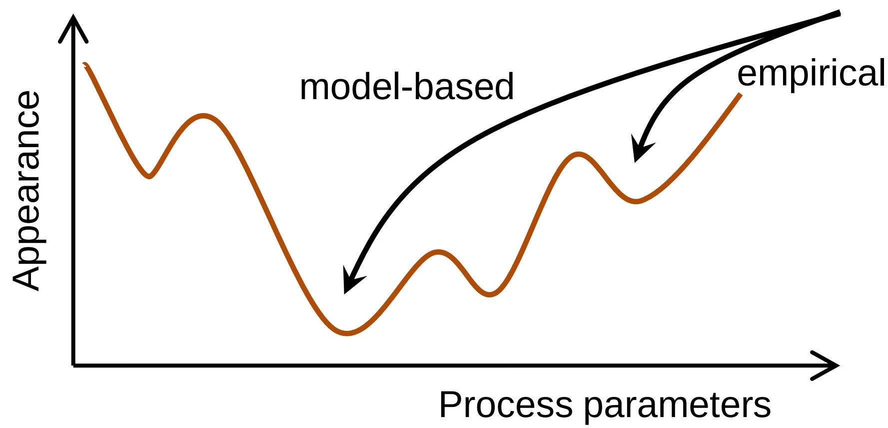




x 10^-4
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Schichtdicke [µm]
0
2
4
6
8
10
x 10^-4
[µm]
10
8
6
4
2
0
x 10^-4
[µm]

Result

- For the first time prediction of paint film leveling based on complete physical description
- Systematic paint formulation with regard to leveling properties
- Automatic process optimisation up to a global optimum

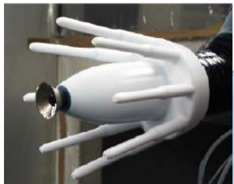


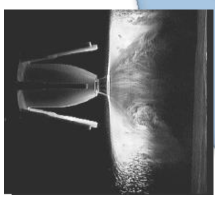
Steps to model-based optimisation

- Model helps to ***understand*** structure formation
- ***Influence*** of paint droplet spectrum, film thickness, viscosity/time curve, gravity, substrate structure, etc.
- Take into consideration ***strong wavelength dependence*** of structural behavior
- Often effects work in ***opposite directions*** (e.g., finer atomisation $\rightarrow$ higher viscosity)
- Control of process parameters by ***optimisation algorithms***
- Achieve ***desired structural spectrum Wa – We***, e.g., even on differing multi-substrate structures (right balance between Wa … We)
- Model also shows the ***limits*** for optimisation? Due to physical restrictions not everything is possible!

Current work and next steps...

Modeling of interrelations between intrinsic physical parameters and process parameters





Application parameters

bell velocity, spraying air, paint flow rate, spraying distance, etc.

Intrinsic physical model parameters

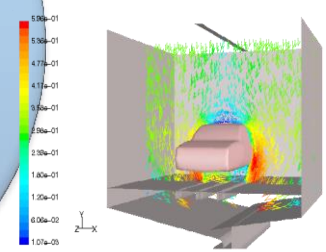
droplet spectrum, surface tension $\sigma(t)$, viscosity $\eta(t)$, solvent concentration $c(t)$, film thickness $d(t)$, substrate structure (Wa-We), density, gravity

Paint properties

temperature, mixture of solvents (high/low boiling), flow additives, anti-sagging additives, etc.

Spray booth/ oven parameters

temperature, relative humidity, air flow, etc.



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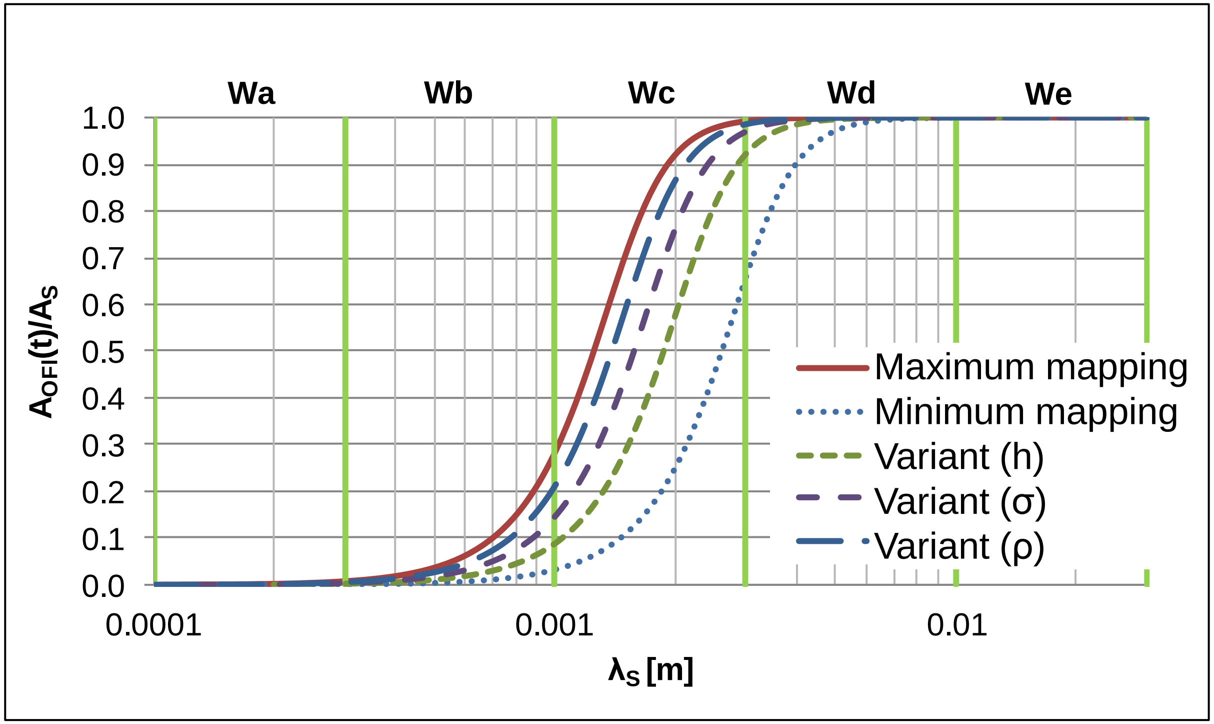
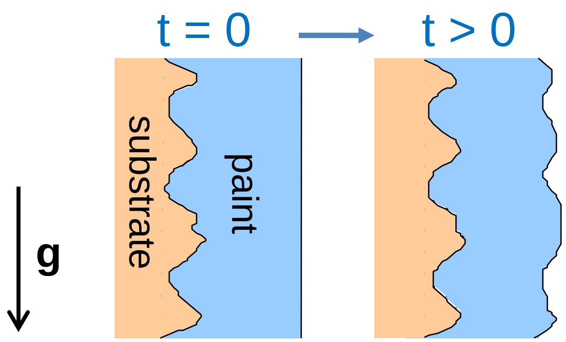
Thank you for your kind attention!

Flow-induced structure formation on wavy substrates (vertical)

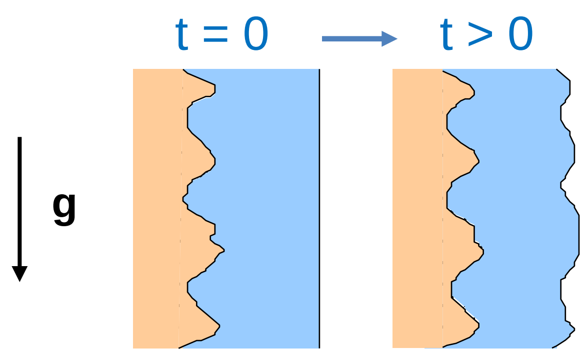




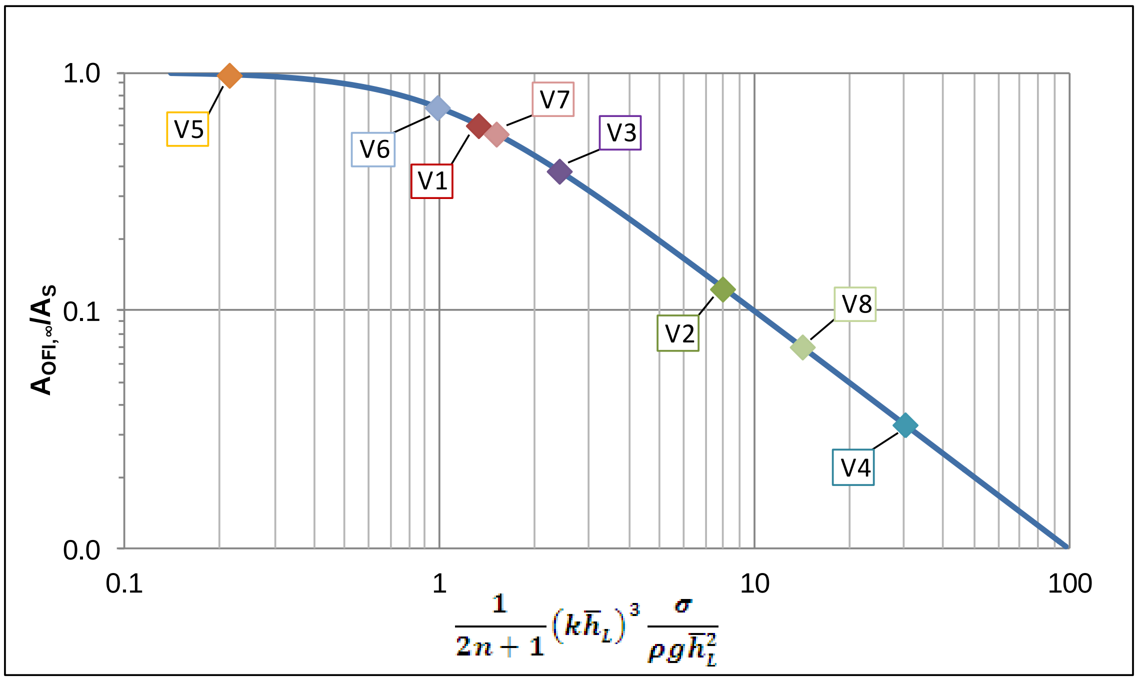
- Almost no effect on Wa and Wb band
- Effect on wavelength band Wc
- Nearly 100 % structure mapping in the Wd and We bands

Flow-induced structure formation on wavy substrates (vertical)

Verification of 3D-simulation



✓ **In accordance with 2D-analytical solution**
by K. A. Smith, R. J. Barsotti, G. C. Bell, Proc. XIV Intl. Conference in Organic Coatings Science and Technology, 1989



Variante	A_S [µm]	λ_S [m]	h_L [m]	σ [N/m]	ρ [kg/m³]
V1	2.36	1.82E-03	1.90E-05	0.050	1000
V2	2.36	5.81E-04	3.00E-05	0.008	1300
V3	2.36	2.50E-03	1.00E-04	0.040	900
V4	2.36	5.00E-04	6.00E-05	0.009	1200
V5	2.36	5.81E-03	1.00E-04	0.050	1000
V6	2.36	3.50E-03	1.00E-04	0.050	1000
V7	2.36	2.80E-03	9.00E-05	0.035	800
V8	2.36	6.00E-04	4.00E-05	0.010	1100

A_{OFI} = Amplitude Structure Paint Film
λ_{OFL} = Wavelength Structure Paint Film
A_S = Amplitude Structure Substrate
λ_S = Wavelength Structure Substrate
h_L = Paint Film Thickness
σ = Surface Tension
ρ = Density

Application to real coating case

Horizontal case

Vertical case