FUNDAMENTALS OF FOAM SHEET EXTRUSION USING A TANDEM EXTRUSION LINE

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FUNDAMENTALS OF FOAM SHEET EXTRUSION USING A TANDEM EXTRUSION LINE

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Abstract

Tandem foam sheet extrusion is a complex process that requires optimization to produce quality sheet at high rates. The goal of this paper is to describe the process, show how rates can be increased, provide a guideline for sheet quality, and provide case studies.

Introduction

Foam sheet is commonly produced using high molecular weight polystyrene (PS) or polyolefin (PO) resins using tandem foam sheet extrusion lines. The sheet is used for many applications including food trays, clamshell takeout containers, egg cartons, and many others. The most common application is thermoforming the sheet into trays and containers. The edge trim foam is repelletized and added back to the line. All applications require that the foam be uniform in thickness (gauge), density, cell size, orientation, and have uniform shrink properties.

The sheet must be produced at high rates and be uniform in density and shrink properties to be economically viable. If the density and shrinkage properties in the sheet are not uniform, the thermoforming process will not be able to make high-quality parts. That is, the part can be warped, have locations that are either thin or thick, or in the worst case the sheet will not be capable of thermoforming.

Tandem foam sheet lines are typically constructed using two single-screw extruders, as shown in Figure 1 [1,2]. The schematic is for a line that uses a physical blowing agent such as supercritical carbon dioxide, butane, or pentane. Chemical blowing agents could also be used. The resin is fed to the primary extruder and plasticated (melted). Near the end of the primary extruder, the physical blowing agent is added and mixed into the resin. Typically, the blowing agent is soluble in the molten resin. A foam cell nucleator such as talc is typically added to the hopper. The resin-blowing agent mixture is discharged from the primary extruder at 220 to 235°C and a pressure near 20 MPa for PS resin. The resin mixture is too hot to foam, and it must be cooled down before it is extruded through the die.

The hot extrudate from the primary extruder is pumped to a larger diameter secondary or cooling extruder. The cooling extruder has a diameter that is typically 30 to 35% larger than the primary extruder to increase surface area for heat transfer. The barrel of the extruder has flow channels that provide a cooling media, usually water, to cool the barrel and the extrudate to a suitable foaming temperature. For PS, the foaming temperature is about 140°C, depending on the physical blowing agent used. The screw is typically multiflighted with very deep channels. The large diameter of the secondary extruder and the deep channels of the screw allow the screw to be rotated at a much slower speed than the primary extruder, minimizing the amount of viscous energy dissipation. The extrudate is now at the foaming temperature and pressure.

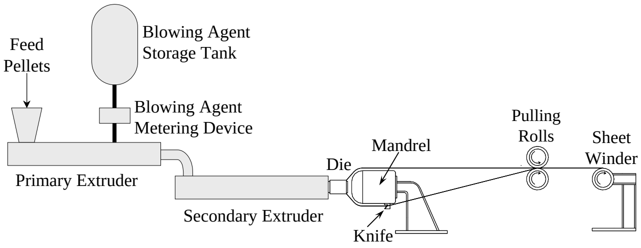

Figure 1. Schematic of a tandem foam sheet line equipped with a physical blowing agent delivery system.

The cool resin is then forced through an annular die. As the pressure is released from 10 to 20 MPa to atmospheric, the blowing agent comes out of solution at the nucleation sites and forms the foam. The tube that is formed is stretched over a water-cooled mandrel, as shown in Figure 1. Next the tube is slit to form a sheet that is wound onto a roll. In many applications the tube is slit at the horizontal positions, generating a top sheet and a bottom sheet.

The ratio of the mandrel diameter to the die diameter is a critical design feature for the process, and it is referred to as the blow-up ratio. For PS resins, the blow-up ratio is in the range of 2.5 to 5.5 [1]. If the blow-up ratio is too low the foam will not have the proper orientation and physical properties, and it can contain corrugations. Corrugations appear as high and low sheet thicknesses. They occur because the foam is expanding at a rate higher than the rate of the blow-up dimension. The sheet velocity and the blow-up ratio provide biaxial orientation and the shrink properties of the foam.

The key to the process is the removal of energy through the barrel wall of the secondary extruder such that uniform foaming can take place at the die. If thermal gradients exist in the extrudate when foaming occurs, the foam density will not be consistent, and the final product will be flawed during thermoforming. The ability to produce quality foam sheet depends on the operating conditions, the screw design for the secondary extruder, and the setup of the die and downstream equipment. Moreover, the maximum rate of the process is controlled by the performance of the secondary extruder.

The goal of this paper is to present the optimal operation of a tandem foam sheet line and show the existing technologies for the cooling screw design. The best technology must provide an extrudate that is uniform in temperature, at the proper foaming temperature, and at high rates. The setup of the die and downstream process are also described.

Secondary Extruder Screw And Operation

The primary extruder has a screw that is very normal for plasticating except that there is a distributive mixer just downstream from the injection port for the physical blowing agent. The extrudate from the primary extruder is typically at 235°C and 20 MPa for PS resin. The primary extruder is not the focus of this paper and will have limited discussion.

As previously mentioned, the secondary cooling extruder is larger in diameter than the primary extruder. For example, a large line would have a 152.4 mm (6 inch) diameter primary extruder and a 203.2 mm (8 inch) diameter secondary extruder. The channel depths on the primary extruder screw are normal while the channels on the secondary extruder screw are extremely deep. The channels are deep to minimize viscous dissipation and the heating of the resin from the rotation of the screw. The larger diameter secondary extruder with the deep channels will allow the extruder to rotate at a much lower speed, again minimizing viscous dissipation in the channels. Moreover, the lead length is typically equal to the diameter in the primary screw, and it is typically increased for the secondary screw, sometimes up to twice the diameter. The typical rotation speeds for a 152.4 mm primary and 203.2 mm diameter secondary extruders are 84 and 13 rpm, respectively. That is, the primary extruder is rotating 6.5 times faster than the secondary extruder. For a properly designed line, the cooling capacity of the secondary extruder should be the rate limiting operation of the process.

The deep channels of the cooling screw make the secondary extruder very sensitive to the axial pressure gradient. An optimal process is reported to occur when the axial pressure gradient is zero [3,4], as shown by Figure 2. That is, the discharge pressure of the primary extruder is equal to the discharge pressure of the secondary extruder. At these conditions, the secondary extruder will operate at the calculated specific rotational (drag) rate. If the secondary extruder is used to develop a portion of the pressure required by the die, then the specific rate for operation will be considerably less than the specific rate for rotation. Operating at a lower specific rate will cause additional energy to be dissipated in the extruder and cause the temperature of the resin to increase and reduce the quality of the foam.

Energy is removed through the barrel wall by flowing cooling water through the barrel zone channels. The first zone temperature at the feed end is typical set high and the rest of barrel zone temperatures are decreased until the discharge temperature is at the optimal foaming temperature, as shown by Figure 2. For example, with PS and carbon dioxide blowing agent, the barrel temperature in the feed zone is maintained at 180°C, the barrel temperatures are decreased to about 90 to 140°C at the discharge. High heat transfer coefficients are maintained at the inside barrel wall due to small clearances between the flight tip and barrel wall and the multiple wipings per turn by the four flights.

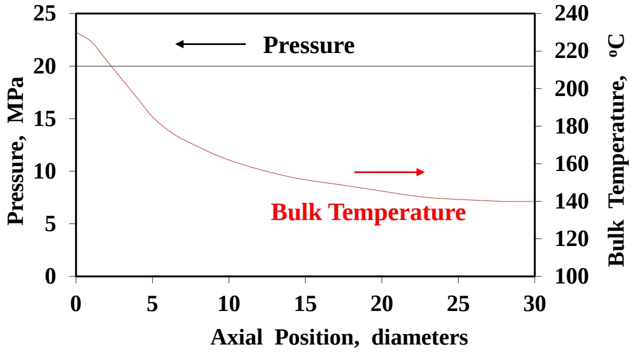

Figure 2. Schematic of the axial pressure and temperature profiles for a secondary extruder running PS resin and super critical carbon dioxide as a physical blowing agent [4].

Barrel cooling causes the molten resin near the barrel wall to decrease in temperature, and the recirculation due to the rotation of the screw causes the resin temperature at the screw root to be cool. The resin that is in the center of channel, however, is considerably higher in temperature, as shown by Figure 3. The hot resin in the center of the channel must be mixed with the cooler resin before the resin is foamed. The geometric features on the screw cause the needed mixing to mitigate thermal gradients. Three different technologies or screw designs are currently used commercially. The technologies are slots in the flights [4], four channel ENERGY TRANSFER^{TM} (trademark of Robert Barr, Inc., ET) screws [4-6], and the TURBO^{TM} (trademark of Plastic Engineering Associates Licensing, Inc.) screw [7,8]. These technologies will be described next.

The slotted flight screw is the most widely used technology, and it provides the baseline performance for rate and foam quality. For this design, the screw will typically have four flight starts, a lead length that is twice the diameter, and periodic slots in the flights as shown in Figure 4a. The slots go all the way down to the screw core. The channel is deep and constant in the axial direction. The slots allow a portion of the cooler and hotter resin to flow to the channel behind it, providing a level of thermal homogenization. The slots, however, decrease the local heat transfer coefficient because the barrel is not wiped by a passing flight as often. For example, if the screw has four flight starts and one of the flights is slotted at a given axial distance, the barrel would be wiped 3 times per rotation versus 4 times.

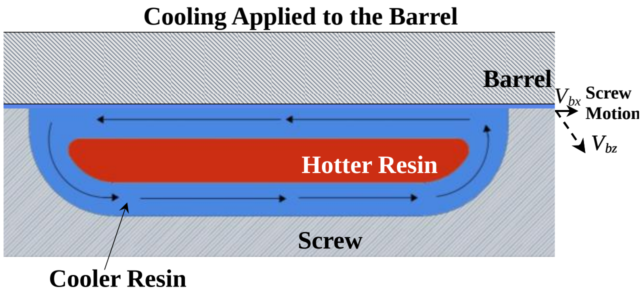

Figure 3. Schematic of the temperature gradients in the deep channels of a secondary extruder screw [4].

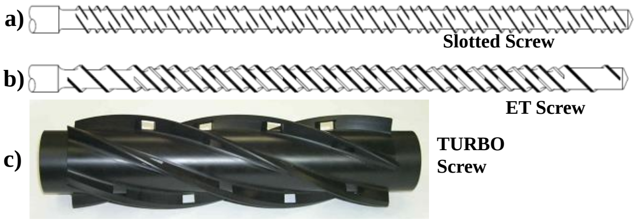

Figure 4. Schematics for commercially available screws for the secondary extruder: a) slotted flight design, b) four channel ET screw design (courtesy of Jeff A. Myers of Robert Barr, Inc.), and c) a segment of a TURBO screw (courtesy of James D. Fogarty of Plastic Engineering Associates Licensing, Inc.)

ET cooling screws are also four channel designs with a lead length that is twice the diameter [6], as shown by Figure 4b. The channel depths, however, oscillate and the flights are selectively undercut, allowing a portion of the resin to flow over to the channel behind it. The undercuts are typically about a third down into the flight. Thermal homogenization occurs with the ET screw by selectively undercutting the flight. Like the slotted flight technology, the local heat transfer coefficient is reduced by the undercut flight. The ET screw provides enhanced performance over the slotted flight technology screw.

The TURBO screw uses “windows” cut through the flights to flow molten material from the center of the channel to the channel behind it. These windows are shown in Figure 4c. This technology allows the thermal homogenization of the hotter and cooler regions of the molten resin while providing a high heat transfer coefficient at the barrel wall because all sections of the barrel are wiped by tight flight clearances. This technology solves the reduced heat transfer problem associated with the other two technologies.

Optimization of Extruded Foam Sheet Quality

Controlling the extrudate temperature and uniformity at the exit of the die are key factors for obtaining quality foam sheet. Once the melt temperature of the extrudate is optimized, there are several other processing conditions that control the quality of extruded foam sheet. A simple foam sheet processing guide is listed in Figure 5. Across the top of the figure is a series of extruded sheet properties (the response) and along the left side is a series of processing conditions (factors). Within the figure is a series of different colored and numbered arrows. A solid red arrow is the primary effect, an open red arrow is an intermediate effect, and an open black arrow is a minor effect.

Using Figure 5, the foam sheet properties can be optimized by changing the processing conditions. For example, if the sheet thickness (gauge) needs to be increased, the takeaway (S-wrap) speed can be reduced as a primary effect. If the desire is to reduce the density of the foam, the level of physical blowing agent could be increased as a primary factor.

The challenge with optimizing the quality of the foam sheet is that processing conditions interact, and by changing one processing condition the other sheet properties are changed. For example, and as mentioned previously, if the desire is to increase the thickness (gauge) of the foam sheet and it is accomplished by slowing down the takeaway (S-wrap) speed, an additional effect is that the orientation of the extruded foam sheet in the machine direction (MD) is greatly reduced. If the desire is to reduce the density of the extruded foam sheet by increasing the blowing agent level, the number of foam sheet corrugations will increase. The number of corrugations is dependent upon the type of blowing agent. To help manage these interactions for the increase thickness example, minor changes to the level of blowing agent and talc levels may be required to maintain foam sheet density and cell size. As the second example of reducing the density of the extruded foam sheet by increasing the level of blowing agent, minor changes in the level of talc and the speed up of the takeaway may be required to maintain the cell size and the thickness of the foam sheet.

In the two case studies mentioned in this paper for PS and PO foam sheet, the properties of the two foam sheets were significantly different given their final packaging applications. They varied greatly in thickness, density, and cell size to meet the needs of the applications. Regardless, obtaining the optimum extrudate temperature at the die was the main key factor.

From Figure 5, the extrudate (die melt) temperature is listed as a processing condition. Two foam sheet properties controlled by the extrudate temperature are thermoformer puff and brittleness. Puff refers to the increase in sheet thickness when the sheet is heated in the thermoformer. With many foam sheet properties, the desire is to have higher thermoformer puff and less brittleness. Higher extrudate temperatures greatly reduce the thermoformer puff and greatly increase the brittleness of the extruded foam sheet. Both end property trends are undesirable and are correctable with an optimum extrudate temperature.

Once the extrudate temperature is optimized, managing the final desired foam sheet properties such as thickness, density, and cell size are much more manageable by adjusting the interactive processing conditions. Fine tuning the foam quality is, however, considerably more complicated and beyond the scope of this writing.

Experimental Extrusions

All three screw technologies can be used to make acceptable and high-quality foam sheet. But if the process is not operated correctly, then poor foam quality and reduced rates are likely. The next sections provide case studies that were observed in the field.

Case Study – PS

A PS foam sheet line was built using a 120 mm diameter extruder for the primary extruder and 165 mm diameter for the secondary extruder. The line was originally set up with a screw using the slotted flight technology. The line could produce quality foam at reduced rates, but not at rates high enough to be commercially viable. When the rate was increased, the foam density become uneven and the shrinkage characteristics during thermoforming were unacceptable.

The performance parameters for the slotted screw are provided in Table 1. Here the slotted screw operated at a specific rate of 22.4 kg/(h rpm) and the motor was inputting 650 J/g into the resin. Although the extrudate temperature at the die was not known, it was considerably higher than the temperature required for high quality foam.

The foam quality for the slotted flight screw was very poor with a high level of corrugations caused by density variations. Moreover, the shrinkage properties were not uniform, contributing to poor-quality thermoformed parts. The foam passing over the mandrel was photographed using an infrared (IR) camera to determine the average temperature of the sheet and the level of thermal gradients. The photograph is shown in Figure 6a. Here the average temperature was 75°C and large thermal gradients were evident. The high temperature areas were yellow in this photograph. Moreover, it shows evidence for the hot interior locations in the channels, appearing as yellow blotches in the photograph.

Table 1. Performance data for the slotted flight and ET screw technologies for PS foam sheet.

Parameter	**Slotted Flight**	**ET Screw**
Rate	Base Rate	Base Rate
Specific rate, kg/(h rpm)	22.4	29.6
Specific energy, J/g	650	502
Foam quality	Poor	Excellent

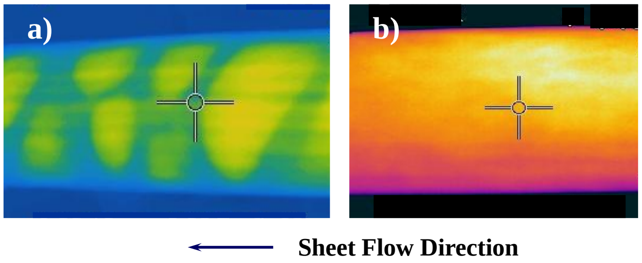

Figure 6. Thermal images of PS foam sheet over the mandrel: a) image (average temperature was 75°C) is for a slotted technology screw operating beyond the designed rate, causing thermal gradients in the foam in a pattern of the screw flights, and b) an image of foam (average temperature was 60°C) produced using an ET cooling screw at the same base rate.

A four channel ET cooling screw was built and installed in the extruder. This screw was built with deeper channels such that the specific rate due to rotation was calculated at about 30 kg/(h rpm). At the base rate, the foam had a very high quality and was easy to thermoform into parts. An IR thermogram was taken for the sheet as it moved over the mandrel as before. The photograph is shown in Figure 6b. The average temperature was decreased to 60°C and no thermal gradients were evident. Thus, the sheet produced with the ET screw was cooler at the mandrel by 15°C and it was thermally homogenous. Thus, the higher specific rate of the screw and the advanced mixing of the flight undercuts allowed the extrudate temperature to be lower and uniform, producing high-quality foam sheet and thermoformed parts.

Case Study – PO Foam Sheet

A tandem line was configured with a 200 mm diameter secondary extruder with a slotted flight technology screw. The line was incapable of producing quality foam sheet using a set of extrusion conditions with a specialty PO resin. The error that was made with this line was that the secondary extruder was used to increase the pressure of the extrudate. That is, the inlet pressure to the secondary extruder was about 15 MPa and the discharge pressure was 18 MPa. The specific rotation (drag) rate of the screw was about 42.5 kg/(h rpm). The positive pressure gradient in the extruder due to the low inlet pressure decreased the specific rate of operation to 34.3 kg/(h rpm).

Optimal operation of a cooling extruder is reported to occur when the inlet pressure is equal to the outlet pressure such that an axial pressure gradient does not exist [3,4]. The screw speeds of both extruders were adjusted to maintain the rate while obtaining the inlet and outlet pressure of the cooling extruder at 17 MPa. At these conditions, the line was producing a high-quality foam at a specific rate of 42.5 kg/(h rpm). Since the axial pressure gradient was zero, the process was operating at the specific rotational rate. As discussed later, additional improvement could likely be obtained by running at higher specific rates and a negative pressure gradient.

The overall energy balances for the process can provide information that may allow optimization of a cooling extruder. For the PO resin process operating at a specific rate of 42.5 kg/(h rpm), the energy balance is provided in Figure 7. The resin is fed to the primary extruder at 25°C and the energy is defined as 0 J/g. The motor on the primary caused 930 J/g to be dissipated into the resin while 360 J/g were transferred out through the barrel wall. The discharge for the primary extruder was at 230°C with a specific energy of 570 J/g. The cooling extruder must reduce the specific energy of the resin from 570 J/g down to 370 J/g for optimal foaming. The motor on the secondary extruder was inputting about 214 J/g and by difference, 414 J/g must be removed through the secondary extruder barrel. If the discharge from the primary extruder can be at a lower temperature and/or the screw on the secondary extruder can be designed to dissipate less energy from the motor, then the cooling load can be reduced on the secondary extruder and a rate increase may be possible.

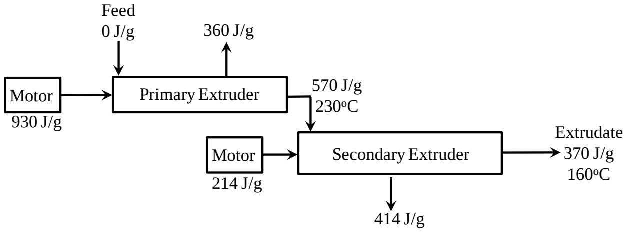

Figure 7. Energy balance of the PO resin process operating at a specific rate of 42.5 kg/(h rpm).

Cooling Screw Comparison Trial

A tandem foam sheet line was used to study the performance of the three different styles of cooling screws using PS resin and supercritical carbon dioxide. The secondary extruder was 88.9 mm in diameter and had a length-to-diameter (L/D) ratio of 30. The line was operated at a rate of 113 kg/h, and the barrel temperatures for the secondary extruder were decreased asymptotically: 180, 175, 170, 165, 160, 160, 140, and 140°C for Zones 1 through 8, respectively. Optimization for the individual screws was not performed since the goal was to determine the differences between these designs. Further tuning of the barrel zones would likely improve the rate and quality of the foam. The performance data are provided in Table 2. The foam produced using the three different technologies were all acceptable in density and shrinkage properties at a rate of 113 kg/h. The foam produced using the ET screw was the best, but the other foams were acceptable. Further optimization of all processes would have likely increased the quality of the foams.

Table 2. Performance of the three screw technologies for cooling extruders running PS resin at 113 kg/h.

Performance	Slotted Flight	ET Screw	TURBO Screw
Specific rate, kg/(h rpm)	6.30	5.16	6.67
Discharge Temperature, °C	147.3	142.9	150.4
Energy out barrel, J/g	381	464	374
Foam Quality	Acceptable	Best	Good

The best foam quality was produced using the ET screw even though it operated at the lowest specific rate. Typically, the discharge temperature is higher for cooling screws that operate at lower specific rates. Moreover, the energy through the barrel wall was the highest for the ET screw at 464 J/g, indicating that it had the highest heat transfer coefficient. This high heat transfer coefficient caused the discharge temperature to be the lowest for the ET screw. Like the process tuning discussed previously, optimization of the screw geometries for the PS resin would likely have provided higher rates and improved foam qualities for all screws.

The rate was increased to 136 kg/h for the ET screw. At this high rate the quality of the foam sheet was still acceptable. The other screws were operating at the maximum rate of 113 kg/h. At higher rates, the foam quality was not as good for the slotted screw and the TURBO screw. As previously discussed, optimization of the slotted and TURBO screws would likely produce acceptable foam at higher rates.

Discussion

Tandem foam sheet lines are complicated to operate properly, but with a few simple optimizations high-quality foam can be produced. The three main operational keys include the pressure gradient in the cooling extruder, a BUR that is proper for the shrinkage required for producing the part, and asymptotically decreasing the barrel temperatures. Since the specific rate of both the primary and cooling extruders depend on the intermediate and discharge pressures, it often takes persistence to tune the screw speeds to obtain a fixed rate and a zero-pressure gradient in the cooling extruder.

Recent trials indicate that operating the cooling extruder at higher specific rates using a negative pressure gradient can allow a rate increase. For these cases, the specific energy inputted by the screw was less. Thus for example, the inlet and discharge pressures to the cooling extruder would be 25 and 17 MPa, respectively.

Gear boxes used on cooling extruders are set up differently than those on normal plasticating extruders. Since a cooling extruder will typically operate at screw speeds less than about 20 rpm, the gear box should be set up with a maximum screw speed of 25 rpm. For a standard motor with a maximum speed of 1750 rpm, the gear box and belt drive (if used) reduction should be about 70:1. A recent commercial cooling extruder was delivered with a maximum screw speed set at 45 rpm. If the extruder is operating at a screw speed 13 rpm, only about 30% of the motor power is available to the process. Torque is lacking on this arrangement, and it will be difficult to design a screw for high rates and quality foam.

Summary

The production of high-quality foam sheet at high rates depends on operational parameters and the screw design for the cooling extruder. These parameters were discussed in this paper.

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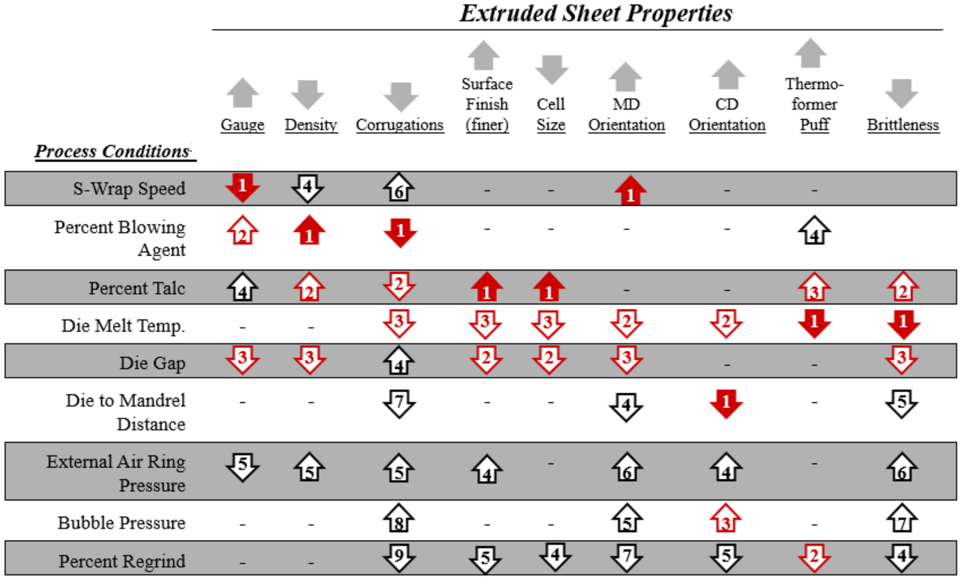

Extruded Sheet Properties

Process Conditions	⬆ Gauge	⬇ Density	⬇ Corrugations	⬆ Surface Finish (finer)	⬇ Cell Size	⬆ MD Orientation	⬆ CD Orientation	⬆ Thermo-former Puff	⬇ Brittleness
S-Wrap Speed	⬇1	⇩4	⇧6	-	-	⬆1	-	-	
Percent Blowing Agent	⇧2	⬆1	⬇1	-	-	-	-	⇧4	
Percent Talc	⇧4	⇧2	⇩2	⬆1	⬆1	-	-	⇧3	⇧2
Die Melt Temp.	-	-	⇩3	⇩3	⇩3	⇩2	⇩2	⬇1	⬇1
Die Gap	⇩3	⇩3	⇧4	⇩2	⇩2	⇩3	-	-	⇩3
Die to Mandrel Distance	-	-	⇩7	-	-	⇩4	⬇1	-	⇩5
External Air Ring Pressure	⇩5	⇧5	⇧5	⇧4	-	⇧6	⇧4	-	⇧6
Bubble Pressure	-	-	⇧8	-	-	⇧5	⇧3	-	⇧7
Percent Regrind	-	-	⇩9	⇩5	⇩4	⇩7	⇩5	⇩2	⇩4

Solid red arrows are primary effects, open red arrows are intermediate effects, and open black arrows are minor effects. The numbers show the relative intensity of the factor with 1 being the strongest and 9 the weakest.

Figure 5. Foamed sheet quality processing guide.