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

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In the development and production of coated products especially for products in the most recent developments of electronic products such as flexible electronics, new battery systems for energy storage it is of utmost importance to select an appropriate coating method. This is necessary for technical reasons as well as for economical matter.

The first step when developing new products is finding the ideal liquid formulation. The second step beside the product performance, but not less important, is determining the ideal application method. New product formulations in the field of flexible electronics or polymer coatings are mostly expensive and available in small quantities only, so economical handling of the chemicals is of big importance from the beginning on.

Coating method

To determine the most appropriate coating method it is important to know the main features of different methods. The most of the self-metered coating processes are not adequate because of their disadvantages over pre-metered techniques. One main characteristic of this last called family of coating methods is mass conservation and the easy calculation of the average coated film thickness following the simple function

\[ H = \frac{Q}{U} \]

with the film thickness \( H \), the volumetric flow rate per unit width \( Q \) and the web speed \( U \).

The main advantages of this group of processes can be summarized as follows:

- Coat weight or film thickness is specified within operating range of process
- Formulation changes do not affect target coat weight
- Reactive liquids (multi-component systems) can be coated continuously
- Coating of multiple layers simultaneously is possible
- Excellent uniformity of coated film in both, cross-web and machine direction
- Coating devices are closed units without any recirculation of fluids and related accumulation of air
- Pre-metered methods are free of contact between the application head and the substrate to be coated

Chemically reactive formulations are becoming more interesting because of improved process control. Especially with short reaction times it is required to run in closed systems with reduced residence time for 100% of the coating liquid. This requires small quantities of the fluids in the circuit, direct blending just before the application and equipment free of dead zones in order to avoid a reaction kickoff in areas in which the liquid can settle. Therefore requires optimized equipment and pre-metered coating processes are providing maximum success.

The possibility to coat multiple layers simultaneously in order to split functions in dedicated layers of a coating and/or to use chemically reactive materials aiming to optimize the subsequent drying or curing process shows a big difference over conventional coating techniques used in R&D and
pilot facilities. These advantages can only be included into the product development process when the possibility to apply continuous coating is available.

For a future production process it is also important to study the R2R-process as the most economic setup. Often in R&D-facilities no such narrow development coating lines are available in house and it is beneficial to work together with specialized partners with a sound understanding of possibilities.

An overview about the different premetered coating methods is shown with the following diagrams:

**Slot Coating**
Premetered coating in the slot format is an attractive method to apply single or multilayer structures of functional layers with the above mentioned advantages. The general specification of features in the coating die and the application window for slot coating is shown in the following figures.
**Tensioned web over slot coating**

The main advantage of this "sub-group" over conventional slot coating is to achieve layers with very low wet thickness and if necessary to apply these with rather high speed. Due to the substrate running over the die lips the uniform web tension becomes very important in order to achieve the desired uniformity.

**Slide bead coating**

In the photographic industry slide bead coating was the "working horse" to apply multilayer structures of sometimes way more than 10 layers in the same path. Nevertheless the application range in terms of fluid properties, wet thickness and speed is narrower compared to slot coating. Thus the properties of the coating liquids have to be optimized especially for this method.

**Curtain coating**

Curtain coating is well know as a high speed coating method, maximum speeds in the paper industry over 2000m/min have been tested successfully. The main characteristic if curtain coating is the stability of the liquids curtain which requires a certain amount of liquid in the curtain itself. In conjunction with high speeds rather thin layers can be achieved, rather thick layers can be applied at reasonably low speeds too.

**Requirements for production and R&D- dies**

Regardless what kind of coating method shall be selected the following requirements apply to all different coating heads.

- 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
- Short downtime for changes or adjustments
- Low fault liability (damages, abrasion ...)
- Specifications for integration (e.g. existing environment)
- Coating heads used in R&D shall be very flexible and must be accepting the unknown future coating applications

When considering pre-metered coating methods some additional requirements are important:

- Appropriate cross-web uniformity according to specific application - "only as good as needed"
- 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")

**Fluid distribution geometry**

Pre-metered coating dies can be designed in different ways in order to achieve a certain performance. The design of the internal distribution system in conjunction with the mechanical precision of
the die slots is mainly influencing a) the uniformity of the coated film, b) the downtime due to interruptions and c) the required time for change-over between subsequent coating runs.

The internal fluid distribution system to dispense a uniform film in cross-web direction can be designed following different possibilities. One well known way is to use the so called "infinite cavity design" using a large distribution cavity and a subsequent narrow and long slot. A more or less appropriate uniformity of the coated film can be achieved, but the biggest disadvantage is the large chamber leading to very low wall shear stress especially for low flow rates and viscosities. Additional to this a big volume needs to be filled before coating.

One proven method to increase the wall shear stress in order to minimize settlement of particles and causing internal contamination is the so called "coat-hanger design". In this the distribution cavity is much smaller in cross-section such that the wall shear stress is higher compared to the large cavities explained above. The pressure drop caused by smaller cavity size especially at higher viscosities and higher flow rates can be compensated by altering the pressure drop through the slot following the cavity. This of course can only be optimal for a rather small range of different products or operating conditions.

The internal TSE- die design consists of a "dual chamber fluid distribution system", which will be optimized for a wide range of applications of products. This consists of a small section coat hanger combined with a subsequent damping chamber allowing to run several liquid formulations under different operating conditions – "from water to honey".

Due to this optimization work no adjustment is needed on the dies when changing the liquid or operating conditions. Even during development stages with unknown future conditions an optimized die can be used with great success. By pre-calculating the expected cross web uniformity of a new product the liquid properties could be optimized first before running expensive trials.

![Infinite Cavity Design](image1.png) ![Optimized Dual Cavity Design](image2.png)

Fig. 4. Comparison of internal distribution geometries

The above graphs show either a side fed die or one half of a centre fed die, in case of a centre fed die the picture has to be mirrored. The liquid is flowing from the inlet through the first cavity horizontal in cross-web direction and from there vertical through the slot and, if used, through the second cavity and slot as well. Between these two extreme examples for the distribution system other design concepts are also available, working with more or less good uniformity over a certain range of products. The design of the distribution system is responsible for the theoretical uniformity determined with the physical fluid properties, the flow rate per unit width and the internal geometry. Due to the optimized coat hanger design the ideal condition can be achieved in terms of pressure uniformity in the exit slot, as shown in Fig. 5.

As mentioned one big difference between infinite cavity and optimized dual cavity design is the size of the first distribution cavity. The smaller dimensions for the "coat hanger" are leading to much higher wall-shear stress, which provides optimum cleaning properties.
Comparison of optimized slot dies with alternative design concepts

In principle there are four different design concepts present in actual die manufacturing. Other concepts may be present in patents and in closed design departments, but mainly the concepts as shown hereafter are used for production and development dies.

a. Generic internal distribution system and adjustable slot height by push-pull units (“Flexible lip design”)

b. Generic or adapted internal distribution system and adjustable slot height by shim foils (“Fixed lip design with shims”)  
c. Distribution system with "diffusor type" die design and shim foils

d. Optimized internal distribution geometry according to customer specific range of applications (“Optimized dual cavity design”)

In general one can say that the first three design concepts are providing flexibility by exchanging parts such as shim foils or diffusors, or by adjusting slot height according to actual requirements. This feature requires a certain effort when changing conditions and leads to some undesired downtime especially in production facilities.

The optimized design concept provides also reasonable flexibility by the design itself – without the need to replace parts or to adjust the geometry.

When the die shall be operated with variable width dies with shim foils usually need the replacement of the shim foils for different widths, which requires opening the die to allow changing the parts. With optimized die design there are inserts available which can be inserted into the die from either side without opening the die.

Advantages of optimized coating dies

With optimized coating dies several advantages can be combined in one fix geometry. First of all optimized coating dies can cope with a large range of different fluids and operating conditions such as film thickness and application speed. Due to a balance between theoretical fluid distribution and mechanical precision of the die slots optimized dies can be designed very robust and forgiving. By this the dies deliver excellent cross profiles for several products and don't need to be adjusted when changing from one product to the other. Especially for production dies – which are some-
times used for small production quantities of a few hours only – it is important to reduce maintenance and downtime to the absolute minimum.

Furthermore these dies provide internal flows with high walls shear stress which help to improve the cleaning of the die between subsequent coating runs (without opening the die) and to avoid contamination during the process, which again leads to shorter cleaning cycles. In conjunction with optimized residence time of the liquid inside the die also chemically reactive liquids can be treated well. By this the development departments have more freedom in optimizing the products in terms of product performance but also in reference to optimized production processes.

**Motivation for using optimized high precision dies**

Especially for new electronic products in the areas of flexible electronics (OLED, OPV), Lithium-Ion batteries or optical films for flat panel displays the requirements for highly precise coated layers are becoming more and more important. Optical films are usually judged by the human eye which is way more sensitive than any other measuring device. With highly uniform layers in Lithium-Ion batteries the capacity of a battery at a given weight can be increased or the weight of a given capacity can be reduced.

In other fields such as high volume production facilities for paper labels or specialty paper products the main advantage of high precision coating equipment is economics. When calculating cost savings of raw material which are possible by installing higher precision equipment the extra cost compared to lower precision equipment are depreciated within a few weeks or months only. There are examples known in which the saving on raw material is in the order of €300'000 per year.

In case of developing products in the field of flexible electronics usually the liquids are available in very small quantities only and additionally they are extremely expensive. Thus an optimized die with minimized dead volume helps to keep development cost as low as possible.

Last but not least the possibility to simultaneously coat multilayer applications is a good motivation to consider optimized coating dies. Even when also the drying processes have to be optimized and the selection of solvents has to fulfil different targets over all coating of multiple layer structures in one production pass is effective and economic.

The premetered coating processes were developed and used since decades in the photographic industry, and here the scaling-up process was proven for a long time. Very often first developments started with maybe 10cm wide dies, and then a first small-scale production was run with maybe 40 or 50cm width, before the full production was started in a width of 1.3-1.5m. The settings and observations found in the small scale can easily be transferred to the production scale. This is also valid for other applications, for example in the paper industry development of liquids often is made with 26cm wide dies, pilot runs and first samples with 50-80cm wide dies, and then production starts with 2-3.5m

**Requirements in manufacturing of coating dies for efficient coating applications**

Regardless which internal fluid distribution system is selected inside a die the fluid has to pass a narrow slot before being transferred to the running substrate. Thus the slot precision is an important factor for the uniformity of the coated film; often this contribution is bigger than the theoretical uniformity itself. Especially for low film thickness of products in the field of flexible electronics highest slot uniformity is required to meet the performance requirements because of tight gaps inside the die.

**Examples for successful implementation of dual cavity dies in R&D and production**

There are several good references for successfully implementing optimized coating dies in different fields. For example coating dies initially designed and produced for photographic products are now in use for coating specialty paper products, with totally different rheology, coat weight and speed. Other applications show how well the self cleaning inside the die works, even with rather high vis-
cous adhesives. These dies are in operation for one year or sometimes much longer without splitting the die apart for cleaning. A third group of dies show how the performance of the final product can be improved by using high precision dies compared to conventional coating methods. The capacity of a Li-Ion battery for example can be increased dramatically with excellently coated, uniform layers. Finally one can find examples of dies in production scale used for chemically reactive liquids with rather short pot life. With conventional application methods such products cannot be applied, the equipment would be blocked after a very short time.

Introduction in multilayer coating applications

Applying multiple layers simultaneously was very common in the photographic industry for several decades. Such a multilayer structure usually contains a primer layer, different colour sensitive layers, buffer layers between the individual colours and a protective layer on top. These structures of sometimes ten or more layers were coated in one coating pass mainly to fulfil economical requirements. Nevertheless also technical reasons were important during the development of the multilayer coating methods. In general they are attractive in different aspects:

- 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

Other examples of simultaneously coated multilayer products shall be called out here in order to describe the possibilities and the range of potential future applications. The two pictograms below show the setup of multilayer cascade or slide dies used in the photographic industry and the most of the following applications:

- High performance inkjet products mostly use thin primer layers in order to improve the fixation of the product to the pre-coated paper. This layer often can improve also the coating process by adjusting the viscosity behaviour. On top of this layer the dedicated, rather thick

Fig. 6. Multilayer Coating Methods mainly used in photographic industry and other applications
ink absorbing layer is applied topped with a thin layer covering the absorption layer and adjusting the optical appearance of the entire product. An example for such a structure is shown in the following Fig. 7.

![Diagram of a multilayer inkjet product](image)

**Fig. 7. Example for multilayer inkjet product [2]**

- By applying a three layer structure of one adhesive layer on the bottom, one polymer film in the middle and a second adhesive layer on the very top a dual-sided adhesive tape can be coated without the need of inserting a fabric or any other structural substrate, only a silicon coated release liner is needed.

![Diagram of a double sided adhesive tape](image)

**Fig. 8. Example for double sided adhesive tape [4]**

- Applying multiple layers with different barrier functions (e.g. grease, flavour, light, moisture and oxygen barrier) helps to coat very thin layers at high speeds and to minimize the risk of tiny pinholes jeopardizing the impermeability of the protective coating.

Mixing of the different layers during the coating process is often a concern when starting with multilayer coating methods. Here we have to distinguish between mixing due to the flow conditions and interfacial mixing on a much smaller scale. Since all known coating flows either in slot dies but also in multilayer slide and curtain dies are laminar, convective mixing driven by the fluid flow is very unlikely. Due to concentration gradients between adjacent layers mixing by diffusion is possible. If this has to be avoided by all means it is generally possible to insert buffer or separation layers be-
tween functional layers - as already mentioned for the photographic products. These layers can be very thin and only have the mono-function to separate layers. Other possibilities are maintaining short diffusion times by fast drying or using phase separation [3].

Adjusting the viscosity and surface gradients in multilayer structures is also important in order to maintain a stable coating process. For example the subsequent layers must wet the underlying layer well – general guidelines are well known in order to optimize this.

Coating of multilayer structures of course is only one part of the process, drying is another important step. Due to the mostly present requirement to evaporate the solvent of the bottom layer through the entire package the layer structure, the selection of solvents and the drying process itself is important to be developed too. The drying process needs to be careful and not all solvents can be combined freely. Experts in drying can help with predictions for an optimized process and the demands to the drying device.

**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**
- 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

**References**

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