Rethinking the Paper Cup – Beginning with Extrusion Process Optimization for Compostability and Recyclability

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ABSTRACT

More than 50 billion disposable paper cups used for cold and hot beverages are sold within the United States each year. Most of the cups are coated with a thin layer of plastic – low density polyethylene (LDPE) – to prevent leaking and staining. While the paper in these cups is both recyclable and compostable, the LDPE coating is neither. In recycling a paper cup, the paper is separated from the plastic lining. The paper is sent to be recycled and the plastic lining, if LDPE, is sent to landfill. In an industrial composting environment, the paper and lining can be composted together if the lining is made from compostable materials. Coating paper cups with a compostable performance material uniquely allows for used cups to be processed by either recycling or composting, thus creating multiple pathways for these products to flow through a circular economy.

A segment of the paper-converting industry uses an extrusion grade of polylactic acid (PLA), frequently for zero-waste venues and for municipalities with local composting and food service items ordinances. The results among these early adopters reveal process inefficiencies that elevate manufacturing costs while increasing scrap and generally lowering output.

NatureWorks and Sung An Machinery (SAM) North America researched the extrusion coating process utilizing the incumbent polymer (LDPE) and PLA. Ingeo™ 1102 is a new, compostable, and bio-based PLA grade designed specifically for the extrusion coating process. The research team identified the optimum process parameters for new, dedicated PLA extrusion coating lines. The team also identified changes to existing LDPE extrusion lines that processors can make today to improve output.

The key finding is that LDPE and PLA are significantly different polymers and that processing them on the same equipment without modification of systems and/or setpoints can be the root cause of inefficiencies. These polymers each have unique processing requirements with inverse responses. Fine tuning existing systems may improve overall output for the biopolymer without capital investment and this study showed an increase in line speed of 130% by making these adjustments. However, the researchers found that highest productivity can be achieved by specifying new systems for PLA. An increase in line speed of more than 180% and a reduction in coat weight to 8.6 µm (10.6 g/m^2 or 6.5 lb / 3000 ft^2) was achieved in this study. These results show that Ingeo 1102 could be used as a paper coating beyond cups.

INTRODUCTION

The modern paper cup was developed in 1908[1] to reduce the threat of transmitting disease from using non-sterile cups. Public health and hygiene needs continue to drive growth in single-use drinking cups.

Another factor contributing to growth in single-use food service products is today’s on-the-go lifestyles that take consumers out of the home more often for meals. Many of these food expenditures occur at fast-food restaurants or other limited service venues where the convenience of lightweight products to carry food from counter to a table or car are valued. Concern about responsible use of resources and environmental damage due to pollution, waste, and littering have increased as use has risen. With more than 50 billion disposable paper cups sold each year in the USA, it is incumbent on society to offer viable end-of-life options that capture the valuable plant fiber and reduce the volume ending up in landfills.

Firmly entrenched as the mainstream incumbent, LDPE is a non-renewable, non-compostable petrochemical plastic coating. For more than 50 years cups have been made with an LDPE liquid barrier. Manufacturing operations and LDPE grades are finely tuned for high speed / low waste manufacturing. Marlex 4517 is a dominant extrusion coating resin for paper cups. In this paper we will refer to it as LDPE-1.

Two parallel efforts are underway to reduce the amount of paper cup fiber ending up in landfills. One increases the amount of fiber being routed to paper mills for recycling and the second expands the number of compostable cups for public venues and fast-food operations. There is potential to have the option for both paths with a compostable polymer coating.

Recycling

Materials, including cups, which are placed in recycle bins are sorted at Material Recovery Facilities (MRFs) based on bale specifications. Bales are sold to mills for fiber recovery. The Foodservice Packaging Institute endeavors to have paper cups included in the bale specifications at recycling centers. Including cups in bales going to mills for fiber recovery would raise the recycling rate and diminish fiber destined for landfills.

Composting

Paper contaminated with food waste collected at venues such as schools, universities, sports and music events, and fast-food companies are suitable for composting, but not recycling. Since LDPE does not compost, one solution would be to extrude a moisture barrier of PLA so the cup can be recycled or composted.

Ingeo™ is a new family of performance materials made from PLA derived from annually renewable plant resources that has been developed for a wide range of applications, including packaging, 3D printing, fibers, and durables. PLA has been used on existing LDPE lines to produce compostable cups. These lines have historically shown reduced line speeds, increased scrap rates, and increased spending on raw materials – resin and scrapped product. Differences in performance were expected, as those lines have been optimized for a completely different polymer going back over 50 years.

To overcome some of the aforementioned difficulties, NatureWorks engaged in a multi-year research effort to develop the new grade of Ingeo 1102, referred to in this paper as PLA-1, which is better suited for extrusion coating applications using assets designed for LDPE. This new Ingeo grade significantly improved output when compared to earlier PLA extrusion grades. However, once this product was commercialized on production size lines, a new hypothesis emerged: could processing results be even better?

A research team of scientists at NatureWorks and Sung An Machinery (SAM) North America began to investigate the extrusion process and its impact on two distinctly different polymers LDPE-1 and PLA-1. The point of the research was to identify the critical process factors responsible for maximum output for LDPE-1 and PLA-1.

CURRENT PROCESSING SITUATION

When investigating current LDPE extrusion lines that run PLA, the researchers found that the typical coating arrangement consisted of:

1. High-shear extrusion coating feed screw;
2. Back-pressure valve open for PLA as opposed to closed for LDPE;
3. Low-pressure T-slot die with internal deckles;
4. Die lip to chill roll – minimum air gap for PLA, maximized air gap for LDPE.

Analyzing this arrangement, the research team concluded:

- Output of PLA was limited due to high melt temperature caused by high shear from the screw. It should be noted that the maximum processing temperature of all PLA grades is at least 55-75°C lower than LDPE.
- Minimum valve pressure setting to reduce heat generation in PLA
- Curtain stability limited due to:
    - High melt temperatures
    - Thinning capabilities at edges
    - High draw down ratios where
        - $DD_{ratio} = \frac{V_{chill\,roll}}{V_{die\,lip\,exit}}$
    - High draw down rates (%/min)
        - $DD_{rate} = 100 * \left(\frac{V_{chill\,roll}+V_{die\,lip\,exit}}{2*Air\,Gap}\right) * (DD_{ratio} + 1)$
- Edge bead (thick bead due to neck-in, which reduces the effective nip pressure and lowers adhesion)
- Neck-in (need to discard more paper – the thick coated part is unusable)
- Curtain stability (gauge variation and draw resonance).

With this understanding of the current processing situation, the research team assembled equipment and designed tests to deconstruct the process to understand the optimum process parameters of LDPE-1 and PLA-1.

EQUIPMENT

The trial studies were run on the laboratory extrusion coating line of SAM NA. The main line includes an unwind station, corona treater, priming station with dryers, flame treater, coating/lamination station, trim station, thickness gauge, and turret rewind station. (Figure 1) A secondary unwind includes a web path to the laminator for optional use in lamination mode. There is a three-extruder co-extruder station with a 5-layer feedblock convertible to 14 layers using layer multiplication as well as an internal deckled T-slot die.

The unwind station is a single-position spindle. The running width limit is 89 cm (35 in) and the diameter limit is 102 cm (40 in). The unwind is fitted with 7.6 cm (3 in) or 15.2 cm (6 in) outer diameter core shafts. 30.5 mm (12 in) core adapters are also available.

The corona treater improves the surface energy of the substrate coming out of the unwind station. Once engaged, the corona treater blasts the substrate’s surface via an electrode to form a charged corona at the web surface to improve wettability.

The flame treater is designed primarily for treatment of paperboard; it applies a flame onto the substrate to treat the surface, bringing up the temperature, and singeing raised fibers from the surface before the substrate has contact with polymer melt curtain. The flame chemistry is managed with a plasma analyzer, and the flame power is measured in BTU/in (kW*h/mm).

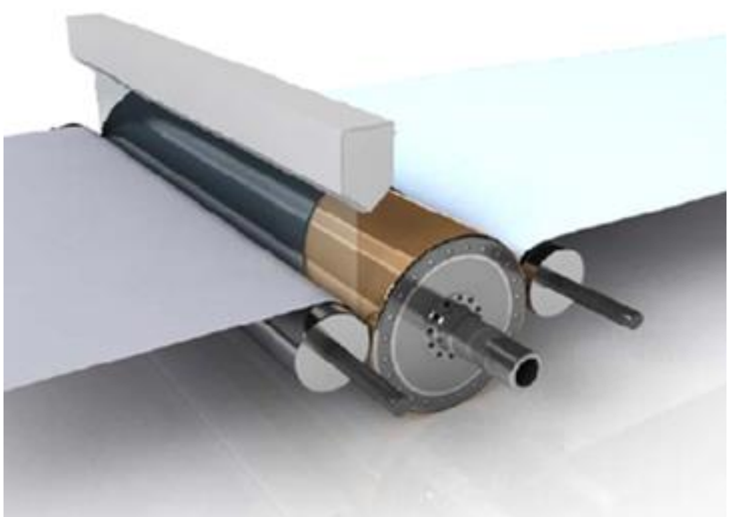


Figure 1: Diagram of extrusion coating line.

The SAM NA lab line coater/laminator is currently configured with one cooling roll, which has a diameter of 75 cm (29.5 in). The pump connected to the cooling roll provides 760 liters of coolant per minute. The coolant used is a mix of 70% of water and 30% of ethylene glycol. Three chill roll finishes are available: #60 matte, #120 Matte, and a mirror polish. Matte surface tends to be easier for material to peel off the cooling roll, while mirror surface gives a higher gloss finish to the coating. The coater/laminator may be arranged with up to 3 cooling rolls in sequence.

A beta scanning gauge is mounted right after the trim station. The gauge is controlled by a computer located right next to the data processing computer. The scanner may be used with the auto-profile control die to manage cross-web coat weight uniformity. The minimum line speed for the gauge is 15 m/min.

The rewind station is a two-direction turret so the web may be wound with either top (coated) side wound in or wound out. Maximum wound roll diameter is 75 cm. The winder is designed with a bump and cut transfer knife or may be alternately set up with a static cut-over (tapeless) system.

SAM NA lab uses three co-extruders mounted on a movable “XYZ” carriage. Screw A, used inside extruder A, is the largest of the three screws with a diameter of 63.5 mm (2.50 in) and an L/D (Length to Diameter Ratio) of 34:1. Extruder A has three different screw designs available: an extrusion coating screw (high shear), a compromise screw (medium shear) and a low shear screw. (Figure 2) The extrusion coating screw has a length of metering and mixing sections that equal 66% of the length of the screw, and it typically creates a resin temperature range between 310 °C to 330 °C (590-630 °F), which works well for extrusion coating grade resin such as LDPE, medium density polyethylene (MDPE), and ethylene-methacrylic acid copolymers (EMAA). The compromise screw has a length of metering and mixing sections that equal 46% of the length of the screw. This creates a resin temperature window from 290°C to 320°C (555-610 °F), which suits moderate temperature extrusion coating grade polymer such as MDPE, high-density polyethylene (HDPE), and linear-low-density polyethylene (LLDPE). The low-shear screw also has a length of metering and mixing sections that equal 46% of the length of the screw, and a resin temperature window from 205°C to 260°C (400-500 °F). The low shear screw is used for specialty shear & temperature sensitive polymers such as ethylene-vinyl alcohol (EVOH), PLA, and ethylene-vinyl acetate (EVA). Key dimensions of feedscrews are provided in Table 1.

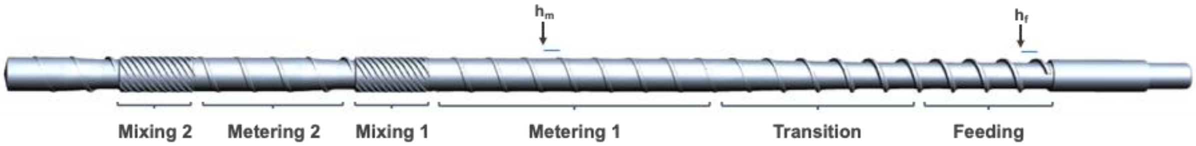


Figure 2: High-Shear Screw Design

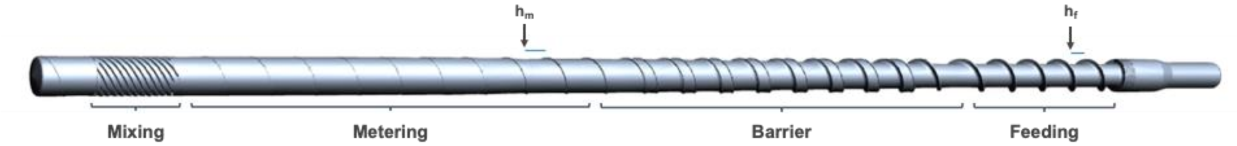


Figure 3: Low-Shear Barrier Screw Design

Key Feedscrew Dimensions					
Feature	Ref	Units	Screw Design		
			Ext. Ctg.	Compromise	Low Shear
Feed Depth	h_f	mm	10.9	12.7	12.7
Meter Depth	h_m	mm	2.8	3.6	4.3
Compression Ratio	h_f/h_m	-	3.8	3.6	2.9
Critical Shear Gaps					
Gap Location		Units	Ext. Ctg.	Compromise	Low Shear
Barrier Undercut		mm	None	1.14	1.14
Mixer 1 Undercut		mm	0.51	0.64	0.76
Mixer 2 Undercut		mm	0.64	None	None

Table 1: Key Dimensions of Feedscrews, see Figure 2 or Figure 3 for location of feed depth(h_f) and meter depth (h_m).

Each extruder has multiple barrel heating zones. Cooling fans are mounted on those zones for temperature control and barrel cooling. A linear valve is mounted at the end of the “A” extruder barrel, which can be controlled from control panel computer to adjust resin pressure, thus providing temperature adjustment.

The coextrusion feedblock and die used in SAM NA lab are from Nordson EDI. The feedblock is a five-layer adjustable vane design; the adjustable vanes are insert mounted on two combining planes. Between the combining planes, a layer multiplier system allows the layers assembled at the first combining plane to be multiplied: 0, 2, or 4x. This allows for up to 14-layer coextrusion. The extruder feed streams are directed into the combining section through an interchangeable flow spool. The die features an internal deckle system, which enables the die to coat different width. The maximum die slot width is 1015 mm (40 in), which allows coating up to approximately 890 mm (35 in) width depending on polymer melt strength and neck-in characteristics. The die has automatic adjustable bolts on one-inch centers across the flex-lip side. The bolts may be adjusted manually or automatically based on total weight feedback from the Eurotherm EGS gauge.

RESULTS

FACTORS IMPACTING COATING SPEED – SCREW DESIGN

LDPE polymer has long and short chain branches with broad molecular weight distribution (MWD) shown in Figure 4.

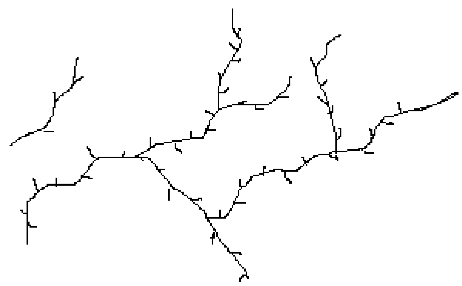


Figure 4: Diagram of low-density polyethylene.

During processing, LDPE has high melt strength and low viscosity with low neck-in, no draw resonance, and increased adhesion through oxidation [2]. Due to the low polymer melt viscosity, the screw design must input high shear stress in the metering/mixing zone to develop the required melt temperature and oxidation. Optimum extrusion temperature is greater than 316°C (600°F).

PLA features linear molecules with narrow molecular weight distribution shown in figure 5.

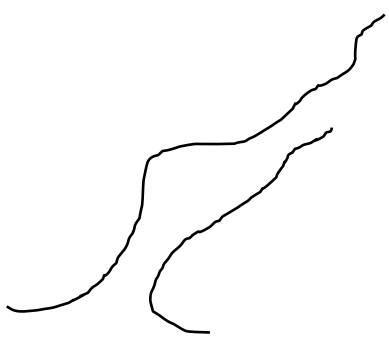


Figure 5: Diagram of polylactic acid.

During processing, PLA has low melt strength and high viscosity with high neck-in, draw resonance that limits line speed, and increased adhesion reducing heat loss. Due to the high polymer melt viscosity, too high of a shear stress input through the metering/mixing zone of the screw may overheat and degrade PLA resins. Optimum operating temperature is less than 250°C (480°F). At higher temperatures, PLA begins to degrade, resulting in excessive fuming and loss of mechanical strength.

As opposed to common knowledge of LDPE, where screw design has a slight effect on melt temperature and therefore the maximum output is not restricted by screw speed, with PLA, the screw design and screw speed have a profound impact on melt temperature and therefore output. Three different screw types were evaluated for their impact on the optimum output of LDPE-1 and PLA-1 based on the optimum operating temperatures of these two polymers. The three screw types tested were:

Screw Design 1: Single Flight Double Mixer – High Shear (SFDM-High Shear). SFDM-High Shear is a typical, high-work screw optimized for LDPE extrusion coating grades. SFDM-High Shear produces temperatures greater than 315°C (600°F), which is optimum for high volume output of LDPE.

Screw Design 2: Barrier Flight Single Mixer – Moderate Shear (BFSM-Moderate Shear). This is a moderate-work screw for low-to-moderate output operations running a mix of LDPE and specialty grades. Output temperature for LDPE exceeds 307°C (585°F) and for specialty grades less than 250°C (480°F).

Screw Design 3: Barrier Flight Single Mixer – Low Shear (BFSM-Low Shear). BFSM-Low Shear is a specialty, low-work screw utilized for production of low-temperature specialty grades such as Ethylene Vinyl Acetate (EVA) and Ethylene Vinyl Alcohol (EVOH). Typical temperatures are less than 240°C (460°F).

All three of these screw types were run at 75 revolutions per minute (RPM). Output and temperature comparisons were measured on both LDPE-1 and PLA-1. (Table 2)

Screw Comparison At 75 RPM

Screw Design	**LDPE-1**	**PLA-1**	**PLA-1**
	Temperature	Temperature	Output
	°F (°C)	°F (°C)	Kg/H
SFDM-High Shear	615 (324)	485 (252)	78
BFSM-Moderate Shear	598 (314)	487 (253)	107
BFSM-Low Shear	579 (304)	481 (249)	119

Table 2: Effect of screw design on temperature.

The tests showed that under controlled conditions of identical RPM, the SFDM-High Shear screw imparted the optimum temperature to LDPE-1 polymer. For PLA-1, the temperatures were similar, but the output rate was much higher on the low shear screw. The low shear screw gives the benefit of high output rate for PLA-1 while not exceeding PLA's optimum extrusion temperature. With the high shear screw, manufacturing is not efficient because the output rate of PLA-1 is low to ensure the maximum temperature is not exceeded. Smoke and fumes indicated the onset of PLA-1 degradation. Excessive fuming was present above 255°C (490°F). Degradation was independent of screw design.

Conversely, the BFSM-Low Shear was improved for PLA-1's temperature requirements but was the worst solution for LDPE higher temperature requirements.

The implication is that with all other factors on the line remaining unchanged, processors wishing to run LDPE and PLA-1 using the same high-shear screw will find the over-heating and degrading PLA a challenge to control. Later in this paper, researchers offer suggestions on what adjustments can be made to optimize existing equipment for PLA-1 extrusion and the efficiencies they can expect compared to LDPE-1.

FACTORS IMPACTING COATING SPEED – MELT-CURTAIN STABILITY

There are multiple factors that impact melt-curtain stability. Two that were studied are:

- The temperature imparted on the polymer by the screw;
- The lip-gap effects of draw-down ratio and draw-down rate.

The screw design has already been discussed. The research turned to study lip-gap effects on the melt curtain stability. Theoretically, the faster a polymer is drawn down from the die, the higher the internal forces causing resonance. Draw resonance places an upper limit of line speed. Neck-in is dependent on the polymer melt strength, output rate, and run speed. Melt curtain stability is the balance of melt strength and drawability.

Extrusion grade LDPE has been optimized for draw down. LDPE, due to its long chain branching and broad MWD, resists resonance and neck-in at optimum temperature and high speed. Neat PLA is the opposite. Due to its linear structure and narrow MWD, it is susceptible to both resonance and neck-in, especially at higher temperatures.

Various adjustments of draw down speed and machine settings were tested. The research found that PLA-1 melt curtain became unstable whenever Draw Down Ratio (DDR1) exceeded 36:1* [* Critical DDR1].

Where

- $DDR1 = \frac{veloctiy\ at\ chill\ roll}{velocity\ at\ lips}$

- $DDR1 \sim \frac{lip\ gap}{coating\ thickness}$

PLA-1 can exceed previous line speed limitations when melt temperature is held below 250°C (480°F) and critical DDR1 – the ratio of 36:1 – is maintained. Reducing die lip gap increases velocity at lips. For example, a base line speed of 150 (m/min) was achieved with a lip gap of 0.63 mm (0.025 in). This was improved to 180 (m/min) at 0.51

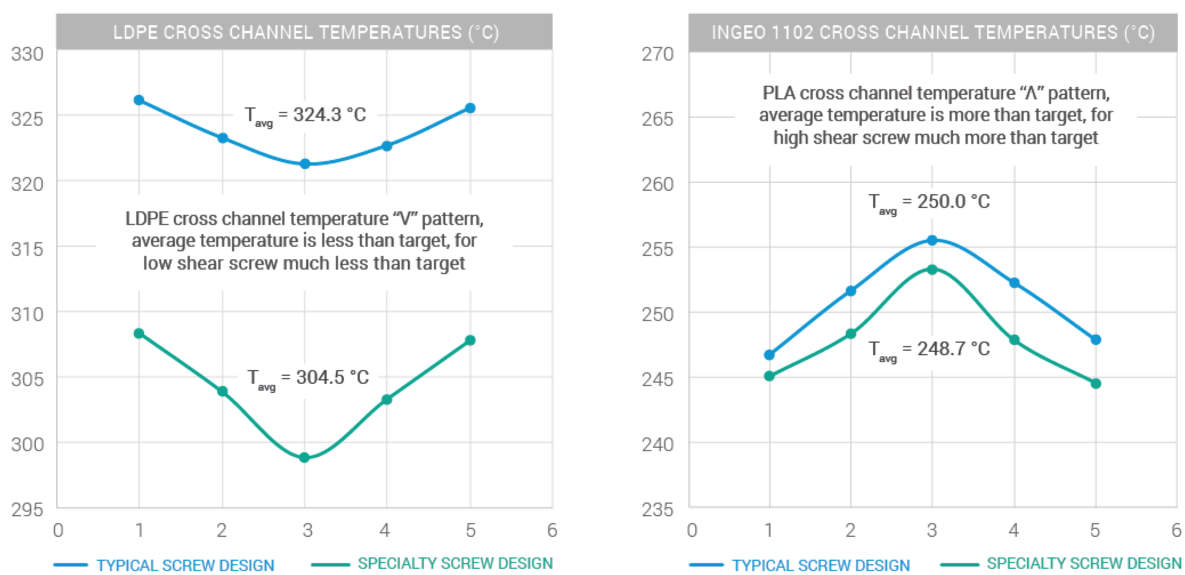
mm (0.02 in) lip gap. In a future report, researchers will show that encapsulating the edges of PLA-1 with LDPE-1 increases the critical DDR1, resulting in even higher line speeds.

FACTORS IMPACTING COATING SPEED – UNDERSTANDING TRUE MELT TEMPERATURE

It is clear that the high-work screw optimized for high melt temperature, low viscosity, thermally stable LDPE-1 is not good for the high viscosity, thermally sensitive PLA-1.

As part of the research, SAM measured temperature of LDPE-1 across the channel and found a **V-**shape temperature variation with hotter temperature near the edges and cooler temperatures near the center of the channel. For optimum performance, the processor should try to lower the wings of the **V** to as straight a line as possible. Note that the minimum temperature will frequently limit LDPE processing due to loss of bond. A Dynisco model RMT retractable melt thermocouple is a low cost means to have a full picture of internal channel temperature.

The channel temperature profile of PLA-1 is the opposite of LDPE-1, see Figure 5 and Figure 6. The profile is an ascending **Λ** with cooler temperature at the edges and hotter temperature at the center. The more this ascending curve can be flattened into a straight line the higher the throughput. Note that the maximum temperature will frequently limit PLA processing due to degradation leading to instability.



Figures 6, 7: Melt temperature as a function of channel diameter for LDPE-1 and PLA-1 using a typical screw and specialty screw.

To find the optimal settings for your existing screw design, one must measure the true center melt temperature as a function of output. In Figure 8, the line speed was increased, and the center stream melt temperature of PLA-1 was recorded. Optimal melt temperature of PLA-1 is 250°C or less. From Figure 8, at a desired coat weight of 23.6 g/m^2 (GSM), the max line speed for our test was approximately 105 m/min. Remember that our output rate was limited by melt temperature, and thus the line speed to generate a specific coating weight is linked to that maximum output rate paired with the coating (and die) width.

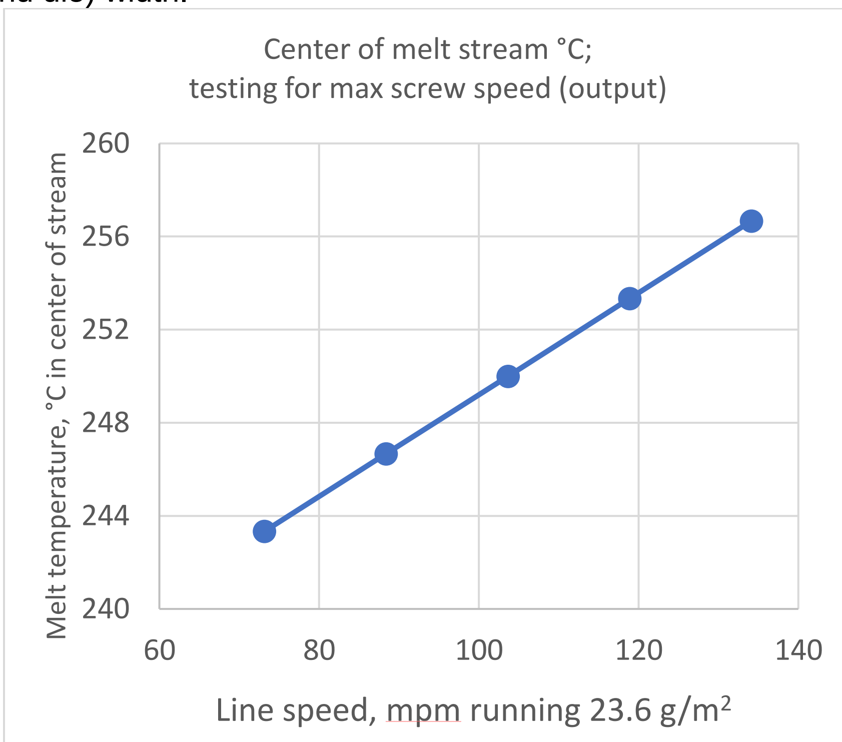


Figure 8: Melt temperature in the center of the PLA-1 stream as a function of line speed in meters per minute at a constant coat weight of 23.6 g/m^2.

COATING WEIGHT AND COATING THICKNESS

It is important to make a point about coating weight and coating thickness. The extrusion industry's standard measure of achieving the correct barrier coat is to measure the weight of LDPE over a square meter sample. PLA-1 achieves the same barrier thickness at 133% of the weight of LDPE-1 because PLA-1 has higher density than LDPE-1. Measurements of thickness of the barrier coat over a square meter of paper should be adjusted accordingly. A coating weight of 23.6 g/m^2 for PLA-1 is comparable thickness to a coating weight of 17.7 g/m^2 for LDPE-1. Both would be roughly equivalent to a 19 µm thickness.

To test the limits of PLA-1 and answer our hypothesis that PLA-1 can coat better than current PLA grades in extrusion coating the line speed was increased while maintaining constant extruder output RPMs. Holding the extruder output constant at 112 kg/hr and increasing the line speed early reduces the coat weight. (Figure 9) Coat weight was reduced to 8.5 g/m^2 (6.9 µm thickness) when the onset of draw resonance was observed. The die gap was also reduced for this experiment to observe the most significant decrease in coat weight possible.

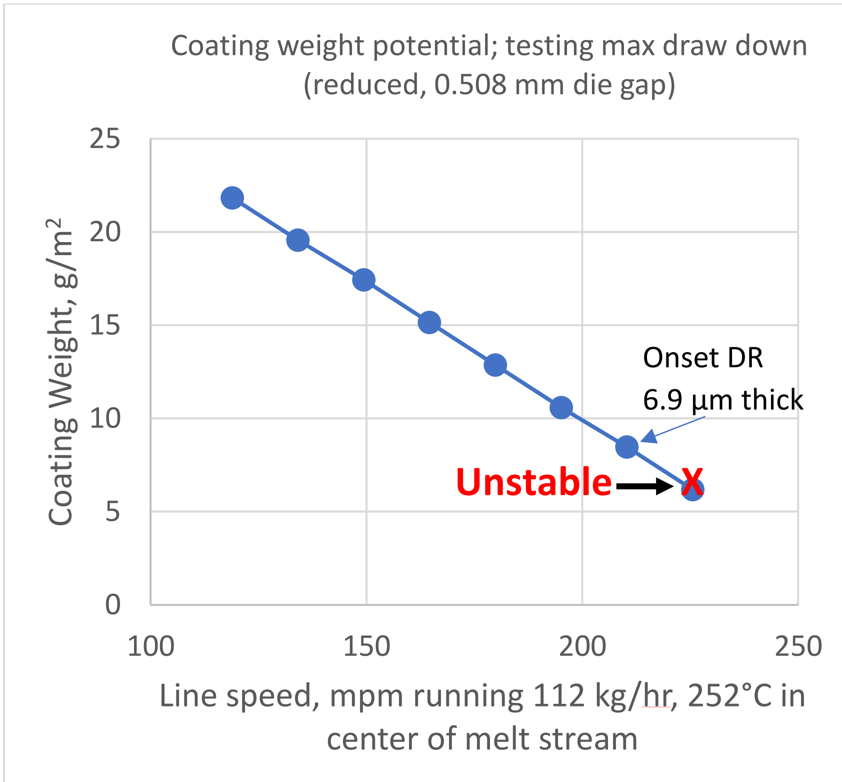


Figure 9: Coating weight in g/m^2 as a function of line speed at constant extruder output of 112 kg/hr of PLA-1.

Table 3 shows the relative output increases during the research project.

	OUTPUT AT 75 RPM		LINE SPEED		
	LDPE-1	PLA-1	PLA-1		
	Output (KgPH) / Temp °C	Output (KgPH) / Temp °C	% increase over typical screw design	% increase over typical screw design	% increase when reducing die lip gap
Single Flight Double Mixer Typical Extrusion Coating Design	50 / 324	78 / 252	-	-	130%
Melt Barrier Flight Single Mixer Moderate Shear Design Compromise Extrusion Coating Design	66 / 314	107 / 253	137%	131%	-
Melt Barrier Flight Single Mixer Low Shear Design Specialty Extrusion Coating Design	64 / 304	119 / 249	153%	143%	186%

Table 3. Relative output increases as a function of screw design, die gap reduction, and edge bead encapsulation.

Coat weight can be significantly reduced under these optimized extrusion conditions by increasing line speed while holding extruder output constant. An astounding coating thickness of just 8.6 µm (0.34 mil or 10.6g/m^2) was obtained at optimal conditions.

CONCLUSIONS

For those operators wishing to use PLA-1 on existing equipment, it is paramount to measure the true melt temperature of PLA-1 across the channel. Maintain a temperature level that is less than 255°C (490°F). We also recommend reducing the die lip gap to increase line speed, striving to ensure the critical DDR1 ratio is less than 36:1. If encapsulated edges are used, then a higher DDR1 may be tolerated.

The highest output extrusion rates for PLA-1 for paper cup applications will be on lines where a BFSM-Low Shear screw is used. The die lip gap must be minimized to less than a DDR1 ratio of 36:1

We saw the impact of several key variables in extrusion coating. We learned that LDPE-1 and PLA-1 have an inverse temperature response, this may be unexpected but is valuable information for operators. Center melt temperatures must be measured and cannot be gauged using historical experience with LDPE. Optimal screw design had the largest impact in lowering melt temperature as a function of throughput, and therefore increasing output of PLA-1. Coat weight requirements should be evaluated based on performance attributes in the final articles to understand if thickness, barrier, or other properties are driving functionality. PLA-1 and this report can be a tool in the toolbox for optimization and training on extrusion coating lines.

The coating thickness needed to provide the functionality required by the packaging article to be made will vary with application. The ability to reduce PLA-1 coating weights using best process and equipment designs opens the application space beyond cups requiring high performance liquid packaging seals to applications where modest barrier or seal strengths and lighter coatings are needed alongside compostability and recyclability. With the exceptional oil and grease resistance (OGR) of PLA, this new coating grade should be considered for paper-based packaging applications in need of OGR.

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