Paper Title: Improvements in the Process Window and Coating Uniformity for Tensioned Web Over Slot Die Coating

ABSTRACT

This paper will provide a brief history of tensioned web over slot die coating (TWOSD), discuss some unique and relevant advances in the academic study of TWOSD coating, present some interesting intellectual property (IP) filings on the subject, and discuss some of the gaps in academic study and intellectual property. The discussion on the practical application of the technology and the gaps in academic and IP will cover some of the fundamental ways to set up a TWOSD process to gain the most success from it.

HISTORY

Tensioned web over slot die coating (TWOSD) is a relatively new twist on existing slot die coating technology. Slot die coating has traditionally been done against a precision backing roll. This process is well established and the advantages and limitations of it are well known and studied. TWOSD, on the other hand, has only come into practice over the last 40 years.

The practice began in the 1970s with hot melt coating and magnetic media coating. The magnetic media industry continued to push TWOSD technology in the 1980s through intellectual property development around the geometry of the slot die lips. Computer technology in the 1990s enabled the study and development of computer models to compare the performance of slot die technology with empirical data. The 2000s saw proliferation of academic and industrial development based on improving the process and speed through computer models and patents.

The driving force behind the development of the technology was the magnetic media industry. Companies were searching for new ways to speed up the coating process and make thinner coatings. Existing slot die coating technology was reaching its limits for both speed and wet coating thickness. The wet coating thickness was limited by the minimum attainable gap between the slot die and backing roll, typically around 100
microns for the coating gap. TWOSD coating changed that because the gap is set by
the thickness of the wet coating and is dynamic. Existing backing roll slot die coating
proved unable to deal with problems caused by debris getting caught in the coating gap
and creating web breaks, or loss of the coating bead because the coating gap was too
large for the wet film thickness desired. TWOSD coating enabled higher coating speeds
and thinner coatings.

TWOSD has some advantages compared to backing roll slot die coating, including:

- It enables the coating of both sides of the web simultaneously
- The process capability and quality are similar to backing roll coating
- The process enables coating of very thin wet films and very small coating gaps
- The coating gap itself is self-regulating
- The TWOSD process has a large number of degrees of freedom and is very
  flexible

Disadvantages of the TWOSD process are:

- The process is sensitive to web handling
- The large number of degrees of freedom
- The practical knowledge and experience pool is limited
- The process can be complex and is interactive

ACADEMIC STUDIES

Academic focus on TWOSD coating has been on modeling the lower limits for thin film
coating applications and comparing empirical data to the model results. Historically in
fact, the primary focus in industry has also been to find the lower limits on coating
thickness and the highest achievable coating speed. The historical application driving
technology was the magnetic media market.

There have been numerous academic studies on TWOSD coating over the past twenty
plus years. The primary assumptions made in those studies (Lin, Liu, Liu, Wu, 2008)
are as follows:

- The flow field is governed by the Navier-Stokes system
- Fluid flow in the coating bead is described by lubrication theory
- The coating web is treated by membrane theory
- Web tension is balanced by fluid pressure at the slot exit
- Fluid flow is two-dimensional and does not vary across the width
- Galerkin finite element analysis is used for solving the equations

TECHNOLOGY APPLICATION
The critical parameters of TWOSD coating can be identified in Figure 1. Items 1 and 2 indicate upstream and downstream web stabilizers. The types and positions of these stabilizers are important for controlling the position of the web as it enters and leaves the coating section. Items 3 and 4 indicate the position and angle of the slot die relative to the web path. Items 5, 6, and 7 identify slot die specific set-up parameters such as the coating gap, slot die lip offset, and the geometrical surface of the slot die lip faces. Item 8 includes the web tension, type of web, quality of web, and speed of the web. Item 9 relates to the design of the slot die relative to item 10, the fluid rheology.

In further discussion of the critical parameters, the upstream and downstream web stabilizers are drawn as idler rollers. In practice, the web stabilizers have traditionally been different types of idler rollers, but have also been listed in patent literature as tenter-frame-like grippers (Okuno, 2005), positive pressure air nozzles (Seidl, 2011), and even negative pressure vacuum nozzles (Anderson, 2012). Other patents and applications have used opposing slot dies, and even different forms of smoothing or spreading bars (Nasu, 2013) opposing the slot die for stabilizing the web at the coating bead.

In comparison, backing roll slot die coating has similar, but fewer critical parameters. These are listed in Figure 2 and explained. The primary difference between TWOSD coating and backing roll coating is that the web is stabilized by the path it takes over the backing roll. This simple change eliminates three of the critical parameters used for web stabilization in TWOSD, and a multitude of web stabilization combinations or permutations. Items 1 through 6 in Figure 2 are related to the geometry and setup of the slot die in relation to the backing roll. Item 7 relates to the coating type and rheology.
In empirical study, the author finds the following parameters relevant for understanding TWOSD: the tension number, pressure number, and capillary length (Lin, Liu, Liu, Wu, 2007). These are further defined as:

- Tension Number, \( T_N = \frac{\mu V}{T} \)
- Pressure Number, \( P_N = \frac{P_{ac}WH}{(D/L)\Theta^*} \)
- Capillary Length, \( L_N = \frac{L}{(\sigma/\rho g)^{0.5}} \)

Where:
- \( D = \frac{Et^3}{12(1-v^2)} \)

- \( P_{ac}WH \) represents total force of the coating on the gap
- \( (D/L)\Theta^* \) represents the internal force of the substrate
- \( E \) and \( v \) are Young's modulus and Poisson ratio of the substrate

The academic research into modeling the lower limits for wet coating has provided valuable insight into the physics governing the TWOSD coating process. It has proven...
the ability to predict vortices within the coating bead and other defects caused by coating bead instability. Academic research has also predicted the performance of certain lip geometries. However, the research and modeling is not yet advanced enough to deal with the three-dimensional problem of coating the full width of a web and non-uniformities within the web itself.

It is much more difficult to find practical or industrial studies on improvements in TWOSD coating. These examples are limited to intellectual property filings and technical publications for conferences and trade shows, so the amount of learning can be limited. In this author’s experience, careful study of the referenced academic literature and intellectual property coupled with some practical experimentation can lead to optimized TWOSD coating processes that have quality and capability equal to traditional backing roll coating processes. The following examples show TWOSD coating processes that have been optimized for specific water-based anode coating on narrow web for lithium ion battery applications.

The first set of results, shown in Table 1, are for a simultaneous double-side coated foil with 142 g/m² dry coat weight coated at 170 mm wide. The coating was a water-based anode at 33% solids coated at 1 m/min. and dried in a flotation dryer.

<table>
<thead>
<tr>
<th>Sample (1 m apart in MD)</th>
<th>OP SIDE</th>
<th>CENTER</th>
<th>GR SIDE</th>
<th>Mean</th>
<th>Range</th>
<th>%</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>282.7</td>
<td>285.5</td>
<td>286.6</td>
<td>284.9</td>
<td>3.9</td>
<td>1.4%</td>
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<td>2</td>
<td>283.8</td>
<td>287.3</td>
<td>285.5</td>
<td>285.5</td>
<td>3.5</td>
<td>1.2%</td>
</tr>
<tr>
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<td>286.6</td>
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<td>285.5</td>
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</tr>
<tr>
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<td>284.8</td>
<td>284.9</td>
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<td>285.5</td>
<td>285.9</td>
<td>284.6</td>
<td>3.5</td>
<td>1.2%</td>
</tr>
<tr>
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<td>286.2</td>
<td>285.3</td>
<td>3.5</td>
<td>1.2%</td>
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<tr>
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<td>286.6</td>
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<td>1.5%</td>
</tr>
<tr>
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<td>284.8</td>
<td>288.0</td>
<td>288.0</td>
<td>287.0</td>
<td>3.2</td>
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<tr>
<td>9</td>
<td>284.8</td>
<td>287.3</td>
<td>288.0</td>
<td>286.7</td>
<td>3.2</td>
<td>1.1%</td>
</tr>
<tr>
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<td>286.6</td>
<td>287.7</td>
<td>286.5</td>
<td>2.5</td>
<td>0.9%</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>283.7</td>
<td>286.6</td>
<td>286.6</td>
<td>285.6</td>
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</tr>
<tr>
<td>RANGE</td>
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</tr>
<tr>
<td>RANGE AS A PERCENT OF MEAN</td>
<td>1.0%</td>
<td>0.9%</td>
<td>1.1%</td>
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<td></td>
</tr>
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</table>

The combination of slightly specialized slot die lips and balancing the web tension force against the coating bead pressure against a tensioned web yielded the results above without the use of any specialized web stabilization. In this case, the coating variation was less than +/-1% across the width.

The next example using the same coating above at 100 g/m² dry yielded similar results for a wider coated width of 300 mm and at a speed of 2 m/min. Although the results shown in Table 2 are not quite as accurate as the results for the 170 mm wide example, the process in this last example was not modified. These results were achieved within a
few hours of testing and further optimization of the process is easily attainable. This example also did not use any special web stabilization means, but does show that uniformity and quality is similar to the even narrower width.

Table 2

<table>
<thead>
<tr>
<th>Sample (1 m apart in MD)</th>
<th>OP SIDE</th>
<th>OC</th>
<th>CENTER</th>
<th>GC</th>
<th>GR SIDE</th>
<th>Mean</th>
<th>Range</th>
<th>%</th>
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<td>99.3</td>
<td>2.1</td>
<td>2.1%</td>
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<tr>
<td>2</td>
<td>99.7</td>
<td>99.4</td>
<td>98.7</td>
<td>99.4</td>
<td>98.3</td>
<td>99.1</td>
<td>1.4</td>
<td>1.4%</td>
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<tr>
<td>3</td>
<td>100.5</td>
<td>99.7</td>
<td>98.3</td>
<td>100.8</td>
<td>100.5</td>
<td>100.0</td>
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<td>2.5%</td>
</tr>
<tr>
<td>4</td>
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<td>99.4</td>
<td>100.1</td>
<td>100.5</td>
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<td>100.0</td>
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<tr>
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<td>100.8</td>
<td>100.3</td>
<td>2.1</td>
<td>2.1%</td>
</tr>
<tr>
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<td>100.1</td>
<td>100.2</td>
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<td>1.4%</td>
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<td>1.8%</td>
</tr>
<tr>
<td>9</td>
<td>100.5</td>
<td>99.4</td>
<td>99.0</td>
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<td>99.4</td>
<td>2.1</td>
<td>2.1%</td>
</tr>
<tr>
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<tr>
<td>AVERAGE</td>
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</tr>
<tr>
<td>RANGE AS A PERCENT OF MEAN</td>
<td>1.4%</td>
<td>1.4%</td>
<td>1.8%</td>
<td>1.8%</td>
<td>2.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSION

These examples of achievable coating uniformity without special web stabilization are the result of experience-based testing. The drawback to the limited knowledge base on optimizing TWOSD coating is that the available academic and industrial knowledge only provides a portion of the information required to optimize a given coating process. The remaining details are found through careful scientific experimentation within the constraints provided. It is worthwhile to note that the machine and cross-machine uniformities for each of the examples were nearly identical in each case. It would be difficult to conclude that the wider web example had greater non-uniformity simply because the web was wider, because the machine direction uniformity is essentially the same as the cross-machine uniformity, indicating a potential machine-direction component to the variation.

Future work includes studying improvements in the TWOSD process for wider webs and confirming that the process is capable of achieving the same quality and uniformity as conventional backing roll coating. The energy storage market is currently coating webs up to 1.3 meters wide, but most commonly coats web widths around 600 mm wide. There are TWOSD coating machines installed within the energy storage industry ranging from 200 mm wide to 1.3 m wide. However, the actual performance of these coating lines is not well known.

In addition, the existing body of academic work for TWOSD coating is focused on thin films and high speeds. The energy storage market is always gearing for higher coating
speeds, but the coating thickness can be at either extreme of the process window for thin and thick coated films.

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References


