Causes for the Formation of Surface Structures on Paint Films

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Components of paint film appearance

- Glanz: Gloss
- Verlauf: Structure
- Farbe: Color
- Effekt: Effect
- Wolkigkeit: Mottling

Source: BYK
Classification of surface structure in wavelength bands Wa – We

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

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

1. *wave-scan* dual (BYK-Gardner)

2. Profilometry (optical/tactile)

Wavelength bands: Wa, Wb, Wc, Wd, We →

Surface profile

Filter algorithm

Source: BYK
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 → stronger mapping ("telegraphing") of substrate structure
  - Powder coating
  - ...

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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
- **Modeling** by *shot-noise* model
- **Structure generation** also in long-wavelength range $\lambda > 1$ mm ($\rightarrow$ much larger than droplet diameter)

![Diagram showing paint droplets and initial structure on a substrate](image)
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Horizontal leveling according to Orchard (2D)

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

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

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

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

- $\nu$ speed of leveling
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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 \textit{Wd} and \textit{We}
Mechanisms for the formation of surface structures on paint films

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Flow-induced structure formation on wavy substrates (vertical)


- **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
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] | $\lambda_S$ [m] | $h_L$ [m] | $\sigma$ [N/m] | $\rho$ [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
$\lambda_{OFI} = $ Wavelength Structure Paint Film
$A_S = $ Amplitude Structure Substrate
$\lambda_S = $ Wavelength Structure Substrate
$h_L = $ Paint Film Thickness
$\sigma = $ Surface Tension
$\rho = $ Density
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Structure formation by film shrinkage due to solvent evaporation

- **Shrinkage** ~ solvent content
  \[ c_{\text{solv}}^{\text{vol}} = (1 - c_{\text{solid}}^{\text{vol}}) \] of paint

- In case without flow:
  \[ S_{\text{paint}} = (1 - c_{\text{solid}}^{\text{vol}}) \cdot S_{\text{substrate}} \]

- **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)

- e.g., 80 % shrinkage in case of 20 % solid content
Example of a 3D simulation
Simulation 3D
Application to real coating case

Horizontal case

- **Ausgangsgebirge_horizontal**
- **Füller_gemessen_horizontal**
- **Clearcoat_gemessen_horizontal**
- **Clearcoat_simuliert_horizontal**

**Wellenlängenbereich**

Vertical case

- **Ausgangsgebirge_vertikal**
- **Füller_gemessen_vertikal**
- **Clearcoat_gemessen_vertikal**
- **Clearcoat_simuliert_vertikal**

**Wellenlängenbereich**
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 $Wa \ldots We$)

- 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.

**Spray booth/oven parameters**
- temperature, relative humidity, air flow, 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.
Thank you for your kind attention!