ECONOMIC BENEFITS OF MACHINE DIRECTION ORIENTATION

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Abstract

Plastics continue to be a high growth raw material for use in packaging applications. Polyethylene (PE) is the largest volume plastic used in the packaging industry, yet it is unclear how a new PE resin can, by itself, address the number one industry priority: *reducing cost*. This paper will demonstrate an innovative approach for addressing this underlying industry need that is a collaborative effort by combining polymer science, extrusion engineering, treating/printing technologies and downstream conversion considerations.

Introduction

The $400 billion global packaging industry consumes 29% of all the thermoplastics produced in the world[1]. Polyolefins represent over 60% of all the thermoplastics globally produced[2]. This implies that there are a lot of polyolefin resins used to produce both flexible and rigid packaging. And why wouldn't there be? After all, polyolefins are the lowest cost resins with the lowest densities compared to other plastics and have the broadest range and flexibility of use in the various fabrication methods and end use applications. In fact, most converters and buyers of packaging would prefer that polyolefins satisfy every "job" that needed to be done. Unfortunately, polyolefins do not always meet the specific end-use requirements, such as applications that demand high heat resistance, high barrier properties or other performance properties that are currently unattainable by solely polyolefin solutions. When PE or PP cannot satisfy the job, more costly materials are used, such as nylon, EVOH, PvDC, foil, metallization, PET, specialty coatings and adhesives.

During the last several years the $20.5 billion domestic flexible packaging industry has faced many obstacles for maintaining and growing profit margins[5]. Two of the more critical circumstances are the shift of power to the retail conglomerates and rising energy and raw material costs. Mergers and acquisitions, stringent focus on supply chain and operations management, competitive attacks on niche markets, and ultimately industry contraction through rationalization and global outsourcing are but a few of the resultant outcomes. To say the least, these events have crafted an understandable new mantra for the flexible packaging industry calling for products and solutions that are *cheaper, faster,* and *better*.

Today, the phrase "serving the industry" has more emphasis on cost than on upgrading performance. Hence, *cheaper* and *faster* should be the first and second considerations when it comes to new innovations. The number of opportunities to be reimbursed for new products or technologies that hinge on *better* is decreasing precipitously. On average, between 10 and 20% of what consumers pay for retail products is attributed to the cost of packaging. Even though packaging will continue to be recognized as a Profit Center in many branded products, it will *always* be a Cost Center. The authors and contributors to this paper recognize that there are diminishing possibilities for new grades of PE or PP to – by themselves – broadly lower flexible packaging costs. Additionally, the contributors of this paper agree that the economic benefits of gauge reduction is beginning to reach systemic limitations in many applications whether it be downstream equipment constraints or consumer perceptions of packaging quality and safety. In order to address *cheaper* and *faster* first, the key elements of the production chain from resin to equipment to ancillary technology providers must effectively collaborate. In today's flexible packaging industry, there is potential for creating value in operations and manufacturing that could guide tomorrow's capital investment dollar. Few converters know where to invest after seven and nine layer blown film coextrusion technology. This paper focuses on a collaborative and innovative concept that has the potential to make packaging films *cheaper* and *faster*; and in certain applications, *better*. The concept combines polymer science, conversion equipment engineering and the latest advancements in treatment and printing technologies using in-line machine direction orientation (MDO) of sheet coextrusion using the unique attributes of bimodal high molecular weight polyethylene resins (HMW-PE).

Discussion

MDO technology has been around for over thirty years. In this time MDO has found utility in diaper and hygiene films, stretch films, and has been gaining attention for mainstream flexible packaging applications. Benefits of machine direction oriented films are improvements in stiffness, tensile strength, optics, gauge uniformity, and barrier properties. Historically, orienting PE films in the machine direction has been severely limited in potential applications due to processability and reductions in important physical properties such as machine direction (MD) tear and puncture strength. For some applications this could be beneficial such as directional tear for easier opening of small primary packaging or lower puncture strength for blister packs. In general, degradation of tear and impact properties impair broad consideration in flexible packaging applications. By combining polymer science and orientation technology these deficiencies can not only be effectively minimized, they can be modeled[3]. Using coextrusion structure design, resin selection, orientation conditions and degree of orientation can produce films that have a broad range of adjustable properties that can meet the needs of many flexible packaging applications; and be fabricated at a lower manufacturing cost.

From an applications standpoint, the technology can be compared and contrasted within two frames. The first frame is those applications that currently take blown films, surface prints them with solvent based inks that are subsequently converted into packaging as pre-made bags or through vertical form fill and seal machines (VFFS). In this context the 'value proposition' is to fabricate packaging films that are still PE-based but have been manufactured at a lower cost while also delivering improved properties such as stiffness, optics, tensile or barrier. Many of these applications, such as heavy duty shipping sacks (HDSS) use predominately linear low density polyethylene (LLDPE) in gauges ranging from 2-mil to over 6-mil (50-300 micron). In this industry, as in most industries, cost is of critical concern. From a performance standpoint there is a consistent demand for higher stiffness *without* sacrificing the other critical properties such as tear, impact and seal-ability. It is not uncommon to find that there are LLDPE-based applications that are over-engineered in gauge based on tear and impact performance in order to deliver the *perception* of quality to consumers from the inherently low stiffness of LLDPE's.

The second frame for the technology is the applications that take blown sealant films that are subsequently laminated to a reverse printed support web such as BOPP or OPET. The laminated packaging webs are then either converted into pre-made pouches or processed through VFFS machines. In this frame, the potential cost benefits magnify. Displacing laminations is not a new concept; however there are fundamental interdependencies with blown films that limit broad feasibility.

There are three key aspects that correlate to the perceived value of BOPP and OPET laminates: stiffness, graphics and heat resistance. Once the support web is removed, the blown sealant film, even with higher density coextrusions, cannot match the stiffness performance of the laminated packaging film. Surface print technology is beginning to demonstrate the ability to match the gloss and graphics performance of reverse printed and laminated packaging. The perception for the need for high heat resistance for converting through VFFS machines is actuality a function of eliminating the *extensibility* of PE films under heat. All three of these critical aspects of laminated packaging can be addressed using MDO technology and PE resin technology.

Polymer Science Overview

The historical limitations of leveraging polyethylenes with MDO technology into flexible packaging applications have included poor uniformity of draw[4], inability to achieve a wide range of drawing ratios, and detriments to machine direction tear and puncture properties. HMW-PE resins significantly overcome these historical *processing* limitations. The combination of the bimodal molecular weight and density distribution enables these resins to be uniformly stretched to a wider range of drawing ratios than conventional PE resins. Due to the higher molecular weights, certain resin types can be uniformly stretched to give significantly improved properties at drawing ratios exceeding 10:1. As seen in **Table 1**, specially designed HMW-PE films drawn to very high drawing ratios show significant improvements in physical properties relative to typical blown HMW-PE films of the same gauge[3]. These oriented HMW-PE films represent the apex of properties for stiffness and tensile strength.

Property	Improvement vs. Unoriented Blown Film
Stiffness (MD Modulus)	10x
MD Tensile @ Break	7x
MD Tensile @ Yield	20x

Table 1: Enhancements in HMW-PE Films after MDO

Figure 1 shows the impact strengths of films of three different specialized structures produced with HMW-PE. Using a specially designed structure permits the unique attributes of each resin to contribute in an additive manner, where typically a reduction in properties is observed with the performance of the film controlled by the weakest material. Films designed with specific HMW-PE resins deliver a new regime of high stiffness and tensile properties with much improved machine direction tear and impact strengths.

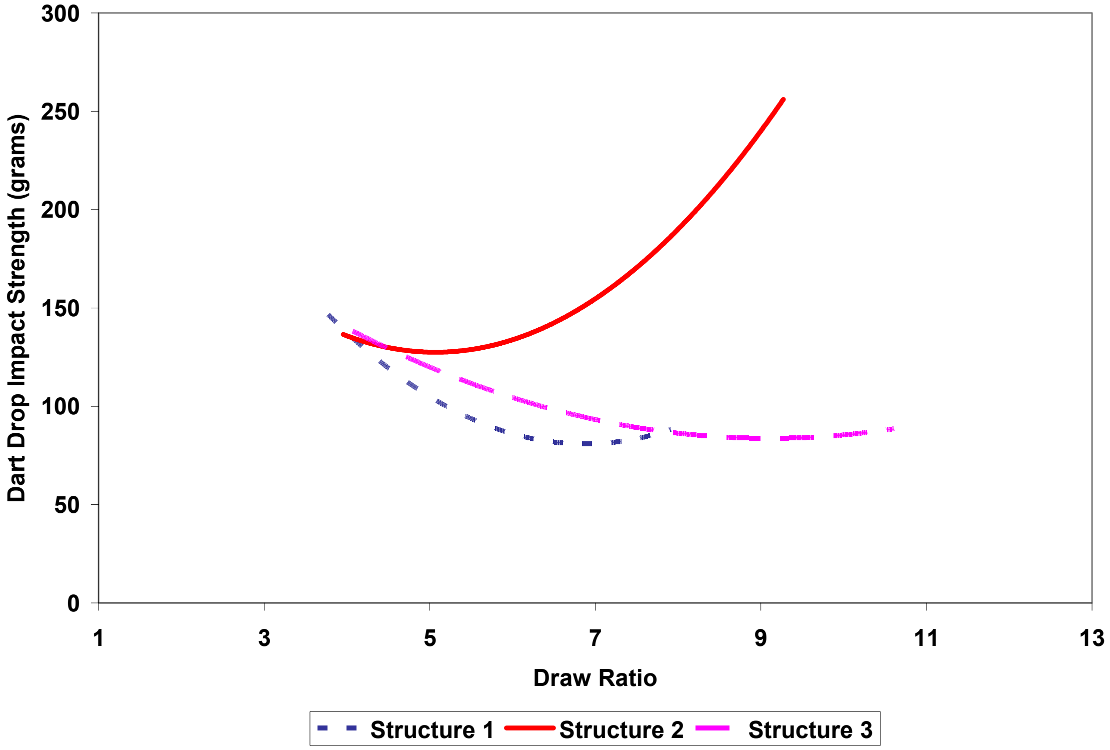

Figure 1: Dart Impact of Machine Direction Oriented Films of Various Structures Containing HMW-PE vs. Draw Ratio

To better understand the dependence of draw ratio on tear and impact strengths requires understanding the relationship between enhanced properties and the polymer architecture. Different polyethylenes have unique responses to stretching. Modeling the interdependencies of resin characteristics and film properties after varying the machine direction stretching provides a resource for designing innovative HMW-PE structures that show unique tear and impact strengths. **Figure 2** shows the balance of machine direction tear strength and modulus for a specific structure of HMW-PE as a function of draw ratio. Based on the required film properties for a specific application, resins can be assembled into specialized structures to build flexibility into balancing machine direction tear and impact properties with enhancements in modulus and tensile strength.

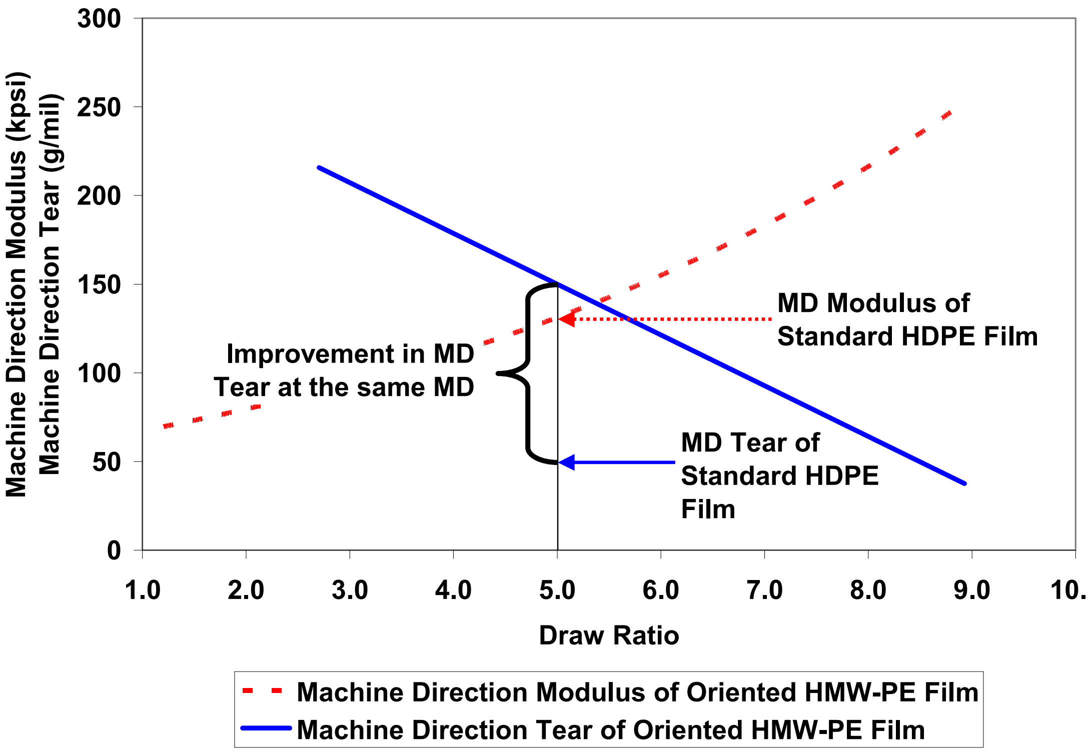

Figure 2: Machine Direction Tear of Specialized HMW-PE Films vs. Draw Ratio

Extrusion Equipment Process Overview

One of the most efficient and highest yield methods for extruding resin pellets is sheet extrusion. Flexible packaging however is not commonly found in gauges ranging from 10-mil to over 50-mil. So why not put an MDO system in-line with the sheet extruder? In this arrangement, the latent heat of the extruded sheet serves as orientation preheat that allows for more balanced structures using high barrier inside layers such as EVOH, PvDC or Nylon versus having to reheat a cold and thick barrier film.

Sheet and film extrusion have been like two cousins in the same family sharing common roots but establishing very different roles. Although extrusion is the foundation of both processes there are some radical differences between film and sheet production. A couple of distinguishing differences are thickness and speeds; thickness where a border line around 10 or 15-mil (250-375 microns) separate both technologies. Everything below these values can be considered film and above them is considered sheet. The other difference is web handling speed which is considerably slower for sheet production. As a result, the hardware required to manage the web is commonly simpler than what is required for the higher speeds of film extrusion. Specifically, the winders need to be more sophisticated for film production because the balance of components and tension control are more variable and demanding. In sheet production the winders are smaller and less complex if the process is out of line with a thermoforming machine for packaging applications. It some cases winders may not be required at all if the sheet line is part of an in-line extrusion-thermoforming operation or if the final product will be used for industrial applications with the thermoforming equipment using flat sheet sections. The new proposed layout for polyolefins processing implies a hybrid between sheet technology for the hot side of the process up to the MDO and film technology for the web management after the MDO. Depending on the final application for the films being produced, special care must be taken when choosing the appropriate winding technology. Gap winding or taper tension control may be needed if tacky or very elastic films are being produce or further shrinkage on the wound rolls is possible.

A sophisticated process control will be required, capable of adjusting extrusion speeds with the MDO multiple speeds and downstream with the winder in order to obtain converting rolls of high quality. Changing lay flat dimensions will require rapid change-out of die blocks which is an inherent advantage for blown film lines. However, the optimum width for MDO stretching aligns well with the standard width of existing CI print presses. It is expected that many of the targeted application would accommodate a converter roll or master roll approximately sixty inches wide.

Undoubtedly, this new proposed hybrid will take the best of both processes to become a very efficient system but will require a bilingual approach of the two languages.

Treatment and Surface Printing Overview

As film markets become more competitive, the use of low cost films such as polypropylene (PP) and polyethylene (PE) are challenging converters to standardize new and cost-effective methods of achieving required surface adhesion levels without expanding inventories of specialized inks and coatings. An obvious method of improving operational efficiency and reducing manufacturing costs is to streamline as many raw materials as feasible to “do more with less” where printing inks and substrates are certainly of highest priority in this regard.

Not all PP, biaxially oriented PP (BOPP) and PE films are created equal. The existence of low molecular-weight organic material which is weakly attached on the film surface is what controls the surface bond of the interfacing ink, coating or adhesive to the film. Surface cross-linking of the polymer by high-energy sources such as corona or flame treatment of the film surface will develop increases in bonding. However, these high-energy surface treatments are not all equal in effect either. They are especially variable when different and low polarity grade polymers are used since some polymers are more prone to crosslink while others are prone to chain scission causing a decrease in molecular weight and surface strength. It is well known that BOPP, for example, is more prone to surface degradation through corona or flame treatment than PE.

Given the ever-increasing challenges of lower polarity films which have greater levels of low molecular weight surface material on the boundary layer and a higher propensity to degradation under traditional surface treatment processes, atmospheric plasma treatment systems are increasingly being used to compensate for these surface issues and significantly enhanced treatment longevity and surface adhesion. Specifically, the atmospheric plasma treatment process features a glow discharge. As such it offers the advantage of being non-filamentary and therefore fully homogenous to the surface, removing low molecular weight organics to expose the base substrate. Ion and electron bombardment micro-etch the surface while variable reactive chemical groups are bonded to the surface. Because surface strength is preserved and functionality is imparted, this process significantly upgrades the bonding surface potential of low grade and previously untreated polymer films.

More attention is also being given to the interface between inks and polymer surfaces, offering opportunities to integrated flexible packaging firms whose activities embrace polymers, coatings and dispersions as well as inks and their ingredients. The latest research in new ink technology is centered on the development of dendritic or hyper-branched polymers which can be incorporated in the inks. The objective is to eliminate the necessity for different ink systems to be used with polar film materials like polyester and polyamide and non-polar ones such as polyethylene or polypropylene. The introduction of hyper-branched polymers into the inks allows a single printing system to be applied with both polar and non-polar plastics. The dendritic polymers attach themselves to the pigments in the ink while also anchoring themselves to the plastic surface. This anchorage is optimized when atmospheric plasma treatment systems are used to remove low molecular weight organic materials to expose the base polymer surface.

Economic Considerations

The potential economic benefits of sheet extrusion using in-line MDO can be effectively compared using the two frames previously introduced. The first scenario compares the concept to blown film fabrication economics for a PE-based film that is presumably surface printed using common solvent-based inks with corona treatment and converted downstream into bags or VFFS. The second scenario compares the economics of laminating a reverse printed oriented web using solvent-based inks to a blown PE sealant film for downstream conversion into pre-made pouches or VFFS. In either consideration, the innovation lies in recognizing that blowing films has reached a limit for plastic throughput per inch of die circumference. Increasing output generally implies investing in a larger extruder and die and running more packaging surface area as a function of time.

Sheet extrusion does not have the constraints of aerodynamics and bubble cooling compared to blown film. More pounds can be processed per unit time and using in-line orientation more surface area can be stretched out the door; even when the blown film bubble serves as double the surface area when tubing is slit into two independent sheeting rolls.

For applications such as heavy duty shipping sacks (HDSS), films are blown at relatively thick gauges ranging from a 2-mil to over 6-mil (50 – 150 micron). Downstream conversion into either pre-made bags or through VFFS machines uses a combination of tubing and sheeting (many applications have downstream conversion interdependencies that have been engineered around the existence of blown film tubing). Generally, surface printing using solvent based inks is the common decorating method however there are lawn and garden bags that are now printed via UV inks with a clear top coat. The basis of economics for converters of HDSS bags and roll stock can be either on the pound or surface area basis (per bag or imprint). On a unit basis, the economic driver is surface area production per unit time spread out over the fixed costs of the equipment. In this context, there is apparent value in a methodology that enables improved cost per surface area that could conceivably be further magnified by material reduction (down-gauging). On a pound basis of selling, gauge reduction is not a financial incentive for the converter and is commonly done strictly in the context of competitive activity. For converters selling bags or printed roll stock on a per pound basis are forced to pass along the value to the buyer. If 1,000 bags are decreased in weight by 10% through down-gauging, the value is the buyers now get 10% more bags for the same poundage. The converter does not retain the value because there lacks a fundamental shift in the cost to produce the thinner bag or film on a per pound basis. If the converter can fabricate the 10% reduced gauge film or bag at a 20% lower production cost, then there is value, and hence interest, by the converter.

Appendix A contains the output of an economic model comparing blown film, sheet extrusion and laminating by the gauges of the final application. *Section 1* shows the economics for blowing PE films. The assumptions used in the calculation are tubing production that is 60-inches wide, PE resin cost of fifty cents per pound, a fixed cost of \$150/hr and a material flow rate of 750 LB/hr (consistent regardless of gauge, see Appendix A for details). Since the material flow rate does not change as a function of gauge, the cost on a per pound basis is the same for all three gauges at \$0.70/LB. Converting the bubble into two flat sheets of 60-inch wide film produces a surface area cost ranging from \$0.05 - \$0.23/MSI (MSI = 1,000 in^2). As can be seen, the calculated winding speeds are within the normal ranges for blown film at 50 – 300 fpm.

Sheet lines that incorporate winders generally run slower than the average blown film line. However, an MDO line will run at winding speeds up to 1,000 fpm. The assumptions in this section of the model were the same fixed cost of \$150/hr and 60-inch wide web production with a drawing ratio of 10:1 and the material throughput was allowed to adjust where the winding speed *of the orienter* is the limiting variable. As can be seen, as the gauge of the application approaches 1-mil there is an adverse impact on material throughput using sheet extrusion. Increasing the gauge from 1-mil to 5-mil increases the material flow rate from 1,469 LB/hr to 4,627 Lb/hr and thus adjusts the advantage of sheet extrusion from a two-fold increase to a six-fold increase over blown film production. The surface area production advantage (MSI/hr) is several orders of magnitude increased for sheet extrusion versus blown film production (including counting the bubble as two parallel sheets). **Table 2** summarizes the output and cost data for 1-mil and 5-mil film production. The cost of surface printing is neglected from the cost data on the assumption that both fabrication methods would use the same printing system and hence would be equal in cost.

	Production (MSI/Hr)	Production (LB/Hr)	Cost ($/MSI)	Cost ($/LB)
Sheet/MDO (1-mil)	**43,200**	**1,469**	**$0.019**	**$0.55**
Blown Film (1-mil)	**22,728**	**750**	**$0.046**	**$0.70**
% Improvement	**90%**	**96%**	**59%**	**21%**
Sheet/MDO (5-mil)	**27,216**	**4,627**	**$0.082**	**$0.48**
Blown Film (5-mil)	**4,546**	**750**	**$0.231**	**$0.70**
% Improvement	**500%**	**516%**	**65%**	**31%**

Note: MSI/Hr production for blown film accounts for tubing equaling parallel production of two sheeting rolls

Table 2: Surface Area, Production Rate and Calculated Cost Comparison of Sheet Extrusion with in-line Orientation vs. Blown Film

As can be seen in **Table 2**, the economic benefits of sheet extrusion with in-line orientation improve substantially as the gauge of the application increases. The economic comparison does not consider potential down-gauging based on improved performance properties of highly oriented films.

Taking the comparison further to incorporate laminating reveals additional economic benefits. Considering the cost pressures in many flexible packaging markets there are obvious economic benefits to eliminating the variable cost accelerator driven by the unwinding of BOPP or OPET, and, the cost of the process and adhesive to bond them together. Unfortunately, this value is difficult to create due to the end use performance requirements of stiffness, thermal properties and graphics. In-line orientation of coextruded sheet addresses these requirements by:

- Tailor-able stiffness via bimodal HMW-PE resin design, coex structure, and draw ratio

- Suitable graphics by leveraging advancements in treating and printing ink technologies

- Suitable thermal properties by eliminating PE’s inherently high extensibility near the polymer melt point using coex design and draw ratio

For example, laminating blown PE sealant films to 50-gauge OPET significantly increases fabrication costs primarily from the consumption of the high cost OPET film ($1.00 - $2.00/LB). The faster the laminator runs there is an obvious proportional demand for more OPET film and hence the greater the cost component that must now be spread out over the higher fixed and variable costs. Moving the economic reference frame from the blown film line to the laminator shows that the surface area (MSI/hr) production matches, or in some scenarios outperforms the in-line orientation of sheet extrusion; but at a greater cost per pound penalty. This implies that a single laminator operating at 1,000 fpm will require more than one blown film line's production of film. **Table 3** summarizes the manufacturing costs of laminating blown films to 50-gauge OPET with in-line oriented sheet extrusion that must be surface printed with a clear top coat in order to achieve similar graphics as reverse printed OPET using cheaper solvent-based printing inks.

	Production (MSI/Hr)	**Production (LB/Hr)**	**Cost ($/MSI)**	**Cost ($/LB)**
Sheet/MDO (1-mil)	**43,200**	**1,469**	**$0.079**[3]	**$0.55**
Laminator[1,2] **(1-mil)**	**43,200**	**3,080**	**$0.081**	**$1.14**
% Improvement	**0**	**(110%)**	**0**	**52%**
Sheet/MDO (5-mil)	**27,216**	**4,627**	**$0.142**[3]	**$0.48**
Laminator (5-mil)	**43,200**	**8,782**	**$0.174**	**$0.85**
% Improvement	**(59%)**	**(90%)**	**18%**	**44%**

1. Laminator running at 1,000 fpm and 60-inches wide using 50-gauge OPET and 12 micron adhesive or PE sealant at a fixed cost of $250/hr
2. Costs: OPET = $2.00/LB, Adhesive $0.55/LB, PE sealant film is transfer cost from Table 2
3. Cost includes an added $0.06/MSI for UV ink with clear coat (50% graphics coverage)

Table 3: Surface Area, Production Rate and Calculated Cost Comparison of Sheet Extrusion with in-line Orientation vs. Laminated Blown Film

Incorporating the higher cost to surface print with UV or e-beam curable inks with clear top coats, and the substantial increase in surface area production for a laminator over a blown film line makes the cost on a surface area basis ($/MSI) parity between sheet extrusion and the incumbent method. The models predict a slight economic incentive on a surface area basis for the applications approximately 5-mil thick. As the cost of radiation curable inks improves, the cost parity would expectantly move in favor of sheet with in-line MDO. On a pound basis, there remains a consistent 40-50% advantage for sheet extrusion regardless of gauge that is a result of the higher cost for blown film fabrication coupled with the cost of oriented support web (BOPP or OPET).

Conclusion

As the commerce structure in the domestic packaging industry continues to change there will continue to be systemic drivers for solutions that produce innovations that address the industry priorities of *cheaper, faster* and *better*. This new environment will continue to place a high priority on performance; however the opportunities to extract premiums for improved film performance will be challenging and elusive. It has become commonplace that new innovations must have a beneficial cost impact somewhere in the value chain even if it may be in the form of making things "simpler" from an operations or manufacturing standpoint. By collaborating with the equipment and technology providers at each critical stage of the process of producing resin pellets and transforming them into primary flexible packaging, a new concept has been developed that has the potential to redefine the economics of manufacturing in certain markets and applications. The notion of in-line orienting sheet requires ingenuity on all aspects from start to finish. The equipment has to be engineered effectively, the PE resins have to process and deliver predictable and consistent properties and the system has to work in concert with the various downstream printing and conversion systems. Converters rarely spend capital for unproven concepts. They buy "technology" that can be implemented on a schedule that does not require decision points and development project stewardship. To develop the concept effectively such that it can become a viable option for tomorrow's capital dollar, the solution must be made tangible – including the development of the initial applications.

The economic benefits of the concept stem from stepping beyond the current and known production rate limitations of blown film extrusion, and, eliminating the essentiality to laminate to an oriented support web for certain applications. Sheet extrusion improves the cost on a per pound basis by 30% compared to blown film and 50% when blown films must be laminated. And, these films can have substantially higher stiffness, barrier properties, optics, and tensile strength with good retention of key properties such as tear and impact strength.

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Key Words

Polyethylene (PE), Polypropylene (PP), biaxially oriented polypropylene (BOPP), polyethylene terephthalate (PET), oriented polyethylene terephthalate (OPET), ethylene vinyl alcohol (EVOH), machine direction orientation (MDO), vertical form fill and seal (VFFS), heavy duty shipping sacks (HDSS), linear low density polyethylene (LLDPE), high molecular weight polyethylene (HMW-PE), thousand square inches (MSI)

Appendix A: Economic Model Output Comparing Sheet Extrusion with MDO vs. Blown Film Extrusion and Laminating

	final Gauge mil	Calculated winder speed fpm	MSI/hr	estimated Fixed Cost $/hr	Var. Cost $/hr	Total Cost $/hr	flow rate LB/hr	Cost $/LB	Cost $/MSI
Section 1	1	263	22727	$ 150.00	$ 375.00	$ 525.00	750	$ 0.70	$ 0.046
	3	88	7576	$ 150.00	$ 375.00	$ 525.00	750	$ 0.70	$ 0.139
	5	53	4545	$ 150.00	$ 375.00	$ 525.00	750	$ 0.70	$ 0.231

	final Gauge mil	Calculated winder speed fpm	MSI/hr	estimated Fixed Cost $/hr	Var. Cost $/hr	Total Cost $/hr	flow rate LB/hr	$/LB	$/MSI	Increased Print Cost $/MSI
Section 2	1	1000	43200	$ 150.00	$ 660.96	$ 810.96	1469	$ 0.55	$ 0.019	$ 0.079
	3	1000	43200	$ 150.00	$ 1,982.88	$ 2,132.88	4406	$ 0.48	$ 0.049	$ 0.109
	5	630	27216	$ 150.00	$ 2,082.02	$ 2,232.02	4627	$ 0.48	$ 0.082	$ 0.142

	final Gauge mil	laminator speed fpm	MSI/hr	50-gauge OPET usage LB/Hr	adhesive usage LB/Hr	Blown PE Sealant film usage LB/Hr	estimated laminator Fixed Cost $/hr	OPET/Adh. Var. Cost $/hr	Total Cost (BF + Lam.) $/hr	Cost $/LB	Cost $/MSI
Section 3	1	1000	43200	937	717	1426	$ 250.00	$ 2,268.65	$ 3,516.57	$ 1.14	$ 0.081
	3	1000	43200	937	717	4277	$ 250.00	$ 2,268.65	$ 5,512.41	$ 0.93	$ 0.128
	5	1000	43200	937	717	7128	$ 250.00	$ 2,268.65	$ 7,508.25	$ 0.85	$ 0.174

With the assumption of 60-inch wide lay flat for blown film extrusion and the average blow up ratio of 2.4 for LLDPE, the die size would be 16-inches. Using a 16-inch die and 750 LB/hr the output rate would be 15 LB/hr/in. Due to the balancing nature of cooling, extrusion efficiency and polymer melt strength the optimum rate of 750 Lb/hr would be recognized at 3-mil film production. The rate would be expected to decrease ~ 10% when reducing the gauge to 1-mil due to extrusion and polymer limitations and by ~5% when increasing the gauge to 5-mil due to cooling limitations. Since there are other considerations such as lower blow up ratios and subsequent larger dies – using the assumption of 60-inch wide lay flat production, the extrusion rate is assumed constant regardless of gauge.