OPTIMIZED PRE-METERED DIE COATING METHODS AND THEIR ADVANTAGES FOR NEW COATING APPLICATIONS

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AIMCAL EUROPE Web Coating & Handling Conference
Cascais, Portugal
June 8th – 11th, 2014
Introduction

In the development of new coated products the requirements to the performance and optimization of the production cost is getting more and more important. Also flexibility becomes more important to cope with smaller production lot sizes.

Using optimized and high precision application technology maintains a minimum of operating cost in regard to raw material consumption. Especially for high volume production the pay-off of the investment can be achieved within a very short time.

The production cost especially in highly developed countries are also influenced by the labor cost in a process line. Thus minimizing the downtime and maintenance is a need for successfully operating production lines in Europe and in the US.

By optimizing the machinery every facility can help to secure its own future.
Outline

• Requirements of new products
• Introduction into premetered coating methods
  – Direct slot coating
  – Tensioned web slot coating
  – Slide bead coating
  – Curtain coating
• Introduction in die optimization of dual cavity die design:
  – Requirements in die design for development and production dies
  – Internal distribution geometry
  – Cleaning properties
  – Particle loaded liquids
• Comparison of optimized slot dies with other concepts
  – Single cavity with body shims and fix lips
  – Single cavity with flex lips (and body shim)
  – Distribution system with "new diffusor type" die design
  – Optimized dual cavity design
Outline cont.

- Flexibility of dual cavity design
- Motivation for using optimized high precision dies
- Requirements in manufacturing of coating dies for efficient coating applications
- Examples for successful implementation of dual cavity dies in R&D and production
- Introduction in multilayer applications
- Summary and outlook
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Product requirements

New product formulations especially in the field of flexible electronics or polymer coatings are mostly expensive and available in small quantities only.

- Small production quantities
- Economical handling of chemicals
- Appropriate coating method
- R2R application process most wanted
- Process must be scalable
- Fluids containing particles are more susceptible for creating problems than solutions or emulsions
- Multilayer structures becoming interesting for example for battery applications \(\rightarrow\) e.g. higher capacity with comparable weight
Development process

Phase 0 / R&D
Development of Fluid

Phase 1 / R&D
R2R trials on Lab Coater

Phase 2 / Pilot line
Small scale production under production conditions

Phase 3 / Production
Full scale production in shifts 24/7 operation
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Coating overview / Application

**Self-Metered**

- Simple methods
- Laydown depends on liquid properties and web speed
- Formulation changes affect laydown
- One layer applied at a time

**Example: Pan (Dip) Coating**

**Pre-Metered**

- More complex – Requires a die distributor and a higher sophisticated fluid delivery system
- Laydown is specified within operating range of process ($H_{\text{wet}} = Q/U$)
- Formulation changes do not affect laydown
- Chemically reactive liquids (multi-component) systems can be coated
- Multiple layers coated simultaneously

**Example: Curtain Coating**
Premetered coating methods

Slot bead coating

Multilayer slot bead coating

Slide bead coating

Slot curtain coating

Tensioned web coating

Slide curtain coating
Premetered coating methods

Slot bead coating
(single and multilayer)

✓ 1 – 600 m/min.
✓ > 5 µm wet thickness
✓ 1 – 10'000 mPas
(order of magnitude)
Premetered coating methods

Slot bead coating
Definitions and operating window [1]
Premetered coating methods

Slot bead coating

- Backing roll
- Slot bead die
- Vacuum box
Premetered coating methods

Tensioned web over slot coating
(single and multilayer)

✓ 30 – 600 m/min.
✓ < 3 μm wet thickness
✓ 1 – 5’000 mPas
(order of magnitude)
Premetered coating methods

Slide bead coating
(single and multilayer)

✔ 30 – 300 m/min.
✔ > 50 µm wet thickness
✔ 1 – 1'000 mPas
(order of magnitude)

Example
ILFOCHROME CPA.1K
9 Layers,
Total dry thickness = 23 µm
Substrate = MELINEX
No interaction between layers!
Premetered coating methods

Curtain coating
(slot die and slide type die)

✓ 30 – 1’800 m/min.
✓ > 5 μm wet thickness
✓ 10 – 5’000 mPas
(order of magnitude)
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Ideal Coating Head

- Appropriate uniformity of coated film in cross-web direction (Cross-Profile)
- Wide range of applications
- Easy handling, assembling and dismantling
- Possibility to alter the coating width
- Easy cleaning
- Short residence times (for multi-component systems)
- Short downtime for changes or adjustments for production units
- Low fault liability (damages, abrasion ...)
- Specifications for integration (e.g. existing environment)
- High grade of flexibility for pilot and R&D units
Distribution geometry

- Requirements on die design
  - Influence on film uniformity in cross-web direction
  - Appropriate cross-web uniformity according to specific application (low, medium, high, excellent)
  - Fixed geometry required for multilayer applications
  - Wide range of applications wanted in terms of
    - Physical fluid properties
    - Coat weights
    - Coating speeds
  - Avoiding of contamination or settlement of particles inside the distribution system ("self cleaning effect")
“Infinite Cavity Design“

- **Basic Idea**: The resistance to flow in the metering slot is much higher compared to the distribution cavity (say by a factor of 100).
- So the pressure in the cavity as the driving force for pushing the liquid through the slot will be almost equal across the width.
- **Disadvantage**: Small wall-shear-stresses in distribution cavity.
Distribution geometry

“Coat-hanger Design“

• Basic Idea: Accurately calculate the pressure distribution in the cavity and adjust the length or the height of the metering slot such that the flow rate exiting the slot will be uniform.

• Advantage: Uniform high wall-shear- stresses along the entire width of the distribution cavity
Distribution geometry

"Infinite Cavity"

Small pressure drop in distribution cavity
↓
Almost horizontal isobaric lines

"Coat Hanger"

Pressure drop in distribution cavity compensated by varying the metering slot length
↓
Horizontal isobaric lines

(Schematic from Durst & Alleborn, 2006)
Distribution geometry

“Dual Cavity Design“

- **Engineering approach**
- **Idea:** Combination of an optimized “Coat-hanger“ distribution system with a secondary distribution system (cavity and slot) in order to dampen potential non-uniformities in the cross-profile.

- **Advantage:** Uniform high wall-shear-stresses along the entire width of the distribution cavity. High uniformity of the outflow profile for a large range of applications regarding fluid properties and operating conditions.
Distribution geometry

- Comparison of design possibilities

![Diagram showing performance of die versus application points for single cavity coat-hanger design and dual cavity design. The diagram indicates "AP" at 100% performance.]
Die optimization

Advantages

- High wall shear stress – self cleaning effect
- Chemically reactive (multi-component) liquids can be coated
- Liquids which tend to sediment can be handled very well
- Distribution system with minimized dead volume possible
- Superior cross web uniformity over big application range
  - Large working window
- No mechanical adjustments
  - Stable process
  - Responsibility for final product quality is not depending on skills of operators
  - Literally no downtime
- No wear and tear even with hard particles due to laminar flow inside the die
Streak defects in coating

Origin of streaks

- Particles
  - Bubbles
  - Solids
  - Gel slugs

- Particle traps
  - Vortices
  - Areas of low wall shear stress

Interaction

Streaks
Streak defects in coating

Prevention of streaks

- Avoid particles ➔ Filtration
- Avoid vortices and areas of low wall shear stress ➔ high wall shear stress everywhere in flow field and all the time.
- Avoid contamination inside distribution cavity and metering slots
Streak defects in coating

Prevention of contamination

- Avoid contamination due to adhesion of particles or build-up of crusts on solid surfaces
- Prevention of contamination means ease of cleaning. ➔ high wall shear stress everywhere in flow field helps
Wall shear stress distribution in cavity can be optimized through intelligent die design.

\[ A = A_0 (1 - \frac{x}{bW})^m \]

- \( m = 1.0 \)
- \( m = 0.75 \)
- \( m = 0.67 \)
- \( m = 0.50 \)
- \( m = 0.25 \)
- \( m = 0.0 \)
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Different die design concepts

• For slot dies in general we can distinguish between four different design concepts
  – Generic or adapted internal distribution system and adjustable slot height by shim foils (“Fixed lip design with shims”)
  – Generic internal distribution system and adjustable slot height by push-pull units (“Flexible lip design”)
  – Distribution system with “diffusor type” die design
  – Optimized internal distribution geometry according to customer specific range of applications (“Optimized dual cavity design”)

• For multilayer cascade dies there is less freedom for adjustability
  – Usually optimized internal distribution geometry following the “dual cavity design concept” is used
Slot dies with “fix lips and shims”

- **Advantages**
  - Possibility to influence the pressure drop by changing the slot height for different products
  - Adjustment of coating width without deckles possible

- **Weak points**
  - Dismantling of the die needed for every change of slot height and coating width → Downtime
  - Low wall shear stress in cavity due to usually large cross section → bad cleaning
  - Cross-profile depends on shim uniformity
Slot dies with “flexible lip design”

- Advantages
  - Possibility to influence the pressure drop and uniformity by adjusting the slot height according to the measured cross-profile from outside
  - Adjustment of coating width from outside possible with deckles and shims in slot

- Weak points
  - Online measurement system for cross-profile needed
  - Low wall shear stress in cavity due to usually large cross section → bad cleaning
  - Adjustment of cross-profile strongly depends on operator skills → quality uncertain
  - Complex system with many push-pull units, some with closed control loop
  - No stable process due to adjustments
  - Calibration needed for different products → Downtime
Slot dies with “internal diffusor”

• **Advantages**
  + “Mechanical” pre-distribution of the coating liquid
  + Possibility to run the die with different liquids under different conditions
  + Short lead time for standard coating widths

• **Weak points**
  – Shims needed for adjusting pressure drop and to optimize CD profiles
  – Low wall shear stress in cavity due to usually large cross section ➔ bad cleaning and large internal volume for R&D dies
  – Width adjustment is difficult
  – Multiple feed ports need to be synchronized especially for wide dies
  – Performance with highly particle loaded liquids uncertain
  – Calibration needed for different products ➔ Downtime
Slot dies with “optimized design”

• Advantages
  + Outstanding cross profiles for specified range of products due to dual cavity design
  + Predictable cross-profile for future products
  + Excellent slot height uniformity
  + No adjustments needed ➔ stable process
  + Optimized self cleaning inside cavities ➔ less maintenance
  + Short changeover times between different products
  + Quality of final product does not depend on operators
  + Adjustment of coating width from outside possible with deckles in slots and cavities
  + Lower production cost in long term view

• Weak points
  – Knowledge of fluid properties needed
  – Definition of application points needed
  – Longer lead times
Outline cont.

- Advantages of dual cavity design
- Motivation for using optimized high precision dies
- Requirements in manufacturing of coating dies for efficient coating applications
- Examples for successful implementation of dual cavity dies in R&D and production
- Introduction in multilayer applications
- Summary and outlook
Advantages of optimized dies

• Dual Cavity Design for large application window
  – Combination of various fluid properties and operating conditions possible with a fixed geometry ➔ robust design
  – Variable coating width adjustment without opening the die

• Excellent cross profiles achievable
  – High product quality <1%
  – Minimum coating liquid consumption

• No adjustments needed
  – No downtime for adjustments or shim foil changes
  – No risk for damages ➔ less repair work
  – No impact of operator skills to final product

• High wall shear stress – “self cleaning effect”
  – Low maintenance time ➔ less downtime
  – Short changeover times between different products
  – Multiple component systems (reactive) usable
  – Liquids which tend to sediment can be handled very well
Advantages of optimized dies

- High efficiency with coating liquids

Example for a functional layer (mass production)

\[
\frac{2400 \text{ kg/h}}{100\%} \times 4\% = 96 \text{ kg/h}
\]

1 kg for 1.00 Euro = 96 Euro/h

\[96 \times 24 \times 7 = 16’128 \text{ Euro/week}\]
Advantages of optimized dies

• Quick change over time between products
  – For width change …
  – For cleaning …
  – For liquid change …

12 minutes per change, one time per day, 30 EURO per man-hour, 45 weeks production per year

\[0.2 \times 30 \times 7 \times 45 = 1'890 \text{ EURO/year}\]

Two hours non productive time per change, one time per day, 30 EURO per man-hour, 45 weeks production per year

\[2 \times 30 \times 7 \times 45 = 18'900 \text{ EURO/year}\]
Advantages of optimized dies

- Better cross-web uniformity
  - Comparison between single cavity and adjustable slot height versus optimized distribution geometry and fixed lips
  - Application 4m wide, first number is startup speed 20% of target coating speed

<table>
<thead>
<tr>
<th>Product</th>
<th>Single cavity (total cross profile)</th>
<th>Double cavity (total cross profile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (22gsm@75m/min, 145µm slot)</td>
<td>7.89% 7.89%</td>
<td>7.31% 7.35%</td>
</tr>
<tr>
<td>B (28gsm@59m/min, 165µm slot)</td>
<td>8.07% 7.67%</td>
<td>6.60% 6.66%</td>
</tr>
<tr>
<td>C (35gsm@47m/min, 180µm slot)</td>
<td>8.80% 8.28%</td>
<td>6.19% 6.26%</td>
</tr>
<tr>
<td>D (41gsm@40m/min, 230µm slot)</td>
<td>13.39% 12.26%</td>
<td>5.28% 5.40%</td>
</tr>
</tbody>
</table>
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Motivation for optimization

Requirements during development of new coated products

• **Excellent uniformity – product performance**
  – Optimized die design
  – High precision manufacturing of coating dies

• **Highly economical operation**
  – Low material consumption of expensive fluids
  – Internal die design for low volume
  – Fluid delivery system designed for very low flow rates

• **Flexible die design**
  – Coating of large range of different products
  – Variable lip geometry for slot and tensioned web coating
  – Multilayer applications

• **Scalable process**
  – The settings found in pilot lines should be transferable into future production
Outline cont.

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Die manufacturing

Requirements in manufacturing of coating dies

• Regardless what kind of internal distribution system is selected the liquid has to pass a narrow slot before being transferred to the running substrate
• The mechanical precision of the exit slot is influencing the CD profiles of the coated film
• The lower the thickness of the coated film shall be the tighter the exit slot will be
• If the internal distribution system is well designed the impact of the mechanical precision is much higher compared to the flow distribution
Mechanical Precision

Influence of the slot height precision to the cross profile

Example:
Nominal slot height: 300µm
Variation of slot: ±1µm
Cross profile: ±1%
Outline cont.

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Examples for optimized dies

• Paper label application / adhesive application
  – High flow rates due to curtain coating application with water based liquids
  – Different adhesives used under various coat weight / speed conditions
  – Die was in operation for 18 months and after first disassembling for a check-up it was found clean inside
  – Another application with solvent based adhesives was in operation for 5+ years without any opening for maintenance and it still was clean inside

• Specialty paper (photo / inkjet)
  – Dies have been designed 25 years ago for multilayer photographic products
  – Dies are now in operation for inkjet paper without changes in geometry

• Lithium-Ion batteries / flexible electronics
  – With highly precise slot dies the capacity of a battery could almost be doubled
  – Film thickness uniformity of <50nm±2% achieved for OLED / OPV application

• UV curable liquids with multiple components
  – Relatively short pot live of the reactive blend in the order of minutes
  – Coating application in a production size of approx. 1.5m
  – Due to optimized cavity shape and residence time inside the die the process is running for the entire campaign without problems in the order of days
Examples for new applications

- Casting films with slot dies
  - Application on steel belt or huge drum
  - Solvent extraction through evaporation or in a precipitation bath
Examples for new applications

• Double sided adhesive tape [4]
  – Only liquids to be handled
    ↩ Two water based adhesives, one water based polymer solution acting like film
  – No additional web handling and winders
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Multilayer Coating

Applications in traditional industries

- Photographic products (film / paper)
- Digital imaging (inkjet paper)
- Speciality papers: Thermal paper / carbonless paper
- Adhesives: Paper labels
- Optical films

Example
ILFOCHROME CPA.1K
10 layers, total dry thickness = 23 µm
Web = MELINEX
No interaction between layers!
Photo courtesy Werner Hasler, ILFORD Imaging Switzerland GmbH, CH-1723 Marly
Multilayer Coating

Why is Multilayer Coating so attractive?

- Traditional (single layer) products can be improved by developing multilayer structures ➔ Example: HERMA PSA labels
- Functions of complex layers can be split into mono-functional structures
- Thus complex chemistry of the single layers can be simplified and less compromises in the design have to be accepted
- Specific layers can be created in order to optimize the production process
- Rather thick layers could be split in a thin layer of low viscosity in order to improve the process and in one highly concentrated layer in order to reduce the overall amount of solvent
- Thin and ultra thin individual layers can be achieved – even at high speeds, due to the combination with a thicker supporting layer or the sum of multiple thin layers
- Usually it is more economical to apply multiple layers simultaneously than one by one, even when the investment cost for the equipment is higher and maybe the coating speed is lower
- The multilayer coating methods are well known and understood
Multilayer Coating

Example for Multilayer Inkjet Product

Multilayer coating in order to optimize both, the coating process as well as the product performance [2]

Production example for multilayer product with 5-layer curtain coating
Multilayer Coating

What is important in Multilayer Coating?

✓ Slot coating 2-3 layers
✓ Slide and slide curtain coating > 10 layers
✓ Mixing between adjacent layers is very unlikely due to laminar flows
✓ Interfacial mixing due to concentration gradients can be avoided by inserting separation layers between functional layers or by short diffusion times as a result of fast drying or using phase separation [3]
✓ Stable processes can be maintained by well adjusting the viscosity and surface tension of adjacent layers
✓ Selecting compatible solvents is important not only for the coating but also for the drying process
✓ Optimizing the drying process is also essential
Multilayer Coating ...

... in the electronic field

- OLED and OPV devices require multiple layers for functional reasons
- Battery products might benefit from multilayer structures for functional as well as for coating process related reasons
- Multilayer coating might be beneficial for large area displays too
- Also for fuel cells multilayer structures are interesting
- First trials with a multilayer slot die in different fields have been carried out successfully
Multilayer Slot Coating

Example: Dual layer slot die
- Ideal development unit
- Minimized dead volumes
- High precision slot coating
- Flexible design
Outline cont.

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Summary

- Optimized die design means
  - High wall shear stress – self cleaning effect
  - Reactive coating liquids can be applied
  - Liquids tending to sediment or deposit particles can be coated
  - Excellent cross profile over entire range of applications ➔ wide operating window due to dual cavity design
  - No mechanical adjustments
Summary cont.

- Optimized die design needs definition of fluid properties and operating conditions
- With optimized dual cavity design a large range of different products can be coated without any calibration during production
- The quality of the final product does not depend on the operators skills
- Downtime (the machine is not productive!) can be reduced to the absolute minimum
- Optimized die design and superior slot uniformity help to achieve the required product performance and low operating cost during development and production in a mid- to long-term view
- Low volume dies in combination with appropriate fluid delivery system help to save expensive and rare coating fluids during development
- Optimizing coating dies needs dialog between die manufacturer and end user
- During the development of the process a partner with designated experience is highly beneficial
- Optimized dies show a short return of investment (ROI)
- TSE is your highly experienced partner for high precision pre-metered coating since 50 years, everywhere in development, pilot and production scale
Outlook

Dual layer slot coating for Li-Ion Batteries (will be presented soon)

Slot coating at hot temperatures
Outlook

• Examples for new applications:
  Coating of plates with slot coating
  – Start/stop procedure is important
  – Very thin dry layers achievable for low viscous applications at rather low speeds

2. **P.M. Schweizer**, “Premetered Coating Methods”, Short course coating and drying at KIT, March 2013


Thank you for your attention

Questions?

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