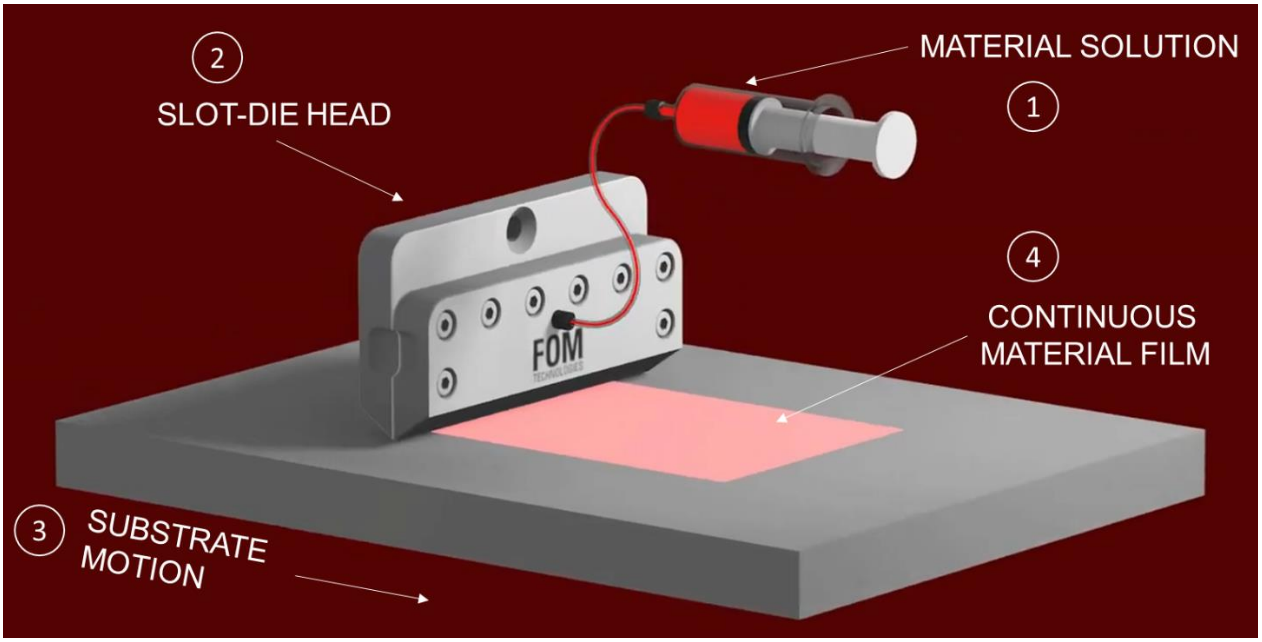
FOM TECHNOLOGIES

SLOT-DIE COATING:

INTRODUCTION AND FAQ

1. What is Slot-Die Coating?



Slot-Die Coating is a highly scalable technique for depositing thin and uniform material films with minimal waste and low operational cost. It was invented in the 1950's by Eastman Kodak Co. for the production of photographic films. Since then, it has seen widespread adoption in industrial manufacturing of electronics, packaging and pharmaceuticals.

Slot-Die Coating works by dissolving the desired thin film material into a coatable solution. This solution is pumped into the Slot-Die Head component, where it becomes uniformly spread along the desired coating width. This results in controlled, continuous thin film production at the Slot-Die outlet, where the solution is received by a moving substrate. Because all of the solution that exits the Slot-Die ends up on the substrate, an optimized Slot-Die Coating process affords nearly 100% material efficiency.

For a short introductory video on the basics of Slot-Die Coating, we encourage you to view our *Discover Slot-Die Coating by FOM Technologies* animation on YouTube.

2. What are the benefits of Slot-Die Coating in thin film research?

Slot-Die Coating has historically been used in industrial roll-to-roll settings due to its precision, reliability and viability for large scale output. It is only recently that traditionally large Slot-Die production machines have been scaled down for use in a laboratory research setting, where spin coating and blade coating are conventionally applied. Slot-Die Coating therefore offers a number of new and exciting benefits for users at the R&D scale, including:

- **Excellent thickness control:** Slot-Die Coating is a “pre-metered” coating process. This means that the thickness of the coated layer can effectively be calculated and “pre-programmed” by selecting the correct pump rate and coating speed. This provides significantly improved predictability and control of coating thickness compared to conventional lab-scale methods.

- **Accelerated commercial viability:** Slot-Die Coating is precise and flexible enough to be used as a standard coating technique in fundamental materials R&D. At the same time, it is innately scalable to large-area coatings and easily compatible with established roll-to-roll production techniques. This provides inherent commercial credibility to lab-scale research that has been developed with Slot-Die hardware, as fundamental materials research and commercial process optimization are coupled together in the experimental process.

- **Unmatched flexibility:** The range of substrates, materials, layer thicknesses and coating parameters that can be used in Slot-Die Coating is simply unmatched by comparable lab-scale techniques such as Spin Coating and Blade Coating. At the same time, Slot-Die Coating is gentle on the coating fluid and resilient against external sources of error such as substrate roughness. In terms of hardware, FOM Technologies Slot-Die tools can be easily customized with modular modifications to exert further control over specific process parameters such as heating, drying, liquid shear and more.

- **Boosted output, reduced spending and waste:** Slot-Die Coating is a continuous process that is capable of coating up to hundreds of meters per minute with nearly complete material efficiency. Comparatively, Spin Coating is a slow, wasteful batch process, while Blade Coating lacks the precision and flexibility of Slot-Die. Simply put, this means that Slot-Die Coating provides an optimal combination of sample quality, sample output and material spending among comparable lab-scale coating techniques.

  We can illustrate this with a simple calculation comparing the resulting sample output and material cost when producing a 1 cm^2 sample of costly P3HT material that is 100 nm thick, as might be used in an organic solar cell.

ASSUMPTIONS

P3HT Price (p)	Slot-Die width (w)	Slot-Die speed (U)	Time per Spin Coating sample	Spin Coating material efficiency (X_{sc})	Slot-Die material efficiency (X_{sdc})
500 USD/cm³	1 cm	1 m/min (modest)	0.5 min	10%	95%

SAMPLE OUTPUT CALCULATION

Spin Coating	Slot-Die Coating
… $t_{sample} = 0.5\ min$	$n_{samples\ per\ min} = \frac{U * w}{1\ cm^2}$ $n_{samples\ per\ min} = \frac{100\ cm\ min^{-1} * 1\ cm}{1\ cm^2}$ $n_{samples\ per\ min} = 100\ min^{-1}$ $t_{sample} = \frac{1}{n_{samples\ per\ min}}$ $t_{sample} = \frac{1}{100\ min^{-1}}$ $t_{sample} = 0.01\ min$

In this example, Slot-Die Coating is shown to produce high quality, uniform samples **50 times faster** than a comparative Spin Coating process. Practically, this disparity is several orders of magnitude larger considering the much higher Slot-Die Coating speeds and slower Spin Coating sample prep processes that occur in a real lab.

MATERIAL SPENDING (S_m) CALCULATION

Spin Coating	Slot-Die Coating
$S_m = \frac{V_{sample} * p}{X_{SC}}$ $V_{sample} = L * W * H$ $V_{sample} = 1\ cm * 1\ cm * 10^{-5}\ cm$ $V_{sample} = 10^{-5}\ cm^3$ … $S_m = \frac{10^{-5}\ cm^3 * 500\ USD\ cm^{-3}}{0.10}$ $S_m = 0.05\ USD$	$S_m = \frac{V_{sample} * p}{X_{SDC}}$ $V_{sample} = L * W * H$ $V_{sample} = 1\ cm * 1\ cm * 10^{-5}\ cm$ $V_{sample} = 10^{-5}\ cm^3$ … $S_m = \frac{10^{-5}\ cm^3 * 500\ USD\ cm^{-3}}{0.95}$ $S_m = 0.005\ USD$

In this example, by virtue of material efficiency, Slot-Die Coating is shown to be **10 times more cost effective** in material spending and waste than a comparative Spin Coating process.

3. Which applications benefit most from Slot-Die Coating?

Slot-Die Coating is highly flexible with respect to the thicknesses, materials and customizations that it can accommodate. For this reason, it is applicable in virtually any process where a pure, uniform material coating is required in the range of nano- to micrometer thickness. Due to its inherent scaling potential and compatibility with flexible substrates, Slot-Die Coating is additionally beneficial in applications where large areas or high throughput manufacturing are required. Short of applications where atomic monolayers are required, if a process requires uniform layers coated on the micro- or nanoscale, Slot-Die Coating is almost certain to provide value.

Slot-Die Coating is currently used in a variety of industrial processes, ranging from crude application of adhesives to precise coating in sophisticated applications such as photographic films, ceramic capacitors and Li-ion batteries.

In the context of modern R&D trends, Slot-Die Coating continues to see increased use in a wide variety of high-tech applications, including:

- **Photovoltaics** such as tandem- and thin film solar cells
- **Energy storage** such as Li-ion, lithium metal and post-lithium batteries
- **Smart surfaces** such as OLED, ECD, conductive foils and molecular sensors
- Novel **medical diagnostics** such as perovskite x-ray detectors and microfluidic lab-on-a-chip devices
- Novel **drug delivery** such as hot-punching of microcapsules or thin film vaccine coatings
- Diverse applications in **additive manufacturing, printed and organic electronic components**

4. What are the typical operating limits of Slot-Die Coating? How do these compare to Spin Coating and Blade Coating?

The operating limits of a Slot-Die process are **highly dependent on the materials being used**. It is therefore not possible to make a blanket statement about operating limits that are universally applicable to all Slot-Die Coating processes. However, it is possible to make general statements about conditions that are reasonably achievable, given proper optimization, based on what has been achieved previously.

Generally acknowledged operating limits for Slot-Die Coating are provided below, and compared with Blade Coating and Spin Coating as the most relevant alternative technologies.[1,2,3] However, it should be noted that Spin Coating cannot truly be compared with Slot-Die Coating. This is because Spin Coating it is an inherently unscalable process. Any process developed by Spin Coating that requires high throughput or coating of areas larger than a few cm^2 will, without exception, need to be redeveloped for a more scalable technique such as Slot-Die or Blade Coating before practical application.

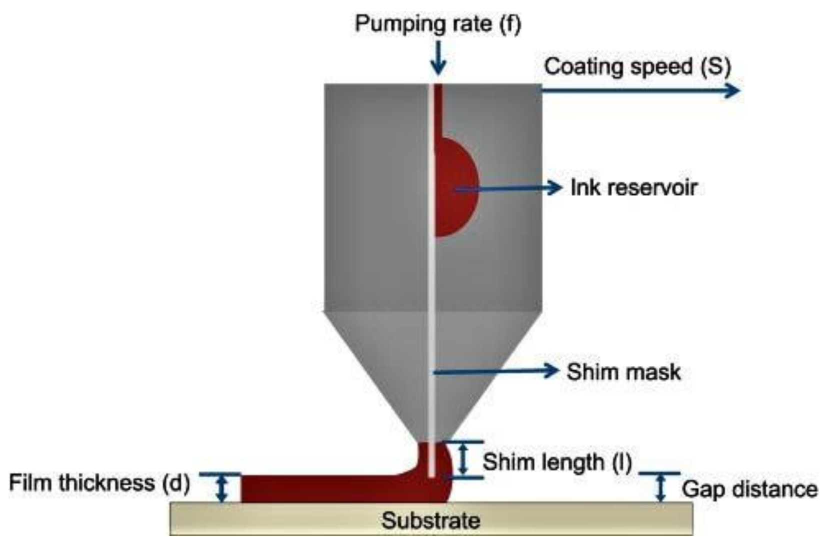
PARAMETER	SPIN COATING	BLADE COATING	SLOT-DIE COATING
Thickness range (dry)	10 nm – 10^2 um	1 – 30 um	10 nm – 10^2 um
Coating speed (m min^{-1})	--	1,500	0.1 – 500
Max. coating area (cm^2)	10 x 10 (typically < 25 cm^2)	400 x L	400 x L
Viscosity range (cP)	< 1,000	< 40,000	< 20,000*
Layer uniformity (%)	< 5	< 10	< 5
Web roughness effect	--	Large	Small
Throughput method	Batch	Continuous	Continuous, intermittent and batch possible
Delivery method	Volumetric, pre-metered	Mechanical, self-metered	Volumetric, pre-metered
Thickness predictability	Low	Moderate	High

*Viscosity range varies depending on whether the application requires solution processed Slot-Die Coating versus melt based extrusion coating. Extrusion is achievable in a Slot-Die apparatus and functions with much higher viscosities.

As a rule of thumb, it can be said that Slot-Die Coating possesses similar precision when compared with Spin Coating, while also being as scalable as Blade Coating, and the most flexible of all three.

Additional techniques such as Inkjet and Gravure are occasionally compared with Slot-Die coating. However, these techniques are fundamentally different in their intended application as "printing" techniques rather than "coating" techniques. While Inkjet and Gravure excel at producing fine-featured ink patterns, when applied in coating applications they suffer significantly in uniformity, processing speed, material compatibility and hardware flexibility. They are therefore not considered relevant for side-by-side comparison with Slot-Die Coating, and are more applicable as supplemental techniques to apply printed patterns on top of Slot-Die Coated layers.

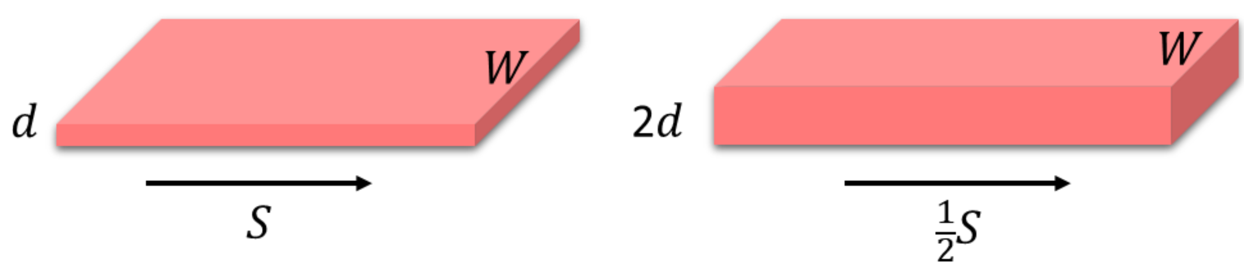
5. How is layer thickness controlled in Slot-Die Coating?



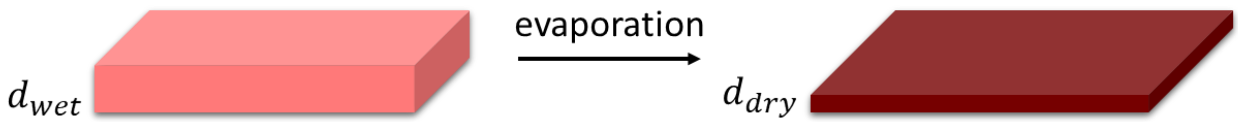
A key benefit of Slot-Die Coating is its "**pre-metered**" nature. This means that the coated wet film thickness (d) can be easily controlled and calculated from the pump rate (f; the rate at which ink enters the system), the substrate motion speed (S; the rate at which the substrate accepts ink from the system), and the coating width (W; the width across which the ink is dispersed upon the substrate).[4]

$$d = \frac{f}{W * S}$$

Unlike in "self-metered" coating techniques such as Blade Coating, **the height of the Slot-Die head does not physically control the thickness of the coated layer**. Instead, the wet layer thickness in Slot-Die Coating is entirely determined by the volume of ink applied to the substrate, divided by the area over which the ink is coated. This affords a highly flexible, "contact free" coating process where the desired wet thickness can be precisely targeted by choosing the correct pumping and coating speeds.



The final dry thickness is determined by the volume of active material left behind on the substrate after solvent evaporation.



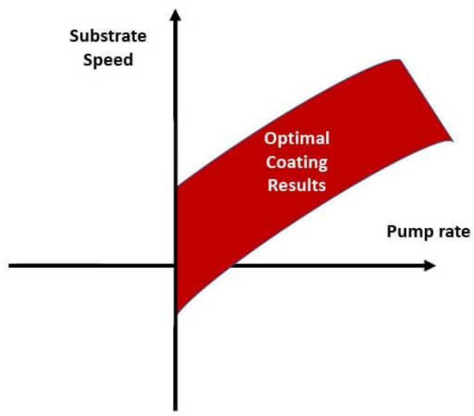
The dry thickness can therefore also be predicted prior to coating by simply taking into consideration the wet thickness, solution concentration (c), and density of the final dry material (ρ).

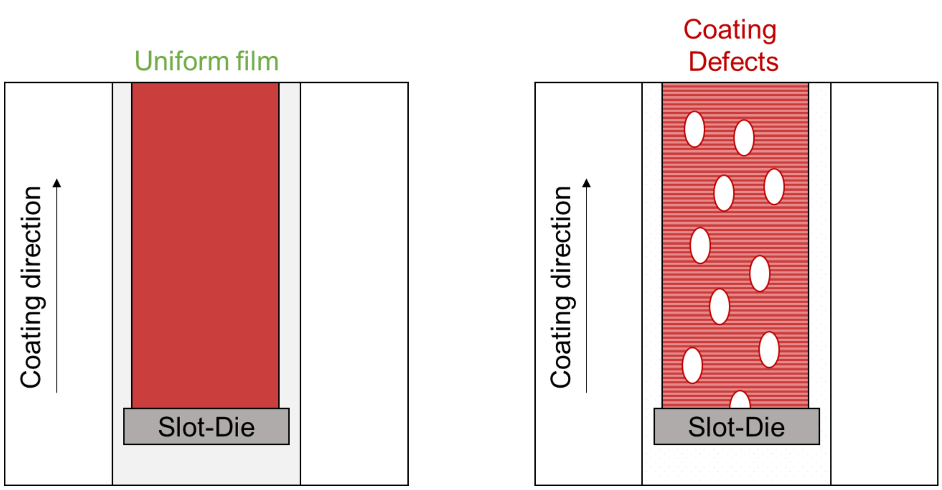
$$d_{dry} = \frac{f}{W \cdot S} \cdot \frac{c}{\rho}$$

6. What determines film quality and uniformity in Slot-Die Coating?

Coating thickness and processing speed are often the primary parameters of interest for users of Slot-Die coating equipment. However, control over the quality of this coating must also be carefully considered. The quality of coating is generally discussed in the context of the "**stable coating window**" of a process. This stable coating window is defined by all of the possible combinations of upstream pressure versus the gap-to-thickness ratio that result in a stable fluid meniscus, thereby avoiding defects in the final coated layer (e.g. dewetting, ribbing, pinholes, etc.).

In practical terms, achieving a defect-free film of a desired thickness is often a matter of choosing a suitable **Slot-Die height**, and simply balancing the **ink pump rate** and the **substrate travel speed** against each other.





However, the boundaries of the stable coating window can also be influenced by the angle of the Slot-Die relative to the substrate, as well as the nature of the inks and substrates being used. Viscosity, fluid surface tension, and surface energy between the fluid and the substrate are just a few of the material properties that can be controlled and optimized to achieve a successful Slot-Die process. At the same time, Slot-Die hardware must be manufactured to a high standard to provide uniform flow and coating properties in any Slot-Die process.

7. What makes Slot-Die Coating so scalable?

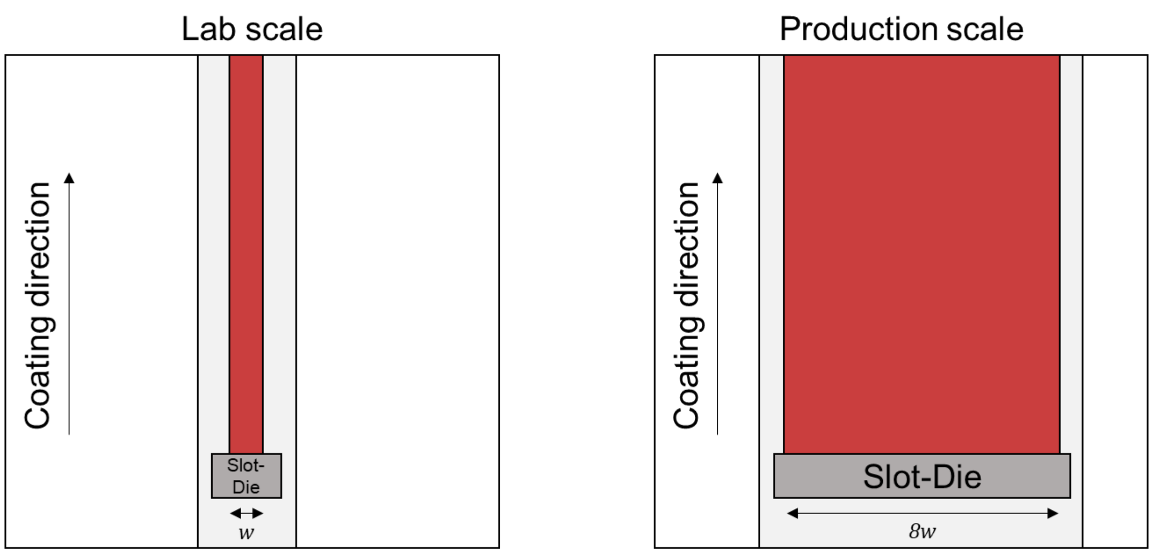
Slot-Die Coating possesses several beneficial properties that combine to make it suitable commercial production, as well as straightforward to move from lab-scale testing to large-area coatings and devices.

A summary of these properties is provided below:

- **Continuous coating:** Slot-Die coating is a continuous, steady-state process. This results in high yield, uniformity and repeatability in the final product. It also makes the process highly time efficient, as many samples can be obtained from a single lengthy coating run with a very large substrate (e.g. a PET foil roll) rather than requiring frequent loading and unloading of smaller substrates in a batch process such as Spin Coating.

- **High material efficiency:** Because nearly all of the coating fluid becomes neatly applied to the substrate, Slot-Die Coating affords excellent material efficiency. As shown in Question 2, results in high output and material cost savings, which are desirable in both research and industry.

- **Rapid throughput and large areas:** Depending on material limitations, Slot-Die processes can be run at up to several hundred meters per minute. In addition to this rapid throughput, the area of a Slot-Die Coated layer can be simply increased by using a larger Slot-Die with a wider coating width. The process of fluid distribution along the substrate remains the same, regardless of the size of the Slot-Die itself. This means that small-scale lab processes can be directly transferred to large-areas via the use of a larger Slot-Die.



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