



Qenos

03

FILM EXTRUSION AND CONVERSION

—
TECHNICAL GUIDE



Alkathene® Alkatuff® Alkamax® Alkatane®



Front Cover

The Qenos Technical Centre operates a range of commercial and laboratory scale extrusion and moulding equipment for the injection moulding, blow moulding, film extrusion (pictured), pipe extrusion and rotational moulding markets. Qenos manufactures a full range of film grades for applications such as food contact, packaging and agriculture, including Alkamax metallocene mLLDPE resin for applications where superior performance is required at a thinner gauge.

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PART A. FILM EXTRUSION

The major application for low density polyethylene (LDPE) and linear low density polyethylene (LLDPE), including metallocene LLDPE (mLLDPE), is in film packaging. High density polyethylene (HDPE) is also used in film packaging. *Alkathene* LDPE, *Alkatuff* LLDPE, *Alkamax* mLLDPE and *Alkatane* HDPE film grades are specifically designed for the extrusion of blown and cast film and for ease in the subsequent conversion of the film.

GRADE SELECTION FOR FILM EXTRUSION

Alkathene, *Alkatuff*, *Alkamax* and *Alkatane* film polymer grades cover a wide range of Melt Flow Index (MFI)* and density and are specially formulated with additive packages to ensure they meet the processing, handling and end use requirements of the many film applications.

Alkathene LDPE film grades are supplied over the range of MFI between 0.3 and 6 g/10 min and density between 0.920 and 0.925 g/cm³. Several base polymer film grades contain no additives, but most grades supplied for packaging film are formulated with a stabiliser package, an antiblocking additive, a slip additive, and, if required, an antistatic additive.

Alkatuff LLDPE film grades are supplied over the range of MFI between 0.8 and 2.5 g/10 min and density between 0.918 and 0.935 g/cm³. These grades are formulated with a stabiliser package and, if required a process aid, an antiblocking additive and a slip additive.

Alkamax mLLDPE film grades are supplied with MFI of 1 g/10 min and density between 0.917 and 0.926 g/cm³. These grades are formulated with a stabiliser package, a process aid, and, if required, an antiblocking additive and a slip additive.

HDPE grades for film extrusion are supplied with MFI of 0.1 to 0.8 g/10 min and density of 0.949 and 0.960 g/cm³.

Grades for film extrusion are continually being developed to meet customer requirements and formulations not limited by the above ranges may be possible.

The end use properties of film will depend upon the MFI and density of the polyethylene used. The diagram in Figure 1 indicates the effects of changes in the MFI and density on the properties of polyethylene film. Low MFI is desirable for good impact strength but extrusion is more difficult. Increasing the density leads to improved stiffness and higher tensile strength, but will reduce the machine direction tear strength (the film becomes very splitty).

* For the purposes of convenience, MFI, in this document is defined as the mass of polymer (measured in grams) extruded at 190°C through the die in 10 minutes under a load of 2.16 kg

For further details on the properties of *Alkathene* and *Alkatuff* film grades, readers are referred to the accompanying publication: General Properties.

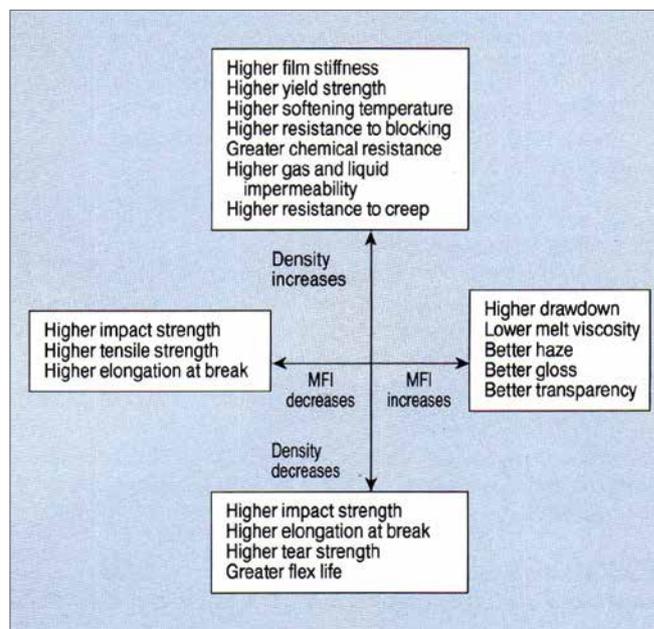


Figure 1: Effect of Changes in MFI and Density on Properties of Polyethylene Film

Comparison of Product Types and Classes

In the previous section, the effects of melt flow index and density were outlined. Another dimension that determines the polymer performance is the class of polyethylene. In the General Properties publication, the main classes of polyethylene were described: LDPE, LLDPE, mLLDPE and HDPE.

It is possible to have an LDPE, an LLDPE and an mLLDPE with the same melt flow index and density. In films, these different classes of PE produce different film properties, even if the MFI and density are equivalent.

Compared to *Alkathene* LDPE, an *Alkatuff* LLDPE with similar MFI and density will typically produce films with

- Higher stiffness
- Higher tensile strength at break
- Higher tear strength
- Higher puncture resistance
- Better heat sealing properties, superior hot tack
- Higher impact strength, especially at low temperatures
- Higher softening point and hence higher heat resistance
- Better drawdown

An *Alkamax* mLLDPE, also with similar MI and density, will typically produce films with

- Much higher impact strength
- Further improved heat sealing properties, especially hot tack performance

On the other hand, the *Alkathene* LDPE will typically show the following benefits

- Lower extruder power consumption
- Lower melt temperature
- Lower tendency to suffer from melt fracture
- Improved bubble stability
- Higher film clarity

Alkatane HDPE grades have significantly higher density than LDPE and LLDPE grades. As shown in Figure 1, films produced with HDPE will typically show

- Much higher stiffness
- Much higher yield strength
- Improved creep resistance
- Lower permeability to gases

Table 1 below summarises some key differences typically observed between films produced with different classes of PE.

For these reasons, different classes of PE are often combined in a film to obtain the best balance of properties for the application. Products can be combined by blending and by coextrusion.

Blending of Alkatuff LLDPE, Alkamax mLLDPE and Alkathene LDPE

Alkatuff LLDPE, *Alkamax* mLLDPE and *Alkathene* LDPE are normally compatible. Linear-rich blends or LDPE- rich blends are widely used in film applications. Blends containing 40 – 60% LDPE are not so common.

Addition of LDPE to LLDPE or mLLDPE improves several properties, including processing and optical properties. Such linear rich blends have rheological properties intermediate between those of the two polymers and their processing performance is modified sufficiently to improve the film processing with little loss in the desirable mechanical properties.

In particular, a small addition of LDPE to LLDPE makes the LLDPE less sensitive to disturbances and significantly decreases the tendency for bubble instability.

The blending of a small amount of LDPE into LLDPE also gives a considerable improvement to the gloss and haze of the film.

As would be expected, the properties of the linear-rich blends are modified slightly away from those of LLDPE or mLLDPE towards those of LDPE but generally this is not a serious disadvantage. At the other end of the scale, small amounts of *Alkatuff* LLDPE or *Alkamax* mLLDPE (less than 40%) blended into *Alkathene* LDPE improve processability, with enhanced tensile properties, stiffness, puncture resistance and heat sealability which may allow the benefits of down gauging.

Further details of the properties of blends are given in later sections.

Table 1: Comparison of Film Properties for the Different Classes of PE

Property	LDPE	LLDPE	mLLDPE	HDPE
Haze	Low	Medium	Medium	High
Tensile Strength	Low	Medium	Medium	High
Elongation	Medium	Very High	Very High	High
Tear Resistance	Medium	Variable	Variable	Low
Impact Strength	High	High	Very High	Variable
Puncture Resistance	Low	Very High	Very High	Medium
Hot tack	Low	High	Very high	NA

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Blending of HDPE with LLDPE and LDPE

Some film applications require a combination of stiffness and toughness, which may be achieved by blending LLDPE or mLLDPE with HDPE. For example, addition of LLDPE to HDPE will improve impact strength, tear resistance and can improve sealing properties. Even greater improvements are typically achieved if mLLDPE is used. Alternatively, addition of HDPE to LLDPE or mLLDPE will improve stiffness and creep resistance, with some sacrifice of toughness properties.

The choice of HDPE grade depends on the film properties required. Where toughness and creep resistance are important, a low MFI grade is preferred. However, in some extrusion lines, low MFI HDPE grades may not mix well with higher MFI LLDPE grades. In this case, a higher MFI grade of HDPE may be necessary. The higher MFI grade of HDPE will still improve the film stiffness, but there will be a reduction in film toughness.

For some applications, a blend of HDPE, LLDPE and LDPE may be required. Typical examples may include films where a low proportion of HDPE is added to a blend of LLDPE and LDPE to improve stiffness or creep resistance. As noted in the previous section, the appropriate HDPE grade depends on the toughness required and the extrudability. Combinations including LDPE and low MFI HDPE are more prone to show poor dispersion. Hence, some work may be required to find the optimum blend and extrusion conditions for the application and extrusion line.

Coextrusion

Coextrusion of multiple layers within a film can increase the options available in designing films. For example, each layer can be optimised to perform a different function. Examples include:

- A surface layer for sealing may contain an excellent sealing resin such as metallocene
- Non-sealing layers may contain a higher density blend to provide stiffness without affecting sealing
- Antiblocking additives can be added to only the surface where they are required
- Stretch wrap film can be produced with high cling on only one side
- In some cases, film can be produced with more slip on one side
- High gloss surfaces can be produced
- Films can be produced with high barrier resins (e.g. Nylon, EVOH)
- Incompatible resins can be used in different layers

By taking advantage of some of these options, significant cost savings can be achieved. These cost savings are typically achieved by

- Minimising the amount of expensive resins required
- Allowing downgauging
- Replacing more expensive laminate products

A full explanation of film structures is beyond the scope of this guide. Please contact your Qenos Technical Service representative for further information.

FILM EXTRUSION TECHNOLOGY

Process Description

The blown film extrusion process is illustrated in Figure 2. Polymers are typically conveyed to the extrusion line by a vacuum conveying system. The feed system typically contains a number of hoppers for receiving different resins and a mixing system for blending multiple resins. Modern lines typically have gravimetric systems for controlling the blending process and also for metering the resins to the extruders. In the extrusion process, homogeneous polymer melt delivered at a constant rate from one or more extruder screws is extruded through an annular die to give a tube of controlled diameter and wall thickness.

Upward vertical extrusion is almost universally used, but downward or horizontal extrusion is employed in some circumstances. The extruded melt is air-cooled in the vicinity of the die via a cooling ring and the tube of film is inflated to a bubble of the required diameter by air introduced through the centre of the die mandrel. The film is hauled off between a pair of nip rolls so that a constant volume of inflation air is contained within the bubble formed between the nip rolls and the die.

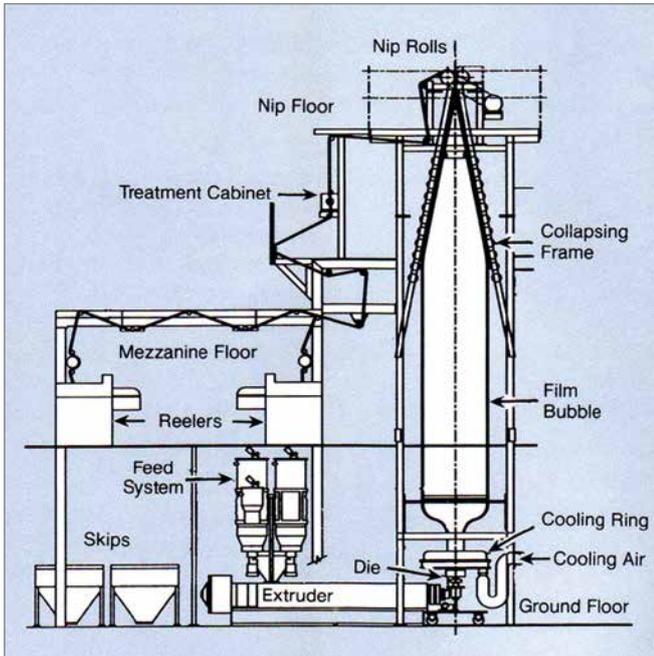


Figure 2: Blown Film Line Schematic Diagram

For a given die diameter, the diameter of the bubble and hence the layflat width of the film (the width of the flattened tube) is determined by the amount of inflation air introduced. The thickness of the film depends on the output from the extruder, the bubble blow-up ratio and the film haul-off rate. Thus, by variation of these parameters, a range of film layflat widths and thicknesses can be produced from the one die.

After the bubble has been collapsed in a collapsing frame and flattened through the nip rolls, the layflat film is wound up under constant tension either as tubular film or after slitting into sheet film. If the film is to be printed, then it is necessary to treat the film surface before winding by means of corona discharge treatment, in order to obtain good adhesion of the printing inks.

This process is basic to the extrusion of film from all film grades, including blends and coextruded multilayer films (see Figure 3). However, some differences in the equipment and extrusion conditions are necessary for optimum extrusion of different types of polymers; these differences are discussed more fully in later sections.



Figure 3: A Modern Blown Film Coextrusion Line with 5 Extruders

Blown Film Parameters

The parameters of the blown film process are illustrated in Figure 4. The final characteristics of the film are its thickness in microns (t) and its layflat width in millimetres (LFW). The parameters of the extrusion process are the mass output rate of the extruder in kilograms per hour (G), the bubble diameter in millimetres (D) and the line speed or haul-off rate in metres per minute (V). The extruder is fitted with an annular die of fixed diameter in millimetres (d) and a die gap in millimetres (h).

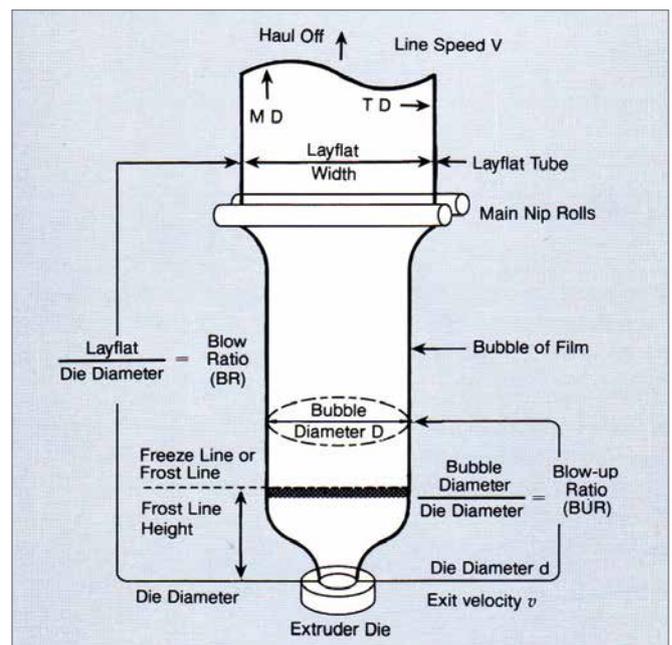


Figure 4: Parameters of Blown Film Extrusion Process (MD = Machine Direction, TD = Transverse Direction)

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Some useful calculations for this process are shown in the following equations. The significance of these terms will be explained in later sections.

$$\text{Blow-up Ratio (BUR)} = \frac{\text{Bubble diameter (D)}}{\text{Die diameter (d)}} = \frac{2 \text{ LFW}}{\pi d}$$

(Note that LFW should be measured before any trimming or slitting occurs)

Blow-up Ratio should not be confused with the less common term Blow Ratio

$$\text{Blow Ratio (BR)} = \frac{\text{LFW}}{d}$$

Drawdown Ratio (DDR) is a measure of the degree of machine direction orientation.

$$\text{Draw Down Ratio (DDR)} = \frac{1000 h}{t \text{ BUR}}$$

An approximate output can be calculated from the film dimensions and extrusion parameters:

$$\text{Output} = \frac{2 t}{1000} \frac{\text{LFW}}{1000} 60 V \rho$$

where ρ is the average resin density in grams per cubic centimetre.

Be aware that small discrepancies in the output can arise due to stretching or relaxation of the film between the measurement of the line speed and measurement of the film dimensions.

In coextruded films, the output formula can also be applied to the individual layers.

RHEOLOGICAL CONSIDERATIONS

The processing of PE as blown film involves a consideration of the rheological characteristics of the polymer. Processes for extruding LDPE film have been developed over many years. With the advent of HDPE in the 1960s and then LLDPE in the late 1970s, an understanding of the differences in rheological performance between the polymers was vital for adapting the LDPE processes and developing new technology which was optimum for the new polyethylenes.

The rheological differences between the product types are evident as dissimilarities in their behaviour during blown film extrusion processing. These differences basically arise because of differences in their molecular structure. This has been outlined in the publication: General Properties.

In summary, *Alkathene* LDPE polymers have a relatively broad molecular weight distribution with 1 to 5 long chain branches per 1,000 carbon atoms. On the other hand, *Alkatane* HDPE, *Alkatuff* LLDPE and *Alkamax* mLLDPE polymers have a narrow molecular weight distribution and no long chain branching. The polymers also differ in their short chain branching characteristics; this does not affect their rheology but accounts for significant differences in the crystallinity and mechanical properties of the polymers.

These structural differences lead to significant variations in the shear viscosity, extensional viscosity, melt elasticity and flow behaviour between the polymers.

Flow in Shear

The melt flow behaviour in shear is represented by a flow curve of shear viscosity vs. shear rate or shear stress. Typical flow curves for two *Alkathene* LDPE and two *Alkatuff* LLDPE polymers are given in Figure 5. These flow curves demonstrate the shear thinning nature of polyethylene, i.e. the shear viscosity decreases as the shear rate or flow rate increases.

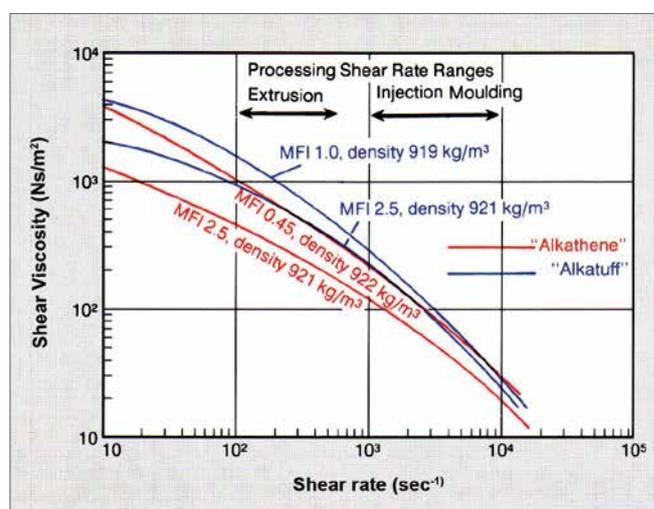


Figure 5: Variation of Shear Viscosity with Shear Rate for *Alkathene* LDPE and *Alkatuff* LLDPE Polymers at 190°C

Several observations can be made from these flow curves, for the range of shear rates normally encountered during extrusion (100 to 500 sec⁻¹) and for polymers of similar MFI and density:

- The shear viscosity of the *Alkatuff* LLDPE polymer is significantly higher than that of *Alkathene* LDPE at the same shear rate. In fact, an MFI 0.45 g/10 min *Alkathene* LDPE has lower viscosity than an MFI 1.0 g/10 min *Alkatuff* LLDPE. This means that the LLDPE will be much

more viscous and require greater torque to extrude than the LDPE at the same temperature. Consequently, higher extrusion temperatures and extruders with greater horsepower are required for LLDPE resins.

- The *Alkathene* LDPE curves have steeper slopes than the *Alkatuff* LLDPE curves, i.e. *Alkathene* LDPE polymers are more shear thinning. This is because of the wider molecular weight distribution and the presence of long chain branching (LCB) in the *Alkathene* LDPE polymers. This difference also means that LLDPE has substantially better melt pumping efficiency (e.g. output per screw revolution) than the LDPE during extrusion, with lower drop-off in output as the head pressure increases.

The behaviour of *Alkatane* HDPE and *Alkamax* mLLDPE resins are similar to *Alkatuff* LLDPE resins, though the Melt Flow Index also plays a role.

Extensional Flow

During the bubble blowing process, the polymer melt exiting the die is being stretched or drawn with the melt undergoing extensional flow. Typical strain rates during blown film extrusion are between 0.01 and 3 sec⁻¹. This extensional flow also contributes to the molecular orientation in the melt which is "frozen-in" at the freeze line and affects the final film properties such as tear strength. The viscosity of the polymer undergoing extensional flow is also important in film extrusion as it relates to the melt strength.

Flow curves of extensional viscosity vs. extension or strain have been measured. Lower MFI grades typically have higher extensional viscosity at the same strain. However the type of polymer is also important. Some examples are shown in Figure 6 for polyethylenes of the *Alkathene* LDPE and *Alkatuff* LLDPE type with equivalent MFI; the following descriptions apply to polymers with similar MFI.

Of particular importance is that *Alkathene* LDPE because of its broad molecular weight distribution and long chain branching is tension-stiffening or strain hardening, i.e. the extensional viscosity increases at higher strain. At high strains, the *Alkathene* LDPE has much higher extensional viscosity than *Alkatuff* LLDPE. This can be described as a higher melt strength.

By comparison, linear polymers including *Alkatuff* LLDPE, *Alkamax* mLLDPE and *Alkatane* HDPE have a lower extensional viscosity and show a much reduced tendency to strain-harden. These differences have important implications in the processing behaviour of these polymers. The linear polymers will typically show reduced bubble stability in film extrusion.

On the positive side, the lower extensional viscosity and reduced tendency to strain-harden mean that *Alkatuff* LLDPE, *Alkamax* mLLDPE and *Alkatane* HDPE polymers are much easier to draw down to thin gauges and can tolerate some contamination in the melt without film breakage.

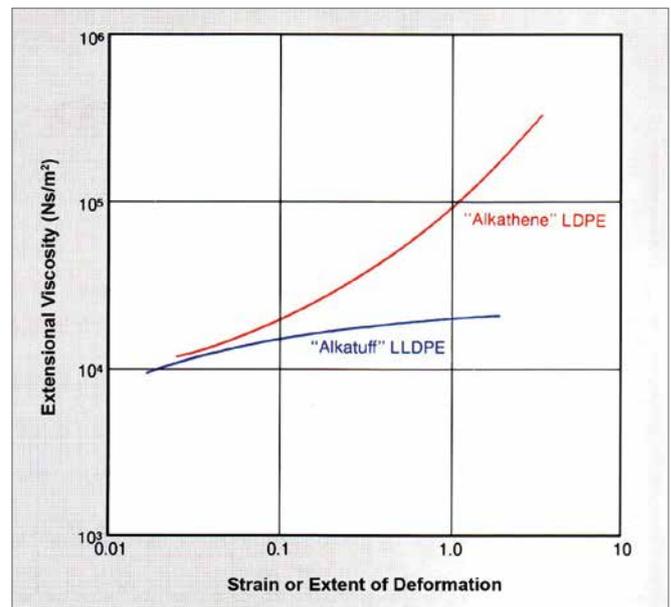


Figure 6: Extensional Viscosity of *Alkathene* LDPE and *Alkatuff* LLDPE Type Polyethylene (MFI 2) at 150°C and 0.1 sec⁻¹ Strain Rate

Melt Relaxation

LLDPE and HDPE have a much lower melt elasticity than LDPE at similar MFI, because of their lack of long chain branching and fewer large molecules. This difference also contributes significantly to the lower degree of molecular orientation "frozen-in" to *Alkatuff* LLDPE and *Alkamax* mLLDPE films compared to *Alkathene* LDPE films at the freeze line and affects the final film properties such as tear strength.

Surface Melt Fracture

A processing difficulty which is observed with narrow molecular weight distribution polymers like LLDPE is that above a critical flow rate they are prone to an extrudate surface roughness defect called sharkskin or surface melt fracture. This roughness first shows as a loss of gloss.

As the flow rate increases, the sharkskin defect becomes worse. It is characterised by a series of parallel ripples on the surface of the extruded product and in film by curled elongated ridges. The critical shear rate at which this problem is first observed decreases (i.e. the problem gets worse) as the MFI of the polymer decreases and the temperature is reduced.

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Sharkskin is an interface phenomenon and arises because of a change in the flow pattern of the polymer at the die wall and exit. There are two possible theories to explain its cause.

The first postulates that slippage of the flowing melt at the die wall occurs at a critical shear stress, due to a loss of intimate contact or a breakdown of adhesion of the melt to the die surface in the die land region. This creates a slip-stick effect at the interface and this is responsible for the observed melt fracture. In fact slip velocity measurements in the die land show a sharp increase with increasing flow rate or shear stress and this slip is invariably associated with surface irregularities for LLDPE. The adhesion of the melt to the die land is dependent on the nature (roughness) of the surface, the type of metal used for the die, and the polymer itself.

The second theory attributes the sharkskin to the sudden acceleration of the surface layer of melt, due to the change in the velocity distribution that takes place as the melt leaves the die lips and accelerates to the speed of the haul off. If the surface stresses exceed the tensile strength of the melt, tearing at the surface results, leading to the sharkskin-type surface roughness.

Several approaches can be used to delay the onset of the surface melt fracture. Extrusion can be carried out below the critical shear rate, by using wide die gap technology. Alternatively the melt temperature can be raised. The metal used for manufacturing the die can be chosen so that slippage is less likely. Another approach is to incorporate a suitable adhesion promoter or processing aid which modifies the flow pattern at the die surface and delays the onset of the melt fracture. Addition of LDPE or increasing the level of LDPE may also reduce melt fracture. These approaches are discussed later in the section 'Wide Die Gap Extrusion' (see p. 16).

THE EXTRUSION PROCESS

Extrusion is the basic process for converting pelletised raw material into an homogeneous melt for delivery to a die and forming into the final shaped product, in this case a thin blown film.

The extruder consists essentially of a cylindrical heated barrel within which rotates a close-fitting Archimedean screw. The polyethylene pellets are fed to one end of the screw from a feed-hopper and are forced forward by the rotating screw, being melted partly by heat conducted through the walls of the barrel from external heater bands and partly by frictional heat generated by the shearing action of the screw.

The molten and compacted polymer is then forced through an annular die as a thin tubular film, cooled and hauled off by nip rolls.

Many different designs and sizes of extruders are used for the production of film (see Figure 7).

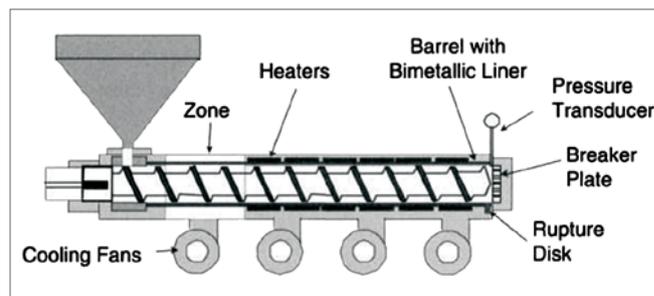


Figure 7: Schematic Diagram of a Single Screw Extruder

The principles of the extrusion are described in the accompanying publication: Extrusion, but a few important features will be covered below.

Extruder Drive System

The power of the motor to drive the extruder screw must be adequate to develop heat energy as well as supply the torque necessary to extrude the most viscous grades of polymer. This is particularly relevant to the extrusion of LLDPE, which because of its much higher shear viscosity than LDPE polymers, will require more horsepower, and will develop greater pressure and higher melt temperature. Hence, extruders should be designed for LLDPE. With adequately powered extruders, near-adiabatic operation is possible, i.e. the heat energy produced by the screw is almost sufficient to raise and maintain the temperature of the melt.

Heating and Cooling the Barrel

The extruder barrel is fitted with a continuous wear resistant hardened-steel or alloy liner. The barrel is heated in several zones along its length, generally by electrical resistance heater bands controlled through automatic temperature controllers. Integral barrel cooling is provided for removing excessive heat, with water or air as the cooling medium. The throat section of the barrel is also water-cooled to prevent premature partial melting of the pellets and bridging in the feed hopper.

To ensure that the temperature conditions are met, it is necessary to measure the melt temperature with a thermocouple inserted into the melt in the head adaptor section of the extruder. It is also recommended that a melt pressure transducer is fitted before the extruder breaker plate/screen pack to record the back pressure and assess the homogenising capacity of the screw.

With LDPE polymers, extrusion is generally carried out with a gradual temperature increase along the length of the barrel.

Because of its higher melting point and higher viscosity, *Alkatuff* LLDPE polymers need a higher melt temperature than *Alkathene* LDPE polymers. Reverse or flat temperature profiles are often recommended, to give more heat input (higher temperatures) in the feed zone and lower temperatures in the metering zone.

The optimum melt temperature and an indication of the temperature profile at which a polymer should be processed are often quoted in data sheets. However the temperature profile needs to be established specifically for each particular application as it will vary according to the type of extrusion equipment, the polymer type being extruded and its MFI.

SCREW DESIGN

The most important part of the extruder is the screw, and its design must be such that a high output of homogeneous melt can be fed to the die at a constant rate and pressure with a uniform temperature and viscosity. The functions of the screw are to collect the polymer pellets from the feed hopper, convey them forward, cause them to be melted, at the same time compress and homogenise the melt, and then deliver it to the die.

Conventional Screw Design

The basic design for a single-flight screw of the conventional polyethylene type incorporates three distinct zones or sections along its length: the feed zone, the compression zone and the metering zone. This design is illustrated in Figure 8 and more details are given in the publication: Extrusion.

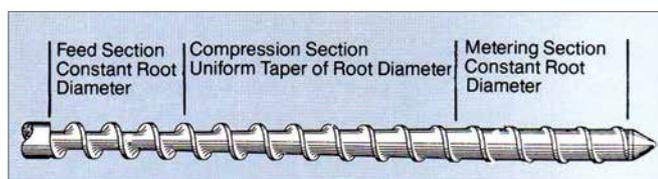


Figure 8: Conventional Polyethylene Type Screw

Most extruder screws have a length: diameter (L/D) ratio of at least 20:1 in order to achieve the maximum degree of mixing, although some older machines with lower L/D ratios still exist. Many modern machines have L/D ratios ranging from 24:1 to 30:1.

The polymer is compressed in the screw by a progressive reduction in depth and hence volume of the screw channel between the feed zone and the metering zone. The compression ratio is the ratio between the volume of the first channel in the feed zone and that of the last channel in the metering zone. For standard screws the compression ratios range from 2.5:1 to 4.5:1 whilst for grooved screws the compression ratio tends to be lower e.g. 1.5:1. Care is required in screw selection to ensure a good compression ratio in order to prevent any inhomogeneities in the melt.

Modified and High Performance Screws

From the basic screw design described above, various manufacturers have developed refinements which include double flights, variable pitch, mixing pins, decompression zones between two compression zones, interrupted flight patterns and other devices to improve mixing efficiency. Refinements such as these lead to reductions in shear stresses and power requirements and can alleviate overheating problems.

Barrier Flighted Screws

Given how critical optimised melting is for the stability of the extrusion process, in particular for fast and high throughput extruders, high performance “Barrier Type” screws have been developed. These screws incorporate a barrier flight further down the extruder, effectively introducing a second screw channel (see Figure 9).

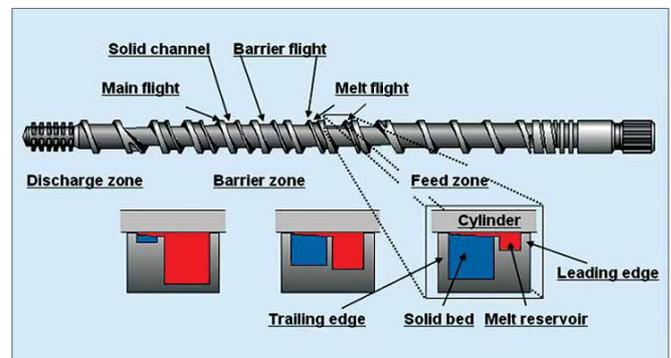


Figure 9: Principle of Barrier Flighted Screw

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The main objective of a barrier flight is to separate already molten resin from unmelted solid polymer. The layer of molten resin against the wall is kept thin, ensuring high shear rates and heat generation in the melt. Separation of the melt into a dedicated, deeper channel also prevents the melt from being over worked by the screw and receiving unnecessary shear heating.

Many manufacturers also supply screws fitted with a high shear mixing section just behind the screw tip for added homogenisation, increased output and a more uniform melt temperature (see Figure 10). More information about these modified screws is given in the Extrusion publication.

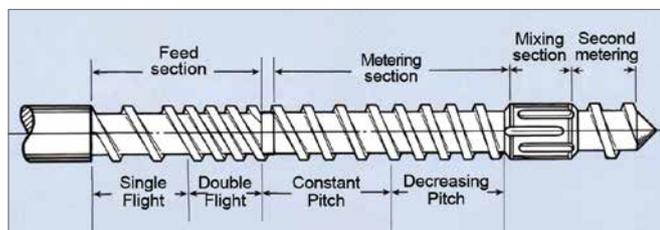


Figure 10: 24:1 L/D Decreasing Pitch Metering Screw

Extruder Head

The extruder head at the delivery end of the barrel contains a screen pack consisting of one or more wire mesh screens between 40 mesh and 100 mesh, supported on a breaker plate. The screen pack is used to increase the back pressure in the metering zone and thus enhance the homogenisation of the melt, and also to prevent contamination from entering the die and the finished product.

A screen-changer apparatus is generally used to insert fresh screens into the melt and prevent excessive pressure build up from contaminants. These screen-changers may be of the slide-plate or continuous variety.

An adaptor fitted to the head acts as the attachment point for the extrusion die. The head and adaptor are heated to keep the temperature of the melt constant, and should be streamlined to prevent any hold-up of material which may crosslink or degrade and eventually slough off into the melt stream.

Grooved Feed Section

Small grooves in the feed section of the barrel, generally longitudinal but sometimes helical, are employed to improve the conveying capacity of the screw feed section.

The grooves extend from the feed zone located under the hopper to a point approximately 4 diameters along the extruder length. The resultant high pressure at the end of the grooved section also greatly facilitates melting of the polymer. For optimum feeding, this type of feed zone must not get too hot since this would cause the pellets to soften prematurely, clog the grooves and output will then drop. Grooved zones are provided with water cooling to guard against over-heating.

Further details about grooved feed sections can be found in the Extrusion guide.

FILM EXTRUSION DIES

The functions of the blown film die are to meter the polymer melt at constant pressure and uniform rate, and to transform it into a thin-walled tube, while maintaining uniformity of the melt temperature. For more information on extrusion dies, refer to the Extrusion publication.

For blown film extrusion, the die comprises a metal outer body and an internal mandrel to form an annular aperture through which the molten polymer is forced to produce a tubular extrudate. The lips of the die are in the form of hardened-steel rings which can be integral with the mandrel and body but more often are bolted on to allow for replacement.

The die is heated to maintain uniform melt temperature. Air for inflating the film bubble is introduced via a channel in the core of the mandrel.

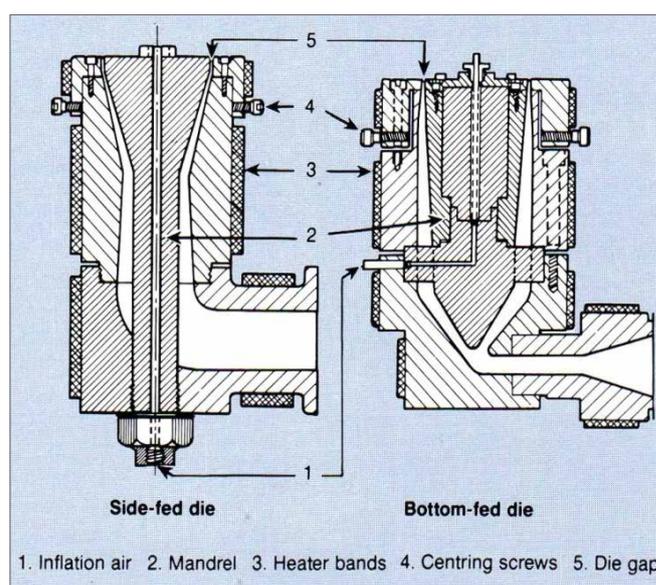


Figure 11: Basic Film Extrusion Dies

Types of Film Die

Film dies are either side-fed or bottom-fed, as illustrated in Figure 11. In both these designs the die lips can be adjusted relative to the fixed mandrel in order to allow uniform melt flow from the die.

Die gap adjustment has traditionally been performed manually at start-up using centring screws around the circumference of the die and measuring the resulting film thickness profile with a film micrometer. In more sophisticated lines, computer feedback of the continuously-measured film thickness profile allows automatic adjustment of the die gap, e.g. through electrically-heated thermal-expansion elements around the die circumference.

Film thickness or gauge around the bubble can vary if the die is not centred, is worn, or if the melt is not flowing uniformly from the die.

Unless corrected, these gauge variations or gauge bands will affect the quality and appearance of the film, and the film roll on windup will become tapered or lopsided or have high spots or ridges. These ridges can subsequently cause trouble during operations such as adhesive lamination, printing and sealing. By spreading the thick bands, the ridging effect will be minimised and the roll appearance greatly improved. One solution to this problem is by slowly rotating or oscillating the die, which results in the bands spiralling or corkscrewing on the bubble, thereby minimising their effects. This solution was common in early film lines, but did lead to high maintenance costs. Newer lines typically have a rotating or oscillating haul-off system, described below.

There is an inevitable disruption to the flow in both the types of die shown in Figure 11, since the melt changes direction and is divided into several streams, by the mandrel torpedo in the side-fed die and by the mandrel supporting carrier, or spider, in the bottom-fed die. This can pose problems of hold-up and subsequent degradation of the polymer, and failure of the melt streams to knit properly after coming together, giving weak memory lines or die-lines in the film. The various measures used to increase back pressure and overcome these problems is discussed in the Extrusion publication.

Spiral Mandrel Dies

One method used for increasing back pressure in the die is by grooving the mandrel in a spiral manner to make the melt path more tortuous. Developments in die design for film extrusion have led to the spiral mandrel die which is based on this principle. In this design the melt is fed to the base of the mandrel of a bottom-fed die, flows via several feed ports to the side of the die, and then enters a series of narrow spiral channels or grooves in the mandrel (see Figure 12a and 12b). These spiral channels gradually decrease in depth as the melt approaches the die lips, causing the melt to flow around the spiral, as well as upward in the annular gap between the die body and the mandrel. The combination of spiral and upward flow ensures uniform melt velocity around the circumference of the die at the die lips. Any unbalanced flow will cause variations in the film thickness.

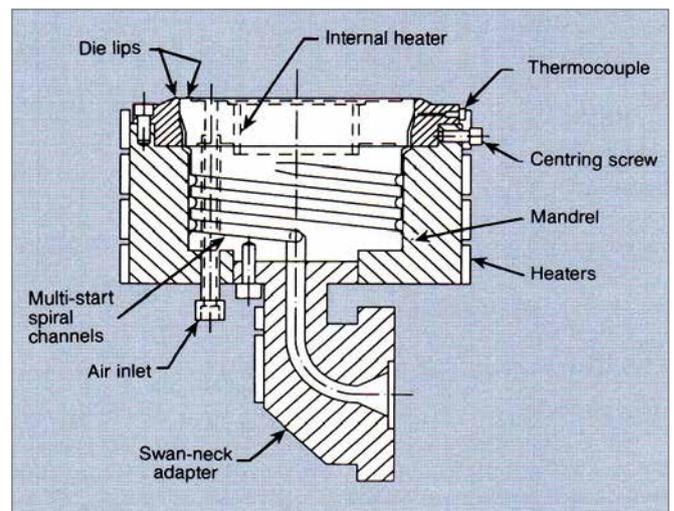


Figure 12a: Schematic Diagram of Spiral Mandrel Film Dies

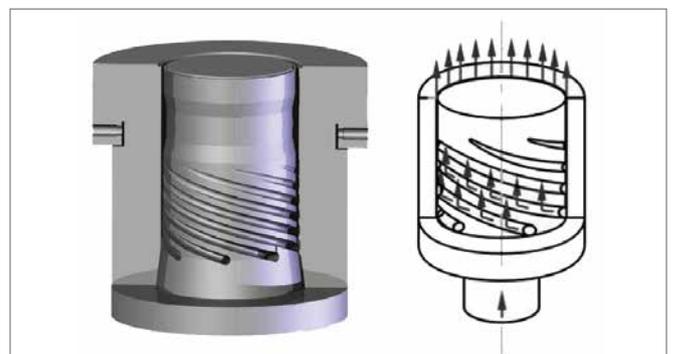


Figure 12b: Spiral Mandrel Film Dies illustrating Polymer Entry Points and Flow Paths

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Coextrusion Film Dies

The basic principles for coextrusion dies are the same as for monolayer dies. However, the die design is more complex as it needs to accommodate a number of different flow paths. The extruders are positioned around the die and each stream enters the die at a different point. Like the dies for monolayer extrusion, coextrusion dies must distribute each layer uniformly around the circumference.

Some coextrusion dies are based on concentric cylinders. Each layer is first formed into an annulus before the layers come together into a single stream and exit the die. Newer coextrusion dies consist of plates stacked together. In this design, each layer is first directed through a gap between two of the plates. Each layer then flows into the central annulus and the layers come together sequentially.

The rheological properties of the individual component polymers are very important in influencing how the melt streams flow together at their interface; any instabilities that occur at the interface can affect the optical and mechanical quality of the final film. As a general rule, the viscosities of two components coming into contact should be matched. However trials should be carried out to decide the choice of polymers and extrusion conditions to be used. As described in the section “Rheological Considerations” (see p. 10), the extrusion temperature has a significant effect on the polymer rheology. Hence, the temperature settings for each extruder barrel, each adapter and the die will influence how the layers combine.

In some lines, one extruder may supply two different layers in the film. To achieve this, the stream is split inside the die before the annuli are formed. While this approach reduces the number of extruders required, a major disadvantage is that there is very little control over the thicknesses of the individual layers.

Die Design Principles for LDPE Polymers

Although both the side-fed and bottom-fed die designs can be readily used for the extrusion of LDPE film polymers, the spiral mandrel dies are generally preferred and are widely used. Better melt uniformity and improved film quality in terms of optical properties and thickness variation are obtained.

The die gap can be of varying size but is usually from 0.5 to 1.2 mm. A rough guide for die gaps for the film extrusion of *Alkathene* LDPE is 0.5 to 0.8 mm for 50 micron film, and up to 1.0 mm for thicker gauges.

Die Design Principles for LLDPE and mLLDPE Polymers

For film extrusion of LLDPE polymers, the dies used for LDPE are generally not suitable at high output rates because of the much higher shear viscosities of the LLDPE at the shear rates normally encountered in film extrusion (see Figure 5 and the earlier section ‘Rheological Considerations’).

The effects of the higher viscosity significantly restrict the extrusion of LLDPE in dies designed for LDPE; excessive die pressure is generated, the melt temperature rises, power requirements increase (possibly beyond the available horsepower of the extruder) and the output rate must in consequence be reduced. In addition, because of its narrow molecular weight distribution, LLDPE is more susceptible to sharkskin or surface melt fracture effects at much low extrusion rates than LDPE, and these can lead to a deterioration of the film appearance and optical quality. For these reasons, the dies optimised for LDPE are generally unsuitable for the processing of pure LLDPE and must be modified, or dies specifically manufactured for LLDPE must be used.

The pressure drop across a die can be significantly reduced by increasing the die gap, decreasing the length of the die land, and increasing the cross-sectional area of any internal restrictions or the grooved flow channels on a spiral mandrel die. These modifications are appropriate for LLDPE and can be made to existing LDPE dies or can be included in the design of new dies specifically for LLDPE.

Wide Die Gap Extrusion

An increase in the die gap will allow extrusion of LLDPE at higher rates without any significant surface melt fracture effects. This is demonstrated in Figure 13 which shows the required gap for the onset of melt fracture as a function of die flow rate and temperature for an MFI 1.0 LLDPE. The effect of MFI on this critical die gap is shown in Figure 14.

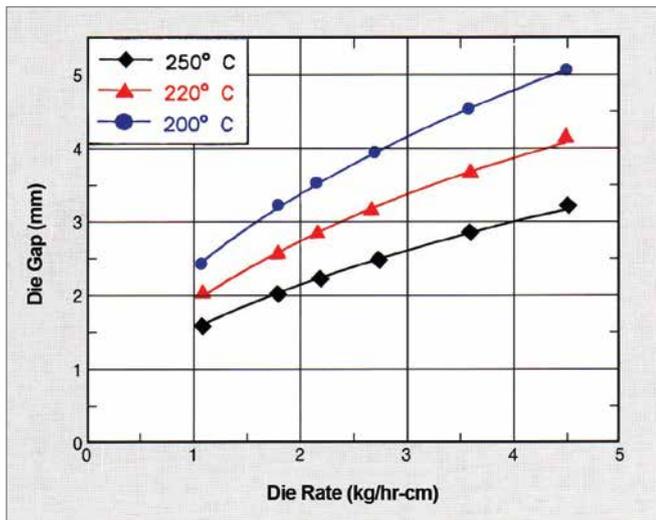


Figure 13: Die Gap for Onset of Surface Melt Fracture as a Function of Die Rate Melt Temperature for an MFI 1.0 LLDPE

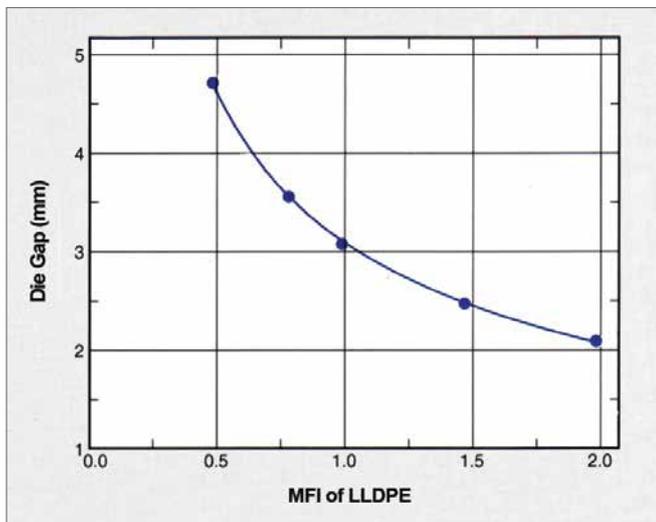


Figure 14: Die Gap for Onset of Surface Melt Fracture as a Function of the MFI of the LLDPE. (Die Rate: 2.7 kg/h cm, Melt Temperature 220°C)

When modifying a die according to the above principles, the practice is to use a trial-and-error approach, by stepwise increasing the die gap and checking the film extrusion performance after each change. If the die pressure is excessive, then the land length can be reduced to less than 25 mm (e.g. 5 to 20 mm), and the flow channels opened up. In retrofitting an existing die, it is important to know the characteristics of the extruder and its maximum operating conditions.

A typical design for the die land for film extrusion of LLDPE is shown in Figure 15. In this design, the die gap is between 1.5 and 3.0 mm and there is a restrictor with a gap of about 1.0 to 2.0 mm. The restrictor is used to provide some back pressure and so minimise any flow and film thickness irregularities.

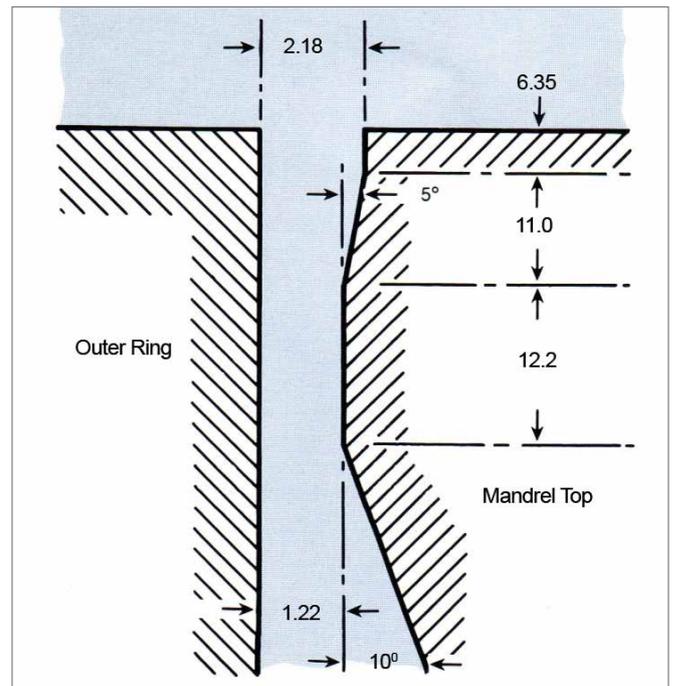


Figure 15: Die Land Design for Wide Gap Extrusion of LLDPE Film (Rate 1.8 kg/h cm for MFI 2 LLDPE at 210°C Exit Temperature – Dimensions in mm)

The criteria for high performance with LLDPE include balanced melt flow from the die, satisfactory die pressure drop and output rates, good film appearance with no melt fracture, and film gauge uniformity. The use of a wide die gap reduces the shear rate through the die and gives a greater latitude before the critical shear rate for melt fracture is exceeded. However there can be several limitations in using wide die gap extrusion; these are increased machine direction orientation due to the higher draw required for a given film thickness, reduced film clarity because of the slower cooling, and reduced gauge control.

If the die is to be used for both LDPE and LLDPE, then two separate sets of die lips or mandrels are recommended. Because of the different extensional viscosities of the two polymers, LLDPE has a greater capability for drawing in the melt state from wide die gaps without melt rupture, whereas LDPE cannot be drawn down to thin gauges.

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The wider die gaps and lower melt stresses mean that LLDPE resins are particularly insensitive to contamination problems. Gels and contamination do not cause bubble breaks and windows as readily as with LDPE extruded through narrow gap dies.

Narrow Die Gap Extrusion

Some film producers do use a conventional film die with a narrow die gap. Unless output rates are low, the use of a narrow die gap may result in the occurrence of surface melt fracture with low MFI LLDPEs, as indicated in Figure 14.

Several approaches can be used to delay the onset of the melt fracture. Obviously, by using wide die gap technology the extrusion operation takes place at a much lower shear rate which is below the critical level for the onset of melt fracture. Higher melt temperatures are also beneficial.

The causes of the surface melt fracture were discussed earlier (see p. 10). As well as the shear rate or velocity of flow of the melt through the die gap and the extrusion temperature, melt fracture is affected by the nature (roughness) of the die land, the type of metal used for the die, and the polymer itself. It has been found that the material of construction for the die land has a significant effect on the flow patterns that occur at the polymer/metal interface and the subsequent melt fracture and film appearance. A die constructed from an alpha brass composition allowed extrusion at much higher rates than with mild steel or chrome-plated dies before the onset of melt fracture. Hence the appropriate choice of the metal used in manufacturing the die may allow much greater output rates through narrow gap dies without melt fracture.

Die Design Principles for HDPE Polymers

Spiral mandrel dies are also used for HDPE extrusion. Where possible, the die should be designed for HDPE. This is particularly important for the low MFI grades. Typically, the die gap is between 1 and 1.5 mm to allow sufficient output rate while generating sufficient back pressure to homogenise the material.

Use of Processing Aids

A widely-used approach to minimise surface melt fracture is to incorporate a small quantity of a processing aid in the LLDPE polymer (less than 0.1 %). The processing aid is incompatible with the polymer and migrates out of the melt to form a coating on the metal surface of the die land. This coating functions by changing the nature of the flow at the polymer melt/die land interface, acting as a lubricating layer between the melt and the metal. The net effect of

the processing aid is to raise the critical flow rate at which surface melt fracture appears, thus allowing extrusion at much higher rates.

Other benefits of using a processing aid are that the die pressure is reduced, allowing lower extrusion temperatures, better gauge control and lower horsepower requirements.

An induction time is required to build up the coating of processing aid on the die. This means that the die must be conditioned with processing aid before extrusion of film product is commenced. This is normally done by extruding a higher concentration of processing aid masterbatch until the melt fracture clears. It should be noted that the processing aid may not coat the die surface very effectively if the shear stress or flow rate through the die is too low.

Proprietary processing aid additives are produced by several suppliers and these are generally very effective in reducing melt fracture effects. Some Qenos grades are formulated with a processing aid to give melt fracture-free film at maximum output rates and with minimum interference of the processing aid with other additives in the formulation (e.g. the antiblock additive).

If surface melt fracture is obtained with LLDPE polymer which does not contain any processing aid, or there is insufficient additive in the polymer, then a small quantity of processing aid masterbatch can be blended into the polymer before extrusion to improve the extrusion performance.

BUBBLE INFLATION

The extruded polyethylene tube on exiting the die is inflated into a bubble of the desired diameter and film thickness by means of an internal injection of air introduced through the die mandrel at a pressure of 15 to 35 kPa. This air is trapped within the film bubble formed between the die and the nip rolls. The ratio of the diameter of the bubble relative to the diameter of the die is known as the blow-up ratio (see Figure 4).

Blow-up ratios as low as 1.5:1 can be used but these can lead to excessive machine direction orientation. Generally blow-up ratios between 2:1 and 3:1 are used. Higher blow-up ratios may lead to bubble instability problems and film creasing.

BUBBLE COOLING

The film cooling process is very important because the cooling can affect the output rate, gauge uniformity, film density, and a number of film properties. The cooling system has four main functions:

- To remove heat from the melt exiting the die and cool the film bubble to the solid state, so that it can be subsequently flattened and wound-up
- To stabilise and support the bubble on its exit from the die and minimise gauge variations
- To control the film density and a number of film properties including impact strength, tear strength and opticals
- To determine the maximum output rate at which the film can be produced without blocking problems. To prevent blocking, the temperature of the film reaching the nip rolls should be less than 40°C

As the film exits from the die annulus, it is in the molten state and must be cooled as soon as possible to stabilise the bubble and achieve a low degree of crystallinity. The freeze line or frost line is the ring-shaped zone where the polymer solidifies after being cooled from the molten state, and the bubble reaches its final diameter (see Figure 4). Slow cooling, i.e. a high freeze line, results in a high crystallinity and a high film density and this can adversely affect both the optical properties and the impact strength of the film.

Air Ring Design Principles for LDPE

The basic form of cooling unit is an air ring (Figure 16) which is fitted above the die. The air ring is designed to direct an air stream uniformly onto the exterior circumference of the film bubble as it emerges from the die. For maximum cooling efficiency, a combination of a high volume of low pressure air at the highest practical velocity must be used. It should not be an air blast of such force as to damage the bubble or to induce flutter. Any variations in the air temperature or flow rate around the circumference of the air ring will give rise to non-uniform cooling rates and as a consequence, irregularities in the bubble and poor film thickness tolerance.

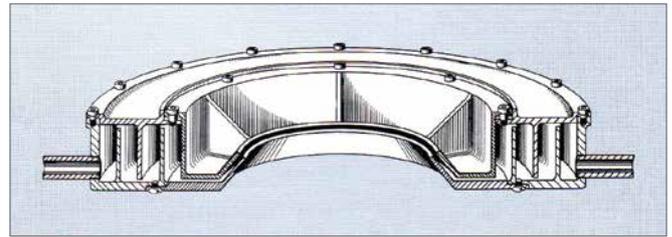


Figure 16: Cooling Ring for Blown Film Extrusion

Most air ring manufacturers have their own ideas on air ring design, giving rise to many different effective types. However, a number of features are basic to their design, in order to ensure uniform air flow around the circumference of the ring:

- The air inlets are placed symmetrically around the ring, and are either radial or tangential
- Internal baffling within the air ring provides a tortuous path to equalize the air flow
- The air ring outlet is at 60 degrees or 90 degrees to the horizontal, to maximise cooling efficiency. The desired air stream is parallel to the bubble surface, and flowing at a high velocity without deforming the bubble or introducing any instability to the bubble shape

The air supply should be as cold as possible, and free from dust, soot, oil droplets and similar contaminants. An obvious means of increasing cooling efficiency is to use chilled air, but the air temperature cannot be reduced too low otherwise condensation problems will be encountered.

Air Ring Design Principles for LLDPE

With conventional air ring designs where the air flow impinges directly onto the bubble, the LLDPE bubble shape can be easily distorted below the freeze line and this highly likely to lead to bubble instability at moderate output rates. It is thus imperative that modifications are made to the air ring, or one specifically designed for LLDPE blown film extrusion is used.

Lower air velocities and higher air volumes are required. Air flow should be directed roughly parallel to the bubble surface and remain in contact as long as possible (see Figure 17). Using chilled air, single-lip air rings based on these principles have been satisfactory for some applications with LLDPE, especially at low output rates (about 1.0 kg/h cm of die circumference).

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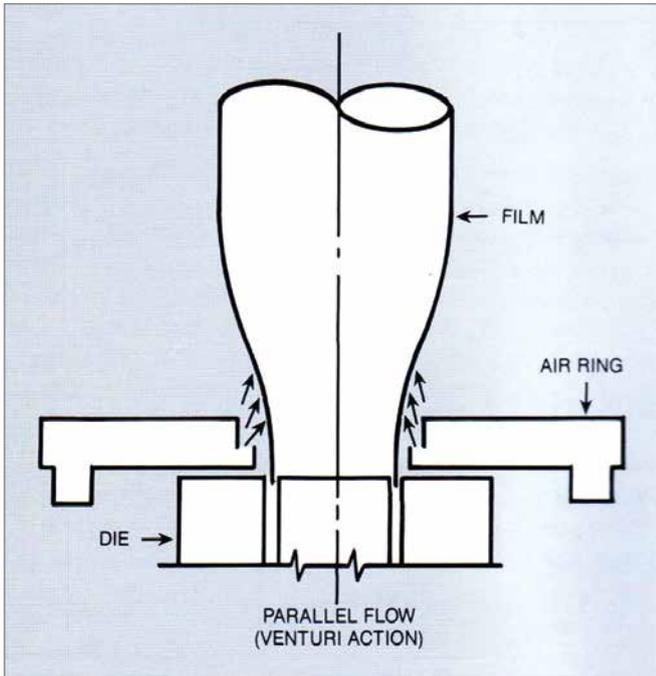


Figure 17: Parallel Flow Bubble Cooling for LLDPE

Venturi-type air rings will allow an increase in output rate. In these rings, the air is directed parallel to the bubble surface in such a way that it causes a partial vacuum effect on the surface of the bubble, sucking it towards the air ring and tending to lock it in position; this prevents any instability occurring and produces a lower freeze line.

Dual-lip air ring designs have proved effective for the film extrusion of LLDPE polymers and are widely used. These rings provide enhanced cooling which effectively stabilises the bubble. A typical design is shown in Figure 18. The air stream from the cooling ring is divided into two portions by a forming cone or flow divider, the low-volume low velocity inner (lower) stream flowing parallel to the bubble surface to provide initial cooling and to act as a 'lubricating' layer, and the relatively greater volume of higher velocity air from the upper lips accelerating the cooling rate. These rings can also incorporate the venturi design with an extended chimney. Output rates varying from 1.6 to 2.3 kg/h cm have been reported using a dual-lip venturi air ring. Again the use of chilled air is beneficial.

Other variations have also been developed to improve cooling.

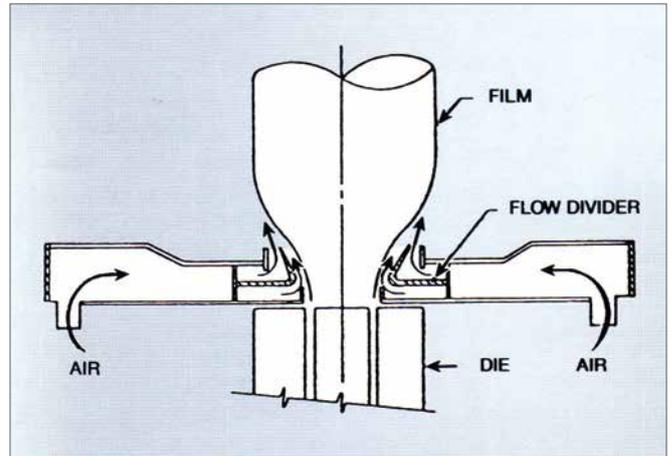


Figure 18: Dual-Lip Venturi Style Air Ring

A venturi-type air ring with an extended tubular shield or collar can be used to promote acceleration of the air flow past the bubble after leaving the air ring and create a partial vacuum. The shield can extend some two-thirds of the freeze line height.

Multiple or stacked cooling rings can be used to improve bubble stability and increase output rates. Improvements in output rates can be up to 50% (for LLDPE). The freeze line is usually determined by the primary air ring. The remaining rings serve mainly as after-coolers to remove residual heat, and are mounted above the primary ring, at a point where they do not interfere with cooling from the conventional cooling ring. The extra cooling rings are useful when the output is limited by the film still being warm enough to block badly when it passes through the nip rolls, for example, with thick film and low nip roll height.

Regardless of the air ring design, the air flow exiting the air lips must be uniform to $\pm 0.5\%$ around the circumference, otherwise gauge and layflat uniformity will be difficult to maintain.

Air Ring Design Principles for HDPE

HDPE rich films, particularly those based on low MI grades, are typically extruded with a long stalk or high neck. This gives the polymer chains more time to be drawn in the machine direction, which allows a thinner gauge to be achieved. Older air ring designs were similar to LDPE air rings where the air was directed vertically; the long stalk was achieved by using a low flow rate of air. Newer designs have been optimised for HDPE and can achieve significantly higher output rates, while still maintaining the long stalk.

Internal Bubble Cooling (IBC) Systems

One of the methods for increasing the cooling efficiency and hence the output rate of blown film production is to use internal cooling of the bubble as well as the external air cooling system. There are a number of variants to internal cooling, from introducing cold air into the bubble, to sophisticated internal bubble coolers (IBCs) which are mounted on the die and utilise a heat exchanger and blower fan system to provide refrigerated cooling air to the internal surface of the bubble (see Figure 19).

The use of internal bubble cooling is effective when extruding LLDPE. Output rates up to 3.5 kg/h cm of die circumference without any bubble instability can be obtained, by using dual-lip air rings together with an IBC. At these high output rates, large die gaps and/or use of processing aids are required to eliminate melt fracture effects, and chilling of the die lips must be avoided.

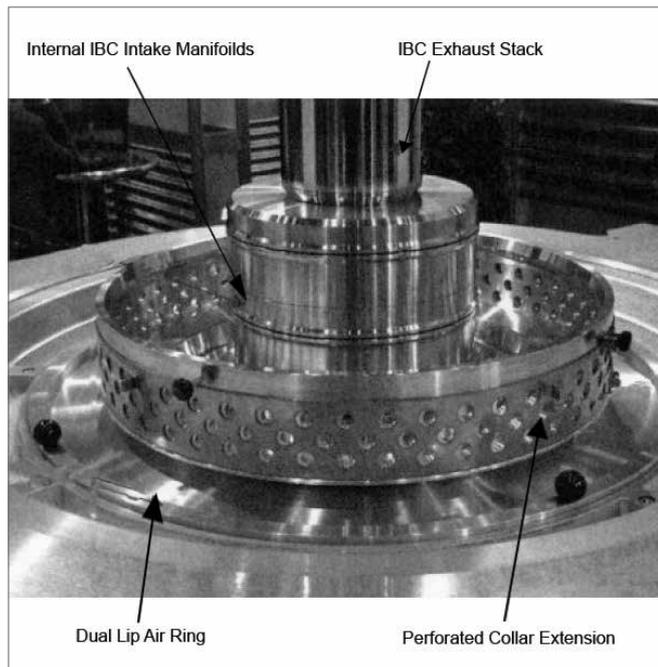


Figure 19: A Picture of the Air Ring and IBC with a Collar Extension (Courtesy of Macchi North America Plastic Machinery Inc.)

Bubble Stability

LLDPE polymers give a much less stable film bubble than LDPE polymers. The instability with LLDPE may take the form of low or high frequency vertical oscillations, or a corkscrew motion or the bubble may actually sag onto the air ring.

This arises because of the difference in the extensional rheology between the two polymers (see p. 10). LDPE is strain-hardening and any disturbances are self-restricting, whereas LLDPE has a much reduced tendency to strain harden, a lower resistance to deformation, and as a consequence is more sensitive to any disturbances in the bubble.

This comparison is further illustrated in Figure 20, which shows the tension developed in the bubble as a function of haul-off speed for several LDPE and LLDPE film grades; the lower tension with LLDPE produces less dampening of any disturbances, and hence bubble instability occurs.

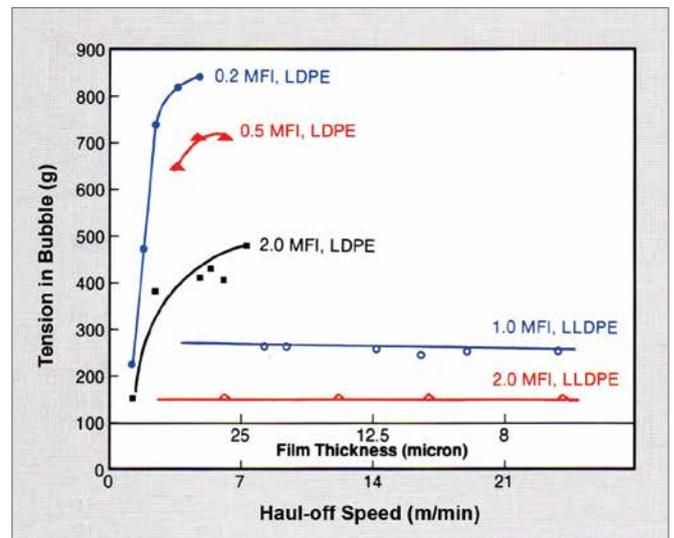


Figure 20: Bubble Tension vs. Haul-off Speed for LDPE and LLDPE Extrusion

In addition, the melt temperature for LLDPE extrusion may be greater because of its higher viscosity. This factor contributes to a reduced cooling efficiency and a higher freeze line. The consequence of the bubble instability and the more difficult cooling is that production rates with LLDPE are limited by the cooling stage of the process.

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The use of an LLDPE grade with a lower MFI will improve bubble stability, as will a reduction in melt temperature. In many applications, a small quantity (10 to 20%) of LDPE polymer is blended into the LLDPE to alter its rheological response and improve bubble stability.

Aspects of bubble stability have been discussed above in relation to bubble cooling, and especially for LLDPE film extrusion. Bubble instability can also arise by the use of high blow-up ratios, a long stalked bubble or very high nip rolls. It may not always be acceptable to modify these extrusion conditions, so alternate procedures are used to help stabilize the bubble.

Freely-rotating guide rolls, iris diaphragms, or specially designed guide cages can be located immediately after the freeze line and before the collapsing frame, to correct any tendency for the bubble to wander in the film tower.

COLLAPSING THE BUBBLE

Prior to entering the nip rolls, the film bubble is collapsed into a flattened tube by means of a pair of angled collapsing frames or boards (sometimes called the A-frame or bat wings). These can take various forms and can be either of solid or hollow construction, or in the form of rollers.

Friction between the film and the surfaces of the collapsing system should not be too high, as this will cause dragging or 'grabbing' of the film, giving rise to wrinkles and creasing. This effect becomes more noticeable if the film is hot or the area of contact between the boards and the film is too large. It can largely be overcome by slightly roughening the surfaces or using coatings to reduce heat build-up and film drag.

Each collapsing frame should be aligned tangentially to the nip roll and positioned symmetrically relative to the vertical. The angle between the frames should not exceed 45 degrees. This angle is suited to the manufacture of light gauge film as the short contact time between the film and the frames tends to discourage the formation of wrinkles. For heavy gauge film which has a relatively low degree of drag, the angle between the frames can be considerably less.

Air flotation collapsing systems can be used to provide nearly frictionless forming surfaces and minimize wrinkling and creasing in film products likely to have excessive drag, e.g. stretch wrap films.

Gusseting

For a number of applications, gusseted layflat film is required for the production of polyethylene bags. Gusseting is achieved by means of narrow wedges or plates which are located within the angle formed by the collapsing frames; these plates are forced into opposite sides of the bubble just before the film passes into the nip rolls, so that it folds in on itself. The gusseting attachments, which can be made from wood or metal, should have smooth surfaces and rounded edges to avoid scratching of the film (see Figure 21).

Handling of LLDPE film in the film tower and nip rolls is similar to that for LDPE film, although LLDPE is not as forgiving as LDPE and is more prone to stretching and wrinkling.

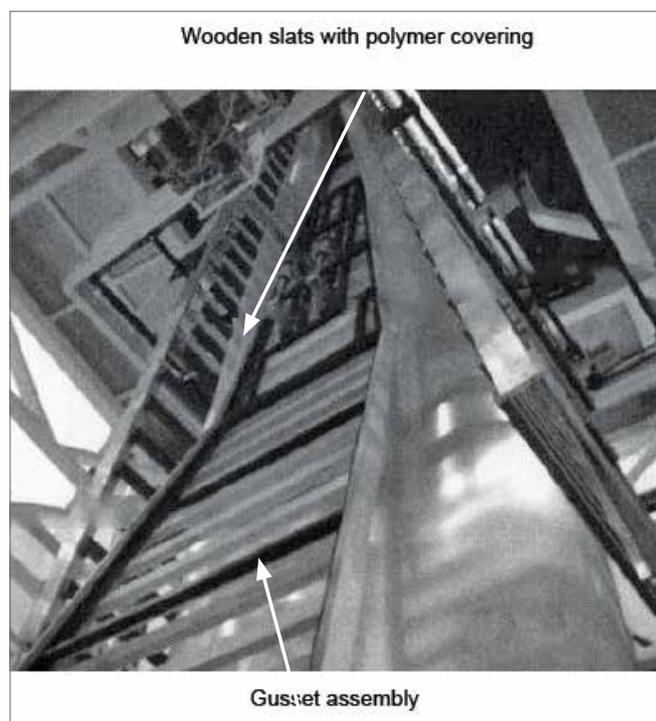


Figure 21: A Picture of Film Gusseting with Wood Slat Collapsing Frame

Nip Rolls

The collapsed bubble passes through nip rolls which flatten the tubular film before the wind-up stage, trap the inflation air in the film bubble, and regulate the take-off speed of the film. The nip roll assembly comprises two rollers, typically one constructed of steel and the other covered with a resilient material such as rubber, to take up flaws in the film.

The nip rolls should be mounted vertically above the extrusion die, at a height of at least two metres, and directly in line with the collapsing frames. When only the conventional air cooling ring is used for cooling the film, the height of the nip rolls above the die has a marked effect on the film production speed, more after-cooling being obtained with higher nip rolls. However very high nip rolls can lead to bubble instability, especially when extruding LLDPE polymers.

The pressure between the two rolls should be even along their length and just sufficient to maintain the steady linear take-off speed and prevent escape of air from the film bubble. If the nip roll pressure is too high, blocking and weak edge-folds will result. Blocking will also occur if the film entering the nip rolls is too hot.

The individual rollers must be kept in good condition and be correctly aligned. Worn or incorrectly set rollers can lead to various problems, including:

- External marking on the film due to scratches or burrs on the rolls
- Escape of inflation air from the bubble caused by wear and poor alignment of the rolls. This will lead to a loss of bubble diameter. Any air entrapped between the two thicknesses of the layflat tube will result in reverse-side treatment of the film
- Creasing and wrinkling due to uneven wear of the nip rolls
- Creasing and wrinkling due to poor alignment of the nip rolls with the extrusion die and collapsing frames

Oscillating Haul-off

Film thickness or gauge around the bubble can vary if the die is not centred, is worn, or if the melt is not flowing uniformly from the die. Unless corrected, these gauge variations or gauge bands will affect the quality and appearance of the film, and the film roll on windup will become tapered or lopsided or have high spots or ridges. Early film lines overcame this problem by oscillating the die.

However, a cheaper more reliable method is used in newer film lines. The top nip rolls are mounted on a platform that oscillates over a range of at least 180° every few minutes. A series of rollers, including some mounted at a 45° angle, allow the film to be carried from the rotating platform to the fixed platform. The rollers in this system must be correctly aligned and well maintained to prevent wrinkles and creases forming in the film.

Slitting

If sheet film is required, the layflat is slit at its edges or at any points across its width to form a number of reels of the desired size. The edge trim and off-cuts so formed can be removed with a vacuum system. The amount of this scrap should be minimised to reduce waste and it is often prudent to reclaim it.

Slitting is normally accomplished using very sharp blades or rotating cutters. Because of the greater toughness and elongation of LLDPE films, slitting is more difficult than with LDPE films. LLDPE films require a very sharp blade to ensure clean cutting and are not as tolerant to a blunted blade as LDPE films. Blade life can be increased significantly by coating the cutting edge with a titanium alloy or tungsten carbide (see 'Film Conversion' section p. 50). Where the film can ride along the edge of the slitting blade, a 30 degree angle between the film and the cutting edge is desirable.

As with slitting, perforating and hole-punching operations on LLDPE films also require very sharp cutting edges to obtain clean cuts. This particularly applies to thin films.

FILM WIND-UP

The final operation of the blown film process is the winding-up of the film. As there is invariably some shrinkage of the film after it has been wound-up, the winding tension must be controlled to preclude the film being too tightly wound on the roll. Excessive tension can induce pressure blocking between film layers, may cause ripples in the film when unreeled, and, in severe cases, lead to telescoping of the roll or collapse of the core. Slack winding allows the film to telescope off the roll, especially if slip agent is present.

Because of the inherent greater extensibility of LLDPE film, strict attention must be given to the precise control of the web tension in order to avoid stretching the film (especially thin film) at high web tensions.

Winding systems are designed to permit a constant winding tension as the film builds up on the roll. Both surface (contact) and centre winding can be used, but contact winders are the standard.

3 FILM EXTRUSION AND CONVERSION

SUMMARY OF DIFFERENCES IN EXTRUSION EQUIPMENT FOR LDPE AND LLDPE

The following are the essential differences required in the extrusion of LLDPE compared with LDPE:

- Greater motor power, up to 0.33 kWh/kg, compared with 0.20 to 0.25 kWh/kg for LDPE
- Screw design with deeper channels and narrower flights, to develop lower torque
- Use a shorter screw, possibly with a decreasing pitch
- Grooving of feed section of the barrel is beneficial
- Wider die gap, shorter land length, less resistance in die
- Alternatively use a processing aid in the polymer for extrusion in normal LDPE dies
- Dual-lip air cooling ring with venturi and chilled air
- Auxiliary stabilising devices in film tower
- Self-sharpening or long-life coated slitting blades to maintain sharpness

TREATMENT OF POLYETHYLENE FILM

The surface of polyethylene film is highly non-polar and inert because of the hydrophobic chemical nature of the polymer. This means that the receptivity of the film surface to inks, coatings, adhesives, etc. is poor and adhesion of these materials to the surface is unsatisfactory. This non-polar nature of the surface is the biggest limitation in the subsequent processing (printing, adhesive lamination) of the film for high quality packaging applications.

Traditionally, surface receptivity has been considerably improved by electrical corona discharge treatment, which oxidises the surface, increases the polarity, and provides acceptable adhesion for subsequent printing and laminating operations.

Electrical Discharge Treatment

The electrical discharge technique for surface pre-treatment (also known as the corona or 'C' treatment technique) is widely used because of its effectiveness, comparative simplicity and flexibility of operation. The process consists of passing the film over an earthed metal roller covered with a dielectric layer, and applying a high frequency high voltage current to one or more electrodes, to generate a corona discharge in the gap between the electrode and the roller. This treatment subjects the film surface to an ionic bombardment, the intensity of which is controlled by adjusting the electrical flux applied at the electrode.

A number of factors affect the level of treatment provided by a specific treatment installation. The level of treatment can be increased by:

- Increasing the power to the electrode system. (The power is conveniently expressed as watts per unit film area treated)
- Using an electrode gap as small as practicable with the electrode parallel to the film surface. A gap of about 1 mm is generally used
- Using an electrode length approximately 15 mm less than the width of the film being treated. This prevents a concentration of the discharge energy at the extremities of the electrode which can eventually lead to premature breakdown of the insulation on the support roller
- Decreasing the line speed of the film web. Treatment problems may occur when treating thin films at high output rates and high line speeds. The time that the film web is in the discharge zone, and hence the level of treatment, can be effectively increased in such situations by using a series of electrodes in tandem
- Operating at low relative humidity and high air and film temperatures
- Treating in-line during the film production process, rather than out-of-line on aged film, in order to avoid the inhibiting effect of film additives

Effect of Film Additives on Treatment

Slip, antiblocking and antistatic additives are commonly incorporated into polyethylene films to improve their handling performance. As some of these additives function by migrating to the surface of the film, their presence can interfere with the treatment process, and adversely affect the level of treatment achieved. It is essential that the film be treated as soon as possible after it leaves the extrusion die, before any appreciable concentrations of additives can build-up on the surface.

The treatment cabinet is normally positioned between the nip rolls and the wind-up stage, preferably immediately after the nip rolls. Even under these conditions it may be necessary to increase the treatment power to a higher setting than that required for film not containing additives, to obtain satisfactory ink adhesion.

After the film has been treated, the migration of additives to the surface continues until an equilibrium layer has built-up. These additives, however, are soluble in the ink formulations and are unlikely to interfere with the adhesion of the printing inks to the treated surface.

In general, LLDPE films respond to corona treatment in a very similar manner to LDPE films, and similar treatment power is required for equivalent film thickness. On some occasions, however, increased treatment power may be required to allow for a higher level of additives used in LLDPE film formulations.

Common Dangers and Difficulties

High Voltages: Because comparatively high voltages are used, the treatment unit must be enclosed to prevent inadvertent contact by an operator. The discharge unit should be designed so that it cannot be operated when the guard over the electrode is removed or swung out of position.

Ozone Generation: Ozone is produced in perceptible quantities during the corona discharge in air. As ozone is toxic at high concentrations, an adequate system of ventilation from the treatment cabinet must be provided to remove this gas.

Radio Interference: Electronic treatment units may cause some local television or radio interference if they are not adequately shielded and earthed. It is sometimes found necessary to fit an efficient screening device around the electrode system.

Treatment Faults

Reverse-Side Treatment

In the corona discharge zone the air is ionised and the resulting charged particles initiate the treatment reactions at the surface. If the tubular film contains entrapped air, some treatment of the internal surfaces of the film will result. Similarly if air is trapped between the lay flat film and the treatment roll, then the reverse side of the film will be treated.

The main draw-back of reverse-side treatment is to cause the pick-up of printing ink from the adjacent printed surface during reeling. The small traces of ink which may be transferred to the reverse-side of the film, apart from being unsatisfactory aesthetically, will lead to technical difficulties during photocell-activated bag-sealing operations.

Reverse-side treatment and internal treatment of tubular film can both cause heat sealing difficulties when the treated surfaces are sealed.

If two treated surfaces are brought into contact, a high level of blocking can develop, particularly under pressure and when the surfaces have very high gloss.

Over-Treatment

Over-treatment of the film does not necessarily impair ink adhesion although gross over-treatment will do so. However, over-treatment adversely affects heat sealing, and this is particularly noticeable in the manufacture of bags by side-sealing or where gusseted designs are required.

Assessment of Treatment Levels

The surfaces of corona-treated films can be characterised in several ways, to identify those film areas which have received treatment and to assess quantitatively the level of surface treatment. Tests which can be readily carried out include the wetting tension test, the printability test and the tape adhesion test. It should be noted that a satisfactory wetting tension does not necessarily indicate acceptable ink adhesion, especially when new film formulations are being evaluated; adhesion-type tests should also be carried out.

Wetting Tension (Dynes Ink) Test

In this test the wetting tension of the film surface is determined, to indicate the level of treatment and hence the degree of printability that can be expected.

Test solutions having a range of different wetting tensions are applied to the film surface in turn until a solution is found which just wets the surface, i.e. it does not globulate within two seconds (ASTM Test Method D2578). The surface tension of this solution is the wetting tension, or dynes ink level, of the surface (in dynes/cm or mN/m). A convenient method for conducting this test is to obtain solutions in pen form, sometimes called treatment pens or corona pens. Pens must be monitored for contamination and replaced regularly. As the chemicals used in the solutions and pens can be hazardous, the supplier's instructions and safety precautions must be followed.

Printability Test

The printability of the treated surface is determined by printing a standard ink onto the surface and then assessing the degree of adhesion of the dried ink layer, by applying a strip of Scotch adhesive tape to the ink and assessing the percentage of ink removed by the tape when it is quickly peeled off. If all the ink beneath the tape is removed the treatment is inadequate, whereas if no ink is removed the treatment is very good.

This test is useful in assessing the actual adhesion of printing ink or adhesive to the printed surface (see ASTM F2252).

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Tape Adhesion Test

The tape adhesion test provides a more quantitative measure of the level of surface treatment. In this test the peel force required to remove a special pressure-sensitive adhesive tape from the treated surface is measured. There is a good correlation between the results from this test and actual ink adhesion. An untreated surface will give a peel force of less than 80 g/cm while satisfactory treatment corresponds to peel forces of 300 to 400 g/cm. Excessive treatment is indicated if the peel force is in excess of 400 g/cm.

Treatment Levels

An untreated film gives a dynes ink level of about 30 mN/m (dynes/cm). It is general practice to treat films to a dynes ink level of 38 to 40 mN/m for normal printing applications, with solvent-based inks. For lamination applications a treatment level of about 42 mN/m is required. Water-based inks and adhesives are increasingly being used because of environmental considerations, and when using these, treatment levels need to be increased by 2 to 4 mN/m compared with the levels required for solvent-based systems.

Alkathene LDPE and *Alkatuff* LLDPE films with treatment levels as suggested above are suitable for printing. Film treated in-line has a long storage life and can be printed satisfactorily at a later stage. On some occasions there may be a small drop-off in treatment level on ageing. Mechanical abrasion or severe scuffing can reduce the level of treatment, but this is unlikely to be a problem when polyethylene film is retained on the roll before printing.

CAST FILM EXTRUSION TECHNOLOGY

Alkathene LDPE and *Alkatuff* LLDPE film grades can be used for the extrusion of chill roll cast film. In particular, grades with MFI of 2 g/10 min or higher are used.

The production of cast film involves the extrusion of a thin molten web of polyethylene through a long slit die; this web is drawn down and cast onto a highly-polished water-cooled chill roll before being taken up by a wind-up system. A sketch of the process is shown in Figure 22.

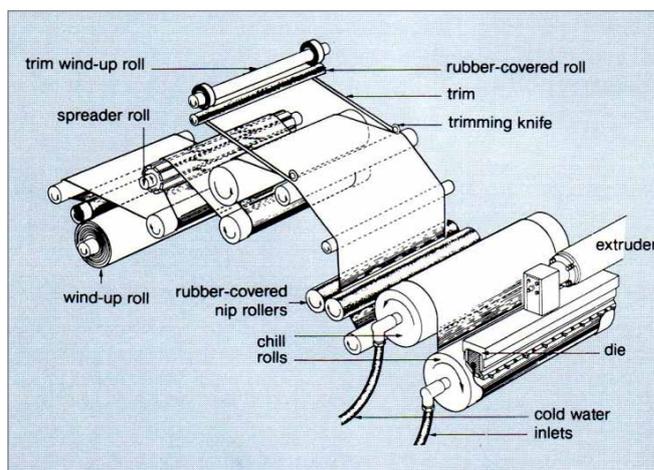


Figure 22: Chill Roll Cast Film Extrusion Process

The extrusion temperatures are generally higher than those used for blown film extrusion, and melt temperatures are typically 225 to 260°C for LDPE and up to 290°C for LLDPE. The chill roll temperature is normally in the range 30 to 40°C.

As in the extrusion coating process (see Extrusion Coating publication), the molten web tends to neck-in by a small amount on both sides of the web to form a thick edge-bead. It is necessary to trim the edges of the film to remove this bead before the film is wound up.

To limit this neck-in, the air-gap distance between the die lips and point of contact with the chill roll should be as short as possible. However short gaps will not allow relaxation of molecular orientation and film of lower impact strength may result. The optimum air-gap distance is between 25 and 75 mm.

Often air can be dragged between the cooling film and chill roll, so lowering the cooling rate. To prevent this, various methods can be used, including an air knife adjacent to the web to push the film positively onto the chill roll surface.

Properties of Chill Roll Cast Film

The main differences between the chill roll cast film process and the blown film process are:

- The much faster rate of cooling with cast film
- The uniaxial (machine direction) orientation in the film process compared with biaxial drawing in the blown film process

These differences have important consequences on the properties of the two types of films.

The rapid cooling of the melt limits the crystallite growth in the film. This leads to a low crystallinity and a low film density. For a given density polymer, the cast film process, will produce a limp film which is more flexible than that obtained by blown film extrusion, and this may not always be acceptable for subsequent conversion and packaging operations. Accordingly higher density base polymers are recommended for chill roll cast film, and *Alkatuff* LLDPE film grades are particularly appropriate.

In general, higher melt temperatures are used in cast film extrusion. This, together with the rapid quenching of the melt on the chill roll, results in excellent optical properties – very low haze, very high gloss and very good transparency.

The mechanical properties of the cast film are determined by both the residual molecular orientation resulting from the drawing process, and the crystallinity of the film. The low crystallinity obtained in cast films will give relatively high impact and tear strengths. However this will be offset if higher density polymers are used to maintain film stiffness.

The molten web is stretched longitudinally in the air-gap to the required thickness. Die gaps are normally 0.5 to 0.8 mm. The longitudinal draw creates high levels of molecular orientation in the film in the machine direction. In contrast to the blown film process, there is no transverse draw. For this reason, cast film may have unbalanced tensile and tear properties in the two film directions. High machine direction orientation will result in low film strength at right angles to the direction of extrusion. When tested in impact, this film will tend to split along the machine direction.

Coextrusion

Like blown film, cast film can also contain multiple layers formed by coextrusion. Typically, the individual layers enter a feedblock where they are arranged in the correct sequence and combined. The combined layers then flow into the die where they are spread to the desired width before exiting the die lips. For optimum extrusion, the feedblock and die must be designed to suit the polymers and formulations being extruded.

Like blown film, the rheological properties of the individual component polymers are very important in influencing how the melt streams flow together at their interface; any instabilities that occur at the interface can affect the optical and mechanical quality of the final film. As a general rule, the viscosities of two components coming into contact should be matched. However trials should be carried out to decide the choice of polymers and extrusion conditions to be used. As described in the section “Rheological Considerations”, the extrusion temperature has a significant effect on the polymer rheology. Hence, the temperature settings for each extruder barrel, each adapter and the die will influence how the layers combine.

Comparison of Alkathene LDPE and Alkatuff LLDPE

As with blown film extrusion, there are differences between LDPE and LLDPE. The low melt strength of LLDPE is generally not a problem in the drawing stage because of the rapid quenching and short air-gap. Thinner gauges without breakage are possible compared with LDPE grades.

LLDPE cast films will have greater stiffness than those produced from LDPE of the same polymer density and this is an advantage since cast films tend to give low film density.

LLDPE cast films are inherently stronger than those extruded from LDPE. LLDPE polymers have a faster melt relaxation and hence a lower tendency for molecular orientation. As a result, they will produce film with more balanced tensile and tear strength in the machine and transverse directions compared with equivalent LDPE cast films.

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PART B. FILM PROPERTIES

In any assessment of the quality of a sample of polyethylene film, the importance of the individual properties can only be determined by considering the applications for which the film is intended. Film applications can be divided into two main categories:

- General packaging, which includes packaging of food, general consumer goods, produce packaging and general shrink film
- Industrial applications, which include agricultural and building uses, drum linings, heavy-duty sacks and shrink wrapping of pallets

General Packaging Applications

Film requirements depend on the nature of the application or user preference/experience. For a high level of consumer appeal in the display of products, general packaging films are required to exhibit excellent optical properties, i.e. high clarity and gloss. This attractive appearance must be coupled with adequate impact and tear strength to withstand the stresses encountered in handling during packaging, transport and retail display.

In most applications, the film should have good heat sealing properties to enable strong heat seals to be formed, and should be formulated with the required level of slip and antiblocking additives for ease of conversion and handling.

Industrial Film Applications

In industrial applications consumer appeal is less important and good appearance is a secondary consideration. These applications require a film with the best possible mechanical properties, i.e. impact strength and resistance to tearing, and a hazy tough type of film may be acceptable. For heavy-duty sacks, mechanical properties, particularly resistance to snagging, are important but additional desirable requirements are the ability to give reliable heat seals and surface properties which permit satisfactory stacking.

Dependence of Film Quality on Polymer Properties

The film properties are dependent on both the properties of the polyethylene and the extrusion conditions by which the polymer was processed. Hence, to meet specific film quality requirements, a choice must be made of the grade of polyethylene to be used and the way in which it is to be processed.

Guidelines for the selection of film grades have been discussed earlier in terms of choice of Melt Flow Index and Density and these effects are summarized in Figure 1. The effects of processing conditions on the properties of the film are discussed in the following sections.

OPTICAL PROPERTIES OF POLYETHYLENE FILM

Introduction

The visual appearance of a polyethylene film is associated with its physical interaction with light, namely the way in which it reflects, scatters, absorbs and transmits the light. Although the term 'clarity' is used loosely to describe film appearance, this is usually a subjective summation of various visual characteristics of the film. The properties usually measured are transmitted light scattering (haze), surface gloss and see-through clarity, though none of these (nor indeed all three collectively) completely defines the optical properties of a sample of film.

The interaction between a polyethylene film and a parallel beam of incident light is illustrated in Figure 23. For a perfectly smooth-surfaced film, the incident beam is split into reflected and refracted rays. The directions and intensities of these are determined by the refractive index of the film and the angle which the incident beam makes with the film. The refractive index lies in the range 1.51 to 1.54 and depends on the degree of branching in the polyethylene and the film fabrication conditions.

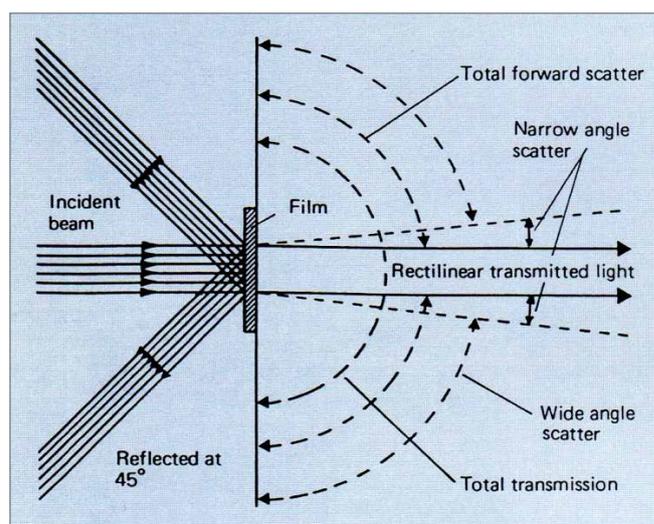


Figure 23: The Physical interaction between Light and Polyethylene Films

In practice, the film surface is not perfectly smooth, but has microscopic irregularities. Irregularities also occur within the film. In addition to the simple reflected and refracted rays, a significant amount of the incident light is scattered or redistributed by these optical irregularities as it passes into, traverses and exits the film, and is then propagated over a continuous range of directions.

For films made from pure polyethylene, absorption of light energy within the visible wavelength range and its conversion into heat energy is not a significant process. However it becomes more significant for films containing a highly absorbing additive such as carbon black.

Haze

Haze is apparent as a 'milky' in the film or a loss of image contrast. It is caused by the transmitted light beam being scattered through relatively large angles with respect to the incident beam, by small irregularities in the film which are comparable in size or smaller than the wavelength of light (less than 0.5 microns).

Haze is defined as the percentage of transmitted light scattered by the film by more than 2.5 degrees from the normal incident beam (wide angle scatter in Figure 23), and is measured using a pivotable sphere hazemeter, according to ASTM Test Method D1003. In films used for display packaging, the measured haze should be low. In addition, the amount of scattering at very wide angles (which can cause an apparent dulling in the colour of a packaged article when viewed through the film) should also be relatively small.

Surface Gloss

Surface gloss is a measure of the reflection of light from the film surface and is thus determined by the smoothness of the surface. For a perfectly smooth film light rays will be reflected geometrically from the surface and the sample will appear very glossy. Scattering from any surface irregularities will confuse reflected images and will lead to a decrease in gloss. With a very rough surface the scattered light will swamp the geometrically reflected rays and the film will appear matt.

Surface gloss is measured as the proportion of light specularly reflected from the film surface at an incidence angle of 45 degrees (see Figure 23), the test method being described in ASTM D2457. Gloss is inversely related to haze via an inexact relationship, so parameters affecting haze will similarly relate inversely to gloss. Figure 24 illustrates how the haze, gloss and clarity of an *Alkathene* LDPE film vary with freeze line distance.

The ability of a film to have a glossy sparkling appearance is an important consideration for film used in some display packaging applications.

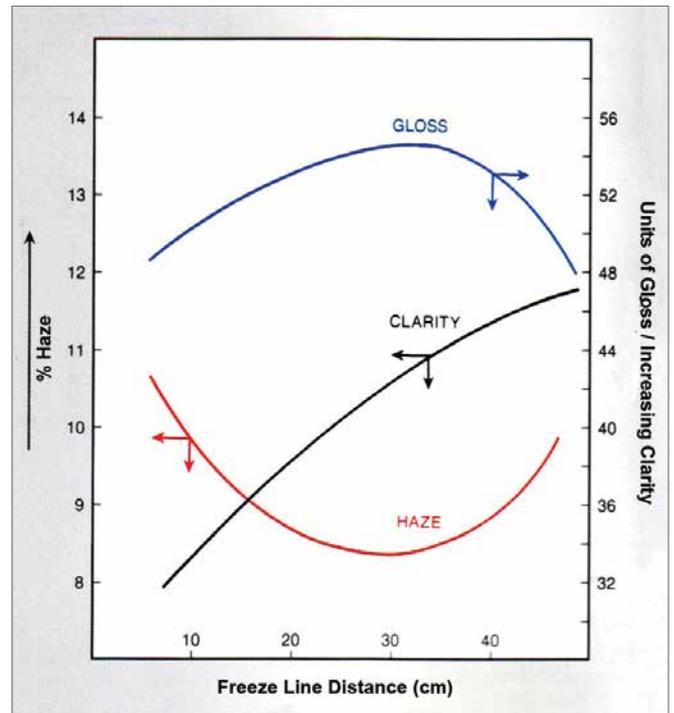


Figure 24: Variation of Film Haze, Gloss and Clarity with Freeze Line Distance for *Alkathene* LDPE Film of MFI 4.0, Density 0.925 g/cm³ (Film Thickness 38 micron)

See-Through Clarity

See-through clarity is a measure of how easily fine detail can be resolved in a fairly distant object when viewed through the film. Poor clarity is caused by light being scattered through small angles relative to the transmitted beam. Low angle scattering arises predominantly from surface or internal irregularities such as 'orange-peel and grain which are much larger than the wavelength of light (i.e. greater than 0.5 microns).

In the laboratory an objective test which shows a good correlation with see-through clarity is the measurement of narrow angle scatter; this is the amount of light scattered forward from the film over an arbitrary annulus subtending a very small range of scattering angles at the film surface (between 1° 12' and 1° 54') (see Figure 23). Low values of narrow angle scatter indicate good clarity.

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The necessity for a high degree of see-through clarity is often questionable as packaging film is usually used in contact with or in close proximity to the contents. Good see-through clarity may be desirable for aesthetic reasons.

Other Optical Defects

Polyethylene film may also suffer from gross irregularities such as graininess, fish-eyes and gels, and die lines; these defects will mar the appearance of the film and deleteriously affect the optical appearance. They can be overcome by using better quality polymer, increasing the stabilisation level in the polymer, increasing the back pressure in the extruder by screen packs, and/or using clean extrusion equipment and scratch-free dies.

On some occasions, oval or elongated thin spots (called windows or lensing) may occur in the extruded film and these may lead to bubble breaks when present at high levels. This effect is caused by trapped volatile material in the melt, either from the polymer itself or from blended additive or pigment masterbatch.

Film Appearance

The objective when attempting to quantify the appearance of polyethylene film is to characterise it in terms of the three simple parameters – gloss, haze and see-through clarity. Whilst these three parameters give a good general guide to the film appearance, it should be recognised that they represent a simplification of the true visual situation. It is the human eye that provides the primary measurement of the real visual effects resulting from the complicated interaction between the basic light scattering, transmission and reflection properties of the film.

Origin of Optical Irregularities

There are three basic causes for the optical irregularities in polyethylene film. These are:

- Surface irregularities caused by melt flow phenomena
- Crystallisation behaviour
- Melt and solid inhomogeneities

These irregularities are frozen into the film when it solidifies in the region of the freeze line.

In *Alkathene* LDPE film, by far the greater proportion of the light scattered occurs at irregularities on the surface of the film. This can be demonstrated by eliminating the surface contributions, by wetting the surfaces with a thin layer of liquid with a similar refractive index to that of the polyethylene, covering the wetted film with microscope slides and making optical (haze or clarity) measurements.

In film made from *Alkatuff* LLDPE, *Alkamax* mLDPE and *Alkatane* HDPE, the crystallisation defects predominate; the molten extrudate of a narrow molecular weight distribution LLDPE on exiting the die can be very clear, with all of its ultimate haze being developed in the vicinity of the freeze line as the polymer crystallises. In addition, surface melt fracture, if not eliminated, will also lead to very poor opticals. HDPE is quite opaque due to the high level of crystallisation.

In general, the inner surface of the tubular film contributes slightly less to the haze than the outer surface, because it cools more slowly, allowing more time for the surface irregularities to smooth out.

The third cause of light scattering is the presence of melt or solid inhomogeneities such as fine filler particles (e.g. particles of antiblocking additive), grain, microgel, cross-linked particles and contamination.

Effect of Processing Conditions on Optical Properties

Extrusion Haze

The most important surface irregularities in LDPE (*Alkathene*) type film are extrusion defects (termed 'extrusion haze') which originate from the complex elastic melt flow behaviour in the extrusion die (see Figure 25a). This defect structure consists of small raised areas less than 5 microns in height. It is thought to be due to the buckling of the surface resulting from differential melt relaxation of the highly sheared melt.

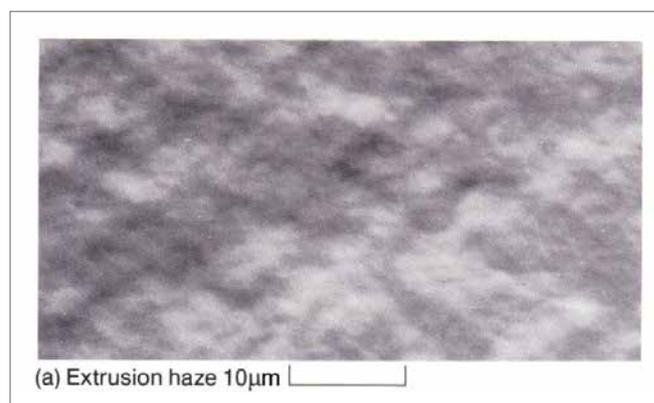


Figure 25a: Basic Types of Surface Irregularities in Polyethylene Film – Extrusion Haze

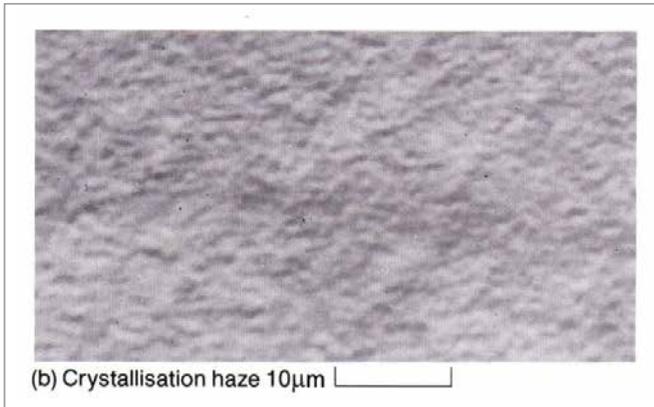


Figure 25b: Basic Types of Surface Irregularities in Polyethylene Film – Crystallisation Haze

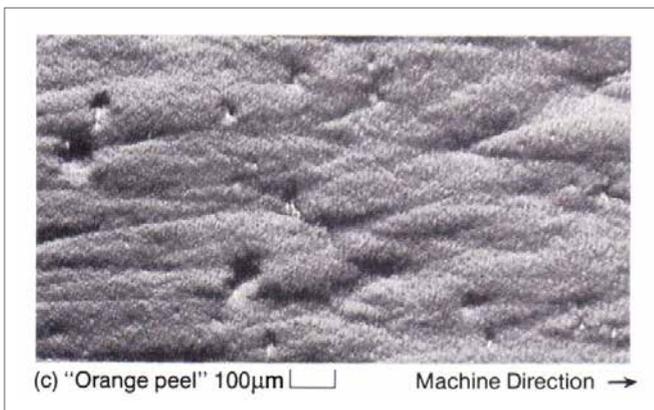


Figure 25c: Basic Types of Surface Irregularities in Polyethylene Film – Orange Peel

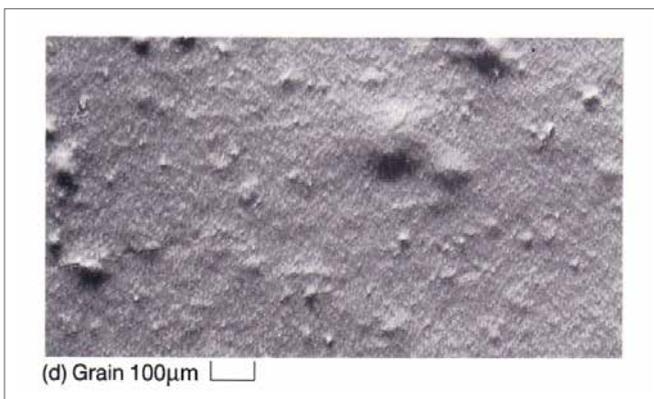


Figure 25d: Basic Types of Surface Irregularities in Polyethylene Film – Grain

Because the defects arise from melt flow phenomena the nature and magnitude depend upon the particular flow properties of the polyethylene itself, and will also be influenced by any extrusion conditions which reduce the shear rate within the die. The biaxial drawing of the melt as the bubble is blown will decrease the height and extend the length and breadth of the defects, so leading to a change in the texture of the film surface. Hence the final texture will be dependent upon the degree of draw and blow ratio. In addition, the melt has a chance to relax and the extrusion defects time to smooth out in the cooling zone up to the freeze line; any increase in the cooling time will decrease the magnitude of the defects finally frozen into the solid film.

The extrusion variables which influence the extrusion haze are:

- Output rate (shear rate) through the die – the extrusion defects will become more severe as the shear rate is increased.
- Melt temperature – a higher melt temperature allows better flow through the die and reduces the tendency for flow defects
- Freeze line distance – a higher freeze line allows more relaxation time for the irregularities to be smoothed. (see Figure 26a)
- Blow-up ratio – an increase in blow-up ratio will allow great relaxation of the irregularities and a reduction in their size
- Haul-off rate (drawdown) – higher line speeds increase the severity of the extrusion haze
- Die geometry – wider die gaps reduce the shear rate in the die

Extrusion haze also decreases as the die entry angle is widened.

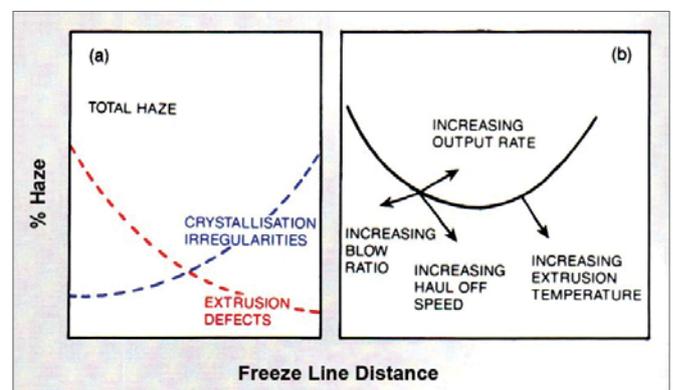


Figure 26a-b: Characteristic Variation of Film Haze with Freeze Line Distance for Alkathene LDPE Film

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Crystallisation Haze

A major cause of surface roughness arises from the growth and aggregation of crystallites at, or near, the surface of the film (see Figure 25b). The irregularities, termed 'crystallisation haze', are small mound-like features approximately one micron in size. They account for some 10% of the total haze in *Alkathene* LDPE type films.

In LLDPE type films, including mLLDPE, crystallisation-induced surface roughness is the major contributor to the haze, because of the ease in which larger crystallites and spherulites can grow compared with LDPE films. In many cases, LLDPE films can have rougher surfaces, and higher haze and poorer clarity than conventional LDPE films. Higher density and higher MFI of the LLDPE polymer will both result in worse opticals.

HDPE has a much higher crystallinity than LDPE and LLDPE. As a result, HDPE films show a very high level of haze and are not suitable for applications where optical properties are important. However, HDPE may be blended at low ratios and still achieve a high clarity film.

The magnitude and intensity of the crystallisation irregularities, as well as depending upon the nature of the polyethylene, will also be significantly affected by the rates of nucleation and growth of crystallites during the cooling stage of the film blowing process. Crystallite size increases with longer cooling time and any change in conditions that will extend the cooling time will therefore contribute to higher crystallisation haze. The important extrusion variables which influence this cooling time are:

- Film haul-off speed – an increase in line speed results in thinner film and a shorter travel time between die and freeze line, i.e. quicker cooling, less crystallite formation and lower haze. With LLDPE, increasing the drawdown increases haze because of stress-induced crystallisation.
- Blow-up ratio – an increase in blow-up ratio for a given freeze line and haul-off speed will give longer cooling times and higher haze.
- Freeze line distance – high freeze lines lead to slower cooling, more crystallite formation and higher haze. This effect is particularly pronounced in LLDPE films (see Figures 26 and 27).
- Output rate – increased output rate for the same freeze line distance facilitates quicker cooling and therefore lower crystallisation haze.
- Melt temperature – any increase in melt temperature necessitates increased cooling; if the freeze line distance is maintained, then lower crystallisation haze will be obtained because of the higher cooling rates.

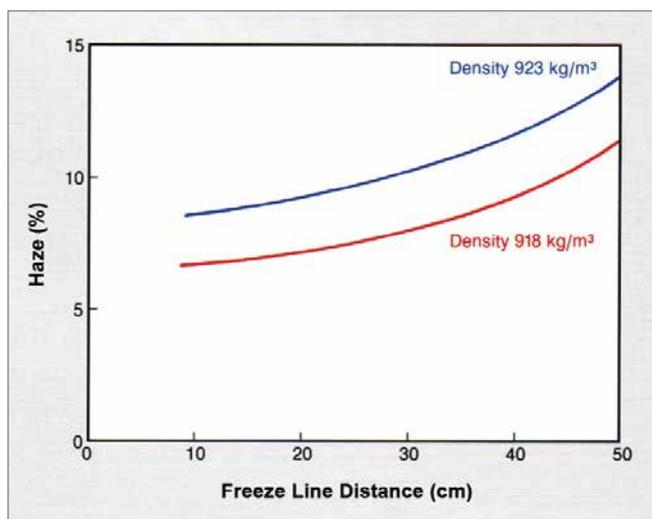


Figure 27: Typical Variation of Haze with Freeze Line Distance for LLDPE Film, Thickness 40 micron (MFI 0.5)

Crystallisation effects also cause light scattering within the film itself, at the boundaries of spherulites and between crystallites. This internal scattering makes only a small contribution to the total scattering in LDPE films (less than 10% of the total haze value), but has a greater effect in LLDPE films. Internal crystallisation effects will be affected by extrusion conditions in the same way as the surface crystallisation haze, as listed above.

Combined Effect of Extrusion Variables

From the above discussion on extrusion and crystallisation haze, it is evident that for *Alkathene* LDPE type film, changes in some parameters, particularly freeze line distance, blow-up ratio and output rate, have opposing effects on these two components of haze. This is typically demonstrated in Figure 26, with extrusion haze decreasing and crystallisation haze increasing with increasing freeze line distance. The general effects of other extrusion variables are shown by the arrows in Figure 26b. Figure 28 shows the combined effects of output rate and blow-up ratio on the haze of 38 micron *Alkathene* LDPE film.

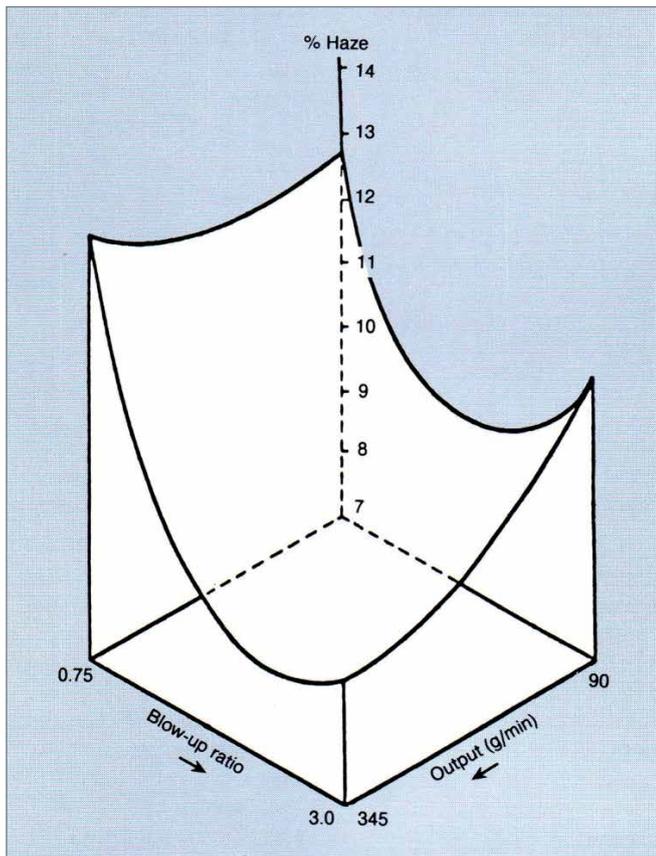


Figure 28: Variation of Haze and Polyethylene Film with Blow-up Ratio and Output Rate for *Alkathene* LDPE Film of MFI 4.0, Density 0.925 g/cm³ (Film Thickness 38 micron)

On the other hand, with film extrusion of *Alkatuff* LLDPE, the dominating effect of crystallisation haze results in a less complex behaviour, with worse optical properties being obtained as the freeze line distance and blow ratio are increased (see Figure 27). Rapid cooling (a low freeze line) is desirable for the best opticals with LLDPE.

Table 2 summarises the effects of varying the processing conditions on the optical properties of *Alkathene* LDPE, *Alkatuff* LLDPE and *Alkamax* mLLDPE films, and may be of assistance in selecting the appropriate conditions for any application.

As optical properties are usually not important for HDPE rich films, the extrusion conditions are not usually altered.

Surface Defects

Surface Melt Fracture (Sharkskin)

“Sharkskin” is a visco-elastic surface defect caused by melt fracture at the die exit and consists of curled ridges normal to the machine direction of the film.

Low MFI narrow molecular weight distribution LLDPE’s like *Alkatuff* are more prone to this defect which is observed at much lower output rates than with LDPE. In this context, it is commonly called surface melt fracture. The defect is an interface phenomenon and arises because of a change in the flow pattern of the polymer melt at the die wall and exit above a critical shear stress. This gives a sharkskin-type surface roughness which creates poor optical appearance and may affect mechanical properties of the film. The surface melt fracture is influenced by output rate, extrusion temperature and die gap.

While the effects of this phenomenon can be reduced by decreasing the shear rate in the die lips (by widening the die gap – see ‘Wide Die Gap Extrusion’ p. 16) and increasing the melt temperature, a processing aid is often included in the film formulation to suppress the initiation of this defect and extend the maximum output rate. It is believed that the processing aid acts by coating the metal surface of the die land and modifying the flow pattern at this surface.

Table 2: Effects of Varying Processing Conditions on Film Optical Properties

Processing Condition	Effect on Optical Properties	
	<i>Alkathene</i> LDPE	<i>Alkatuff</i> LLDPE and <i>Alkamax</i> mLLDPE
Higher melt temperature	Defects reduced, opticals improved	Defects reduced, opticals improved
Higher freeze line	Defects decrease but crystallisation haze higher (see Figure 24)	Crystallisation haze higher, opticals worse
Greater blow-up ratio	Opticals improve at low freeze line and low melt temperature, but then become worse	Opticals worse if freeze line constant
Higher output rate	Defects worse but crystallisation haze reduced	Opticals improve
Thinner gauge (increased haul-off speed)	Defects decrease and opticals improve	Opticals improve

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Orange Peel

Orange peel (see Figure 25c) is a gross surface irregularity which affects see-through clarity of polyethylene film. It is thought to be the same structure as sharkskin except that it is elongated in the machine direction and of coarser texture. The defect arises because of the fracture of the surface by the stresses imposed as the surface layers of the melt accelerate at the exit of the die.

The severity of the orange peel increases with an increase in output rate or a decrease in temperature. Its effects can be lessened by a higher freeze line distance, as this allows the melt a longer period to relax and the irregularities to smooth out. Greater drawdown rates and higher blow ratios also tend to smooth out this defect.

Grain

Grain (see Figure 25d) is caused by melt inhomogeneity and is composed of discrete lumps of material of higher molecular weight than the remainder of the film, which project out of the surface. Extrusion conditions have little effect on this defect although some improvement can be obtained by increasing the amount of homogenisation occurring in the extruder, e.g. by cooling the screw, increasing the back pressure, or improving the screw design.

MECHANICAL PROPERTIES OF POLYETHYLENE FILM

The most important mechanical properties of polyethylene film are tear strength and impact strength. Tensile properties (tensile strength at yield, tensile strength at break, elongation at break) are often measured but these tend to mirror the behaviour of the tear and impact properties and offer little additional information. For tough film applications, puncture resistance is also important. Creep under tension is a key property for films kept under load for some time.

Because of orientation in the film, the tear and tensile properties are directional and values are quoted for both the machine direction (MD) and the transverse direction (TD) – refer to Figure 4 for definitions.

The mechanical properties of polyethylene film are affected to a greater or lesser extent by all processing variables, through the influence of processing on the molecular orientation in the film and the crystallinity (rate of cooling).

Impact Strength

One of the most important properties of polyethylene film in many applications is the ability to withstand the rapid stresses involved during impact. These stresses may arise, for example, during filling of bags with heavy produce, or when bags containing a product fall to the floor. Under such impact loading conditions, a slit-like failure may occur along the machine direction, either in the body of the film, along a weak die-line, or at the edge-fold. Such failures are brittle-type failures. On the other hand, film with very high impact strength will fail in a ductile manner, by a ragged punctured hole.

The impact strength depends on the orientation, density and type of PE used in the film. An increase in machine direction orientation (giving unbalanced orientation when compared with that in the transverse direction) will lead to a greater likelihood of impact failure. Low polymer density and low MFI are required for high impact strength films. However, metallocene resins provide a far superior impact strength for a given MI and density.

Impact strength is measured most commonly by means of the free falling dart test (also called the Monsanto falling dart test, ASTM D1709); in this test, darts of increasing weight are allowed to drop onto the film from a fixed height. The weight at which 50% of the tested samples fail is the F_{50} Dart Drop Impact strength. Other tests such as the falling ball test and the instrumented impact test can also be used (see ASTM D4272).

One limitation of the impact test is that the most likely point of failure in tubular or folded film is along an edge fold rather than in the face of the film. The impact strength of the edge-fold can be determined by dropping the dart adjacent to the edge-fold. The edge-fold can have considerably lower impact strength than that of the body of the film, from 40 to 80% thereof, depending on the properties of the particular polyethylene and the extrusion conditions used. The higher density, higher MFI, more brittle films tend to have the weakest edge-folds.

Tear Strength

Tear strength, or the ability of the film to withstand any extension of a hole or a slit in the film, is an important property in many film applications. Because of orientation effects, poorly-made films can have the undesirable tendency to split readily once a hole or slit is initiated in the film. With heavy-duty sacks a related property is the snagging resistance, or the ability of the film to withstand dragging of the sack over a sharp protrusion.

Tear strength, or more specifically the tear propagation strength, is commonly measured by means of a pendulum in the Elmendorf test (ASTM D1922), in both the machine and transverse directions. This test measures the energy required to propagate a tear formed as a small slit in the film sample. Other tests are available to measure tear propagation (trouser tear, ASTM D1922) and to measure the energy to initiate tearing (ASTM D1004).

Tear strength deteriorates with an increase in polymer density but is relatively unaffected by changes in MFI.

Tensile Properties

Tensile properties (tensile strength and elongation at break) are measured according to ASTM D882, using a conventional tensile testing machine.

The tensile strength at break is normally adequate in polyethylene film and gives little information about serviceability for most applications. Elongation at break is affected in a similar manner to tear strength. The yield strength can be important in applications where the film is stretched in use, e.g. handles of carry bags, stretch wrap and heavy duty sacks; up to the yield point, any elongation is reversible, above the yield point, the film will be permanently stretched. Yield strength is generally related to density. Hence, HDPE will have the highest yield strength. In thin LDPE/LLDPE films, a small proportion of HDPE may be added to increase the yield strength. The shape of the stress/strain curve can provide a great deal of information about the film. As well as giving numerical values for the tensile strength, elongation at break, and the tensile modulus (a measure of stiffness), the area under the curve is a measure of the energy required to break the test film, and hence is related directly to toughness.

Creep in Tension

The creep in tension is an important property for packaging films, bags and sacks which may be under stress for a considerable period of time, e.g. the loading of a pallet of filled heavy-duty shipping sacks.

A heavily-loaded carry bag, and especially the handle area, will undergo tensile creep and possibly yielding if carried for an extended time. This will be particularly so with thin LLDPE bags. Figure 29 shows the percentage elongation of 25 micron film extruded from various LLDPEs when loaded with 9.7 MPa for up to 30 hours at room temperature. Better resistance to creep elongation is obtained with an LLDPE density above 0.925 g/cm³. Alternatively, some HDPE may be included in the film to improve the creep resistance. In particular, high molecular weight HDPE can provide a significant improvement.

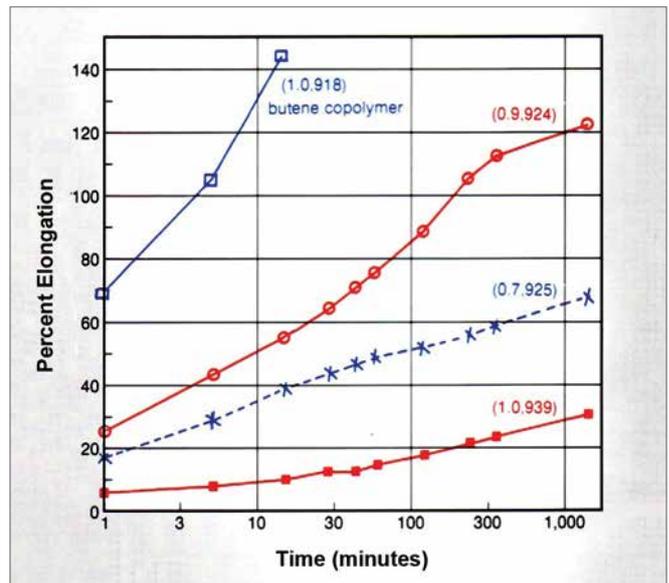


Figure 29: Tensile Creep Under Load of 9.7 MPa for Alkathuff Type LLDPE (MI, Density in brackets) at Room Temperature (Film Thickness 25 micron)

EFFECT OF PROCESSING CONDITIONS ON MECHANICAL PROPERTIES

Molecular Orientation

There is little doubt that molecular orientation is a major factor in controlling the mechanical properties of polyethylene film. Orientation is imposed by stresses during the blown film fabrication process. There are three main sources of stress:

- Shear stress causing flow of the melt through the die – the resulting orientation is in the longitudinal or machine direction
- Stress developed during the drawing of the melt via the nip rolls, causing longitudinal or machine direction orientation
- Circumferential stress arising from the blowing process by which the film bubble diameter is increased – this imposes orientation in the transverse direction

The polyethylene molecules on being extruded through the die gap are aligned in the direction of extrusion. Because of the narrower die gaps for Alkathene LDPE, this alignment will generally be greater than with LLDPE polymers like Alkathuff.

The melt exiting the die can be typically drawn down between 5:1 and 20:1 in the machine (extrusion) direction for LDPEs, and between 10:1 and 50:1 for LLDPEs. In addition the film is stretched transversely by between 1.5:1 and 4:1.

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The molecular orientation imposed during extrusion is thus modified by the drawing and blowing process in the film bubble. Generally the extrusion orientation is small compared with that resulting from melt drawing and does not influence significantly the final orientation.

Stress relaxation times in molten polyethylene are very short, so the imposed stresses resulting from the orientation are continuously being reduced by relaxation occurring in the bubble between the die and the freeze line. The rate of relaxation is largely dependent upon the temperature of the melt and the molecular weight of the polymer. At the freeze line the residual orientation and stresses are retained or frozen-in the film as the melt crystallises.

With narrow molecular weight distribution LLDPEs like *Alkatuff*, stress relaxation is very fast and the polymer has low extensional viscosity and a reduced tendency to strain-harden compared with *Alkathene* type LDPE. These differences mean that the imposed molecular orientation in LLDPE film will be much less than that obtained in an LDPE film.

Effect of Orientation on Tensile and Tear Properties

When the film is oriented in the machine direction (i.e. low blow-up ratio, high haul-off rate), it will have relatively high MD yield and tensile strengths with low MD elongation at break and low MD tear strength. Such a film would have low TD tensile strength but higher TD tear strength. The converse applies to a film with greater transverse direction orientation (high blow-up ratio); such a film has a more balanced orientation and often the tensile and tear strengths in the two directions are each similar in value.

The effects of blow-up ratio and output rate on the tensile and tear strengths are illustrated in Figures 30 and 31, for an *Alkathene* LDPE grade of MFI 2, density 0.921 g/cm³. These figures show that blow-up ratio in particular has a significant influence on the MD tensile strength and TD tear strength, and that a blow-up ratio can be chosen to enable a balanced film to be produced.

The influences of blow-up ratio on the tear strength for some films produced from *Alkamax* mLLDPE are shown in Figure 32. This figure shows that tear strength in both directions decreases as the blow-up ratio is increased.

These graphs, while specific to the experimental extrusion conditions used, typify the property dependencies on extrusion conditions that can be expected in any blown film extrusion process.

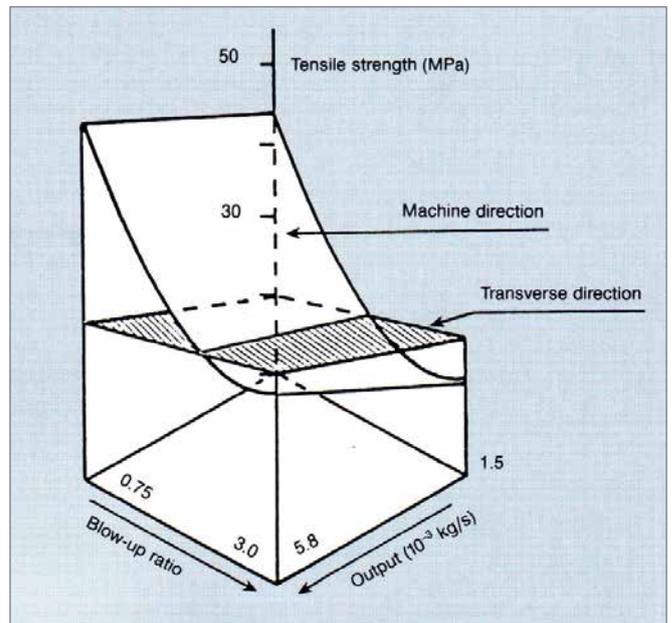


Figure 30: Variation of Tensile Strength with Blow-up Ratio and Output Rate of an *Alkathene* LDPE Grade of MFI 2.0 and Density 0.921 g/cm³ (Film Thickness 38 micron)

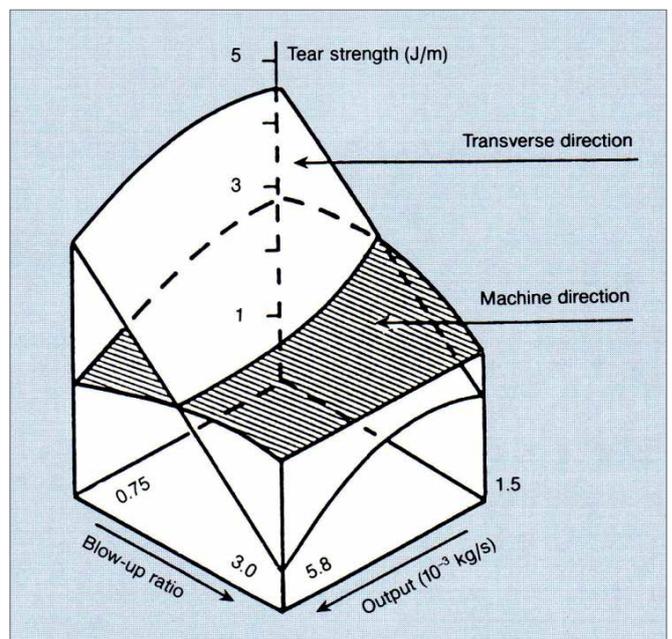


Figure 31: Variation of Tear Strength with Blow-up Ratio and Output Rate of an *Alkathene* LDPE Grade of MFI 2.0 and Density 0.921 g/cm³ (Film Thickness 38 micron)

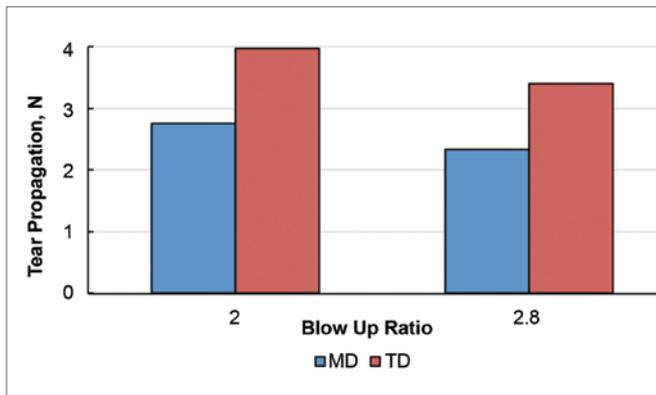


Figure 32: Effect of Blow-up Ratio on Tear Propagation for *Alkamax* mLLDPE Grade of MFI 1.0, Density 0.918 g/cm³ (Film Thickness 25 micron)

Effect of Orientation on Impact Properties

The effects of orientation particularly influence the impact strength of the polyethylene film. Figure 33 shows the steady improvement in impact strength with increasing blow-up ratio and output rate for an *Alkathene* LDPE of MFI 2 and density 0.921 g/cm³. Similar effects are observed with LLDPE polymers.

The most likely orientation to be frozen and retained in the film is that imposed just before the freeze line; orientation imposed earlier is partially or completely relaxed. Hence the order in which the machine and transverse drawing occurs in the drawing zone between the die and the freeze line will determine which one predominates, and which will have most influence on the mechanical properties of the film. If transverse drawing occurs just before the freeze line, then greater TD orientation is obtained. This will result in film with greatly improved impact strength.

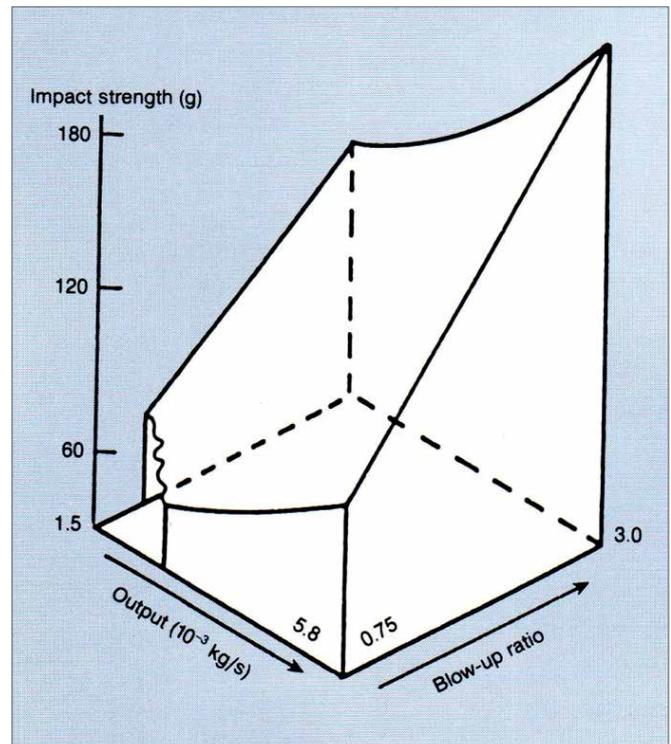


Figure 33: Variation of Impact Strength with Blow-up Ratio and Output Rate of an *Alkathene* LDPE Grade of MFI 2.0 and Density 0.921 g/cm³ (Film Thickness 38 micron)

Effect of Bubble Shape on Impact Properties

The shape of the bubble gives an idea of the order in which drawing will take place. Figure 34 illustrates schematically the hypothetical modes of drawing in the bubble to give alternate bubble shapes. In diagram (a), melt drawing occurs simultaneously in both the machine and transverse directions with the former predominating and results in moderate impact strength. In diagram (b), machine direction drawing predominates before the freeze line, resulting in poor impact strength. In diagram (c), the high impact strength stalk-shaped bubble is illustrated; here transverse drawing is predominant just before the freeze line. Since very little further relaxation can take place before the film is 'frozen', a high level of molecular orientation in the transverse direction is retained in the film. See also Figure 38.

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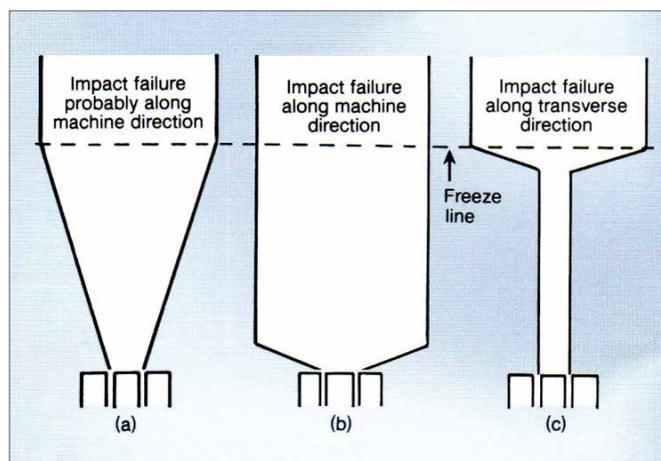


Figure 34: Hypothetical Modes of Drawing of a Film Bubble

The bubble shape in Figure 34 (c) is standard for HDPE film. A higher level of transverse orientation is critical for HDPE to avoid 'splitty' film. The neck height is recommended to be five to eight times the die diameter.

These changes in bubble shape and drawing behaviour become less significant at low blow-up ratios since a smaller amount of transverse drawing takes place. Although the drawing behaviour will be affected by the type of polymer being used, it can be controlled by adjustment of extrusion conditions such as freeze line distance, blow-up ratio, die gap, output rate, and cooling arrangements. For example, the high impact bubble shape can be obtained by raising the freeze line distance at a given blow-up ratio or by increasing the output rate for a given freeze line distance, blow-up ratio and film thickness.

Balanced Mechanical Properties

By comparison of Figure 33 with Figure 30, the high impact resistance obtained at high blow-up ratios and high outputs, is associated with very low tear strength in the transverse direction. Hence a compromise must often be made in choosing operating conditions for the best balance of mechanical properties – approximately equivalent MD and TD tear strengths are obtained and a moderately high impact strength.

Crystallisation and Rate of Cooling

The crystalline structure imposed on polyethylene film during the cooling stage between the die lips and the freeze line is dependent on the density of the polymer and also on the rate of cooling. Fast cooling, i.e. a low freeze line, yields small spherulites, a low crystallinity and a low density. Slow cooling will lead to enhanced spherulitic growth and this will be greater for LLDPE under these conditions.

The crystalline structure has a marked effect on the mechanical properties and particularly the impact strength of the film. Any processing condition that causes faster cooling, for example, a lower freeze line distance, will lead to improved impact strength.

Decreases in film density caused by fast cooling rates will lead to reduced film stiffness, lower tensile strength and higher elongation at break. The effect on tear strength is less clear because of the masking by orientation effects.

With *Alkatuff* LLDPE, film properties will depend on crystallisation effects to a greater extent than with *Alkathene* LDPE and rapid cooling is to be preferred. This can be achieved with a low freeze line, higher output rates and higher extrusion temperatures.

Summary of Effects of Processing Conditions

Table 3 summarises the effects of processing conditions on the mechanical properties of *Alkathene* LDPE and *Alkatuff* LLDPE films. It should be noted that this table is only indicative, and responses may be different depending on the particular balance of orientation, relaxation and crystallisation effects. In particular, experience with *Alkamax* mLLDPE grades is still being developed.

Note that the elongation at break tends to respond in the opposite manner to the tensile strength.

Table 3: Effects of Varying Processing Conditions on Mechanical Properties of LDPE and LLDPE Film

For an increase in Processing Condition	Effect on Mechanical Properties			
	Tensile Strength	Impact Strength	Tear Strength (<i>Alkathene</i> LDPE, <i>Alkatuff</i> LLDPE)	Tear Strength (<i>Alkamax</i> mLLDPE)
Blow-up ratio	Decreases in MD Increases slightly in TD More balanced film	Increases, especially at high freeze line distance	Increases or is constant in MD Decreases in TD More balanced	Decreases
Melt temperature	Tends to decrease	Increases	Decreases	Decreases
Freeze line distance	Relatively insensitive	Variable	Increases in MD Decreases in TD	Relatively insensitive
Output rate	Small increase in TD	Increases markedly	Decreases both directions	MD increases
Die Gap	Little effect	Decreases	Little effect	Relatively insensitive
Stalk-shaped bubble	Decreases in MD Increases in TD	Increases	Decreases in TD	Unknown
Film thickness (haul-off rate)	Relatively insensitive	Increases	Increases in MD Decreases in TD More balanced	Decreases

HEAT SHRINK PROPERTIES OF POLYETHYLENE FILMS

Introduction

Shrink wrapping is the term used to describe the technique of shrinking a film around an article or a group of articles to give a tightly fitting wrap. It is a relatively simple technique widely used for the wrapping of collated goods for transit and distribution, its main advantages being low cost, excellent protection of goods, application to the wrapping of irregularly-shaped objects, and the presentation as neat, tightly fitting, tear resistant packs with good visual appeal.

All polyethylene film will exhibit some degree of shrinkage when heated to a temperature above its softening point. This shrinkage occurs because of molecular orientation introduced into the film during its manufacture.

Alkathene LDPE polymers are widely used to make shrink film, because of the resulting toughness, good clarity and sparkle in the film. LLDPE and HDPE polymers have poor shrinkage characteristics on their own, but are often added to LDPE films to improve toughness and resistance to hole formation.

Types and Requirements of Shrink Film

There are three main types of shrink film: full overwrap, sleeve wrap and pallet wrap. Full overwrap is used to totally enclose packs such as unit presentation packs; two-way shrink is required with shrink values typically 60 to 80% in machine direction (MD) and 40% in transverse direction (TD). Sleeve wrap is used mainly for collating groups of articles, and requires a loose open-ended sleeve with the longest side of the pack placed parallel to the transverse direction; one-way shrink film with an MD shrink of about 60 to 80% and a TD shrink of less than 30% is required. Pallet wrap, also called shrink hood film, is used to stabilise and protect loads on pallets and requires a loose preformed shroud or bag which is placed over the load; balanced shrinkage of 60% in each direction is desirable if end-weld bags made from gusseted tubular film are used. In many cases, pallet wrap has been replaced by stretch wrap.

Film gauges are typically 35 to 100 microns for one-way shrink film, 25 to 100 microns for two-way shrink film and 100 to 150 microns for pallet wrap shrink film.

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Film Shrinkage

Shrinkage in polyethylene film is measured by immersing strips of film 100 mm wide and 100 mm long for 30 seconds in a bath of silicone oil at 130°C (or 70 seconds for films greater than 100 microns thick), and then allowing them to cool while freely suspended. The decrease in length of the strip represents the per cent shrinkage.

The temperature required to achieve maximum film shrinkage will depend largely on the density, MFI and the type of polyethylene used in the manufacture of the film. Figure 35 shows the variation of shrinkage in the machine direction with increasing temperature, for 40 micron film made from *Alkathene* LDPE polymer with MFI 1.0 and density 0.922 g/cm³. This plot indicates that the film must be heated to at least 110°C before any appreciable shrinkage occurs, and that above 115°C, no useful increase in shrinkage is obtained. For films containing LLDPE or HDPE, these temperatures will be higher because of the higher melting point of LLDPE or HDPE. The upper limit of temperature is the point where the film becomes so limp and soft that it pulls open holes in the film during shrinkage.

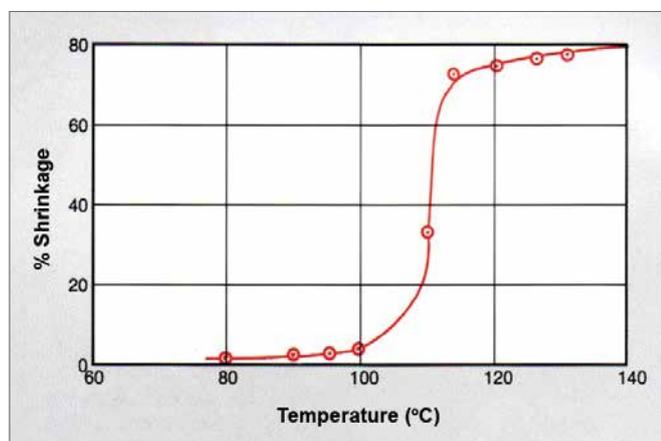


Figure 35: Machine Direction Shrinkage as a Function of Temperature for *Alkathene* LDPE Film of MFI 1.0, Density 0.922 g/cm³ (Film Thickness 40 micron)

Shrinkage occurs on heating polyethylene film because stresses introduced into the film during its manufacture are released at temperatures near the melting point of the polyethylene. These stresses arise as a result of the molecular orientation introduced into the melt during the fabrication process and are retained or “frozen” into the film after its solidification. The origins of molecular orientation in blown extruded polyethylene film have been discussed earlier (see ‘Mechanical Properties of Polyethylene Film’ p. 34).

Film shrinkage is carried out by heating the film rapidly to 120 to 130°C in a hot-air tunnel in which the air temperature is maintained at temperatures in excess of 170°C. The transit time of a film-wrapped package through the tunnel is usually of the order of a few seconds. A hot-air blower can satisfactorily replace the more expensive tunnel, for processing small packs or where production rates are low, e.g. with pallet wrapping.

Figure 36 shows some important parameters during an idealised shrink process. The temperature increases rapidly after the product enters the oven. Soon after, the film melts and shrinks rapidly, and during this time, the film experiences an initial plastic or contracting force. Up to a point, a rapid shrinking is desired. However, if the plastic force is too high, the film may become stationary on the packaged items, leading to “burn holes”.

After leaving the oven, the film cools and recrystallises. It also reaches the final amount of shrinkage. During this time, the holding force or “thermal force” develops. This force is the result of the contraction of the film due to the rapid crystallisation under tension, and is the force that ultimately holds the package together. A certain amount of shrink tension is required to give a tight package but high holding forces should be avoided if the wrapped article is likely to be crushed or distorted.

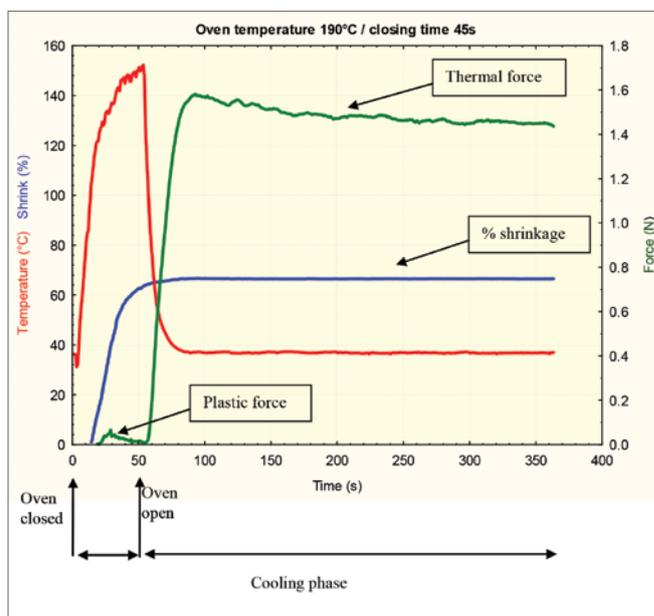


Figure 36: Shrink and Holding Force Relationship with Temperature for Polyethylene Film During a Laboratory Shrink Test

The amount of shrinkage and the holding force depend on the orientation in the film and the polymer MFI and density. Holding force, or shrink tension, is increased by using a lower MFI *Alkathene* LDPE and a high blow-up ratio (see Table 4).

Table 4: Shrink Tension for *Alkathene* LDPE Films (50 micron)

Polymer MFI	Shrink Tension (g/25 mm)		
	Machine Direction	Transverse Direction	
		BUR 2:1	BUR 2.5:1
0.4	340	50	100
2.5	170	0	50

Effect of Extrusion Variables on Film Shrinkage

The actual amount of residual orientation ‘frozen’ into the film can be controlled to a large extent, thus making it possible to produce film with certain combinations of MD and TD shrinkage. The main extrusion variables affecting shrinkage are blow-up ratio, bubble shape, freeze line distance, and film thickness. The film formulation, which is discussed further in the next section, is also extremely important.

Blow-up Ratio

Of all the extrusion variables, blow-up ratio has the most pronounced effect on shrinkage behaviour. The shrinkage tendency is invariably greater in the machine direction because of the higher orientation imposed in this direction during film fabrication. As the blow-up ratio is increased, more transverse orientation is imposed and shrinkage in the transverse direction is increased considerably at the expense of a small reduction in MD shrinkage. This is illustrated by the results given in Figure 37.

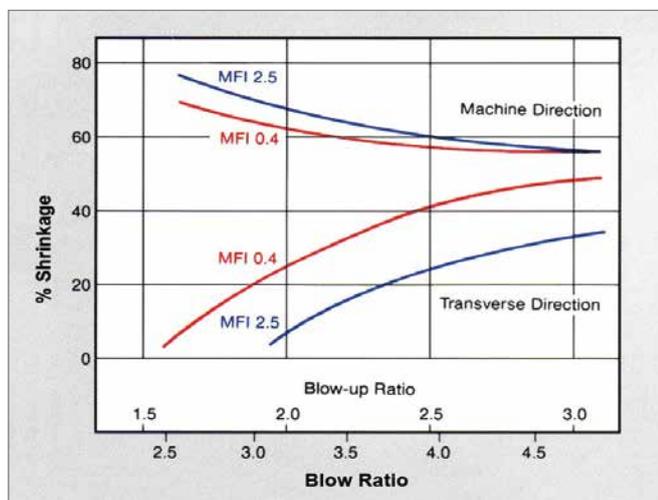


Figure 37: Effect of Blow-up Ratio and MFI on Shrinkage of *Alkathene* LDPE Film (Film Thickness 75 micron)

A film having balanced (approximately equal) shrink of about 60% in both the machine and transverse directions is not often required but can be obtained at blow-up ratios of the order of 4:1. However at blow-up ratios above 3:1, bubble instability is frequently encountered, especially at low output rates and at very low or very high freeze line distances. The use of a bubble guide in the form of rollers or rods around the bubble may be essential to obtain better stability and roll quality.

Bubble Shape

The effect of bubble shape to achieve balanced MD and TD orientation and high impact strength film has already been discussed under ‘Effect of Bubble Shape on Impact Properties’ (see Figures 34 and 38). For a bubble of the shape shown in Figure 38(b), transverse drawing predominates just before the freeze line and a high level of TD orientation is retained in the film.

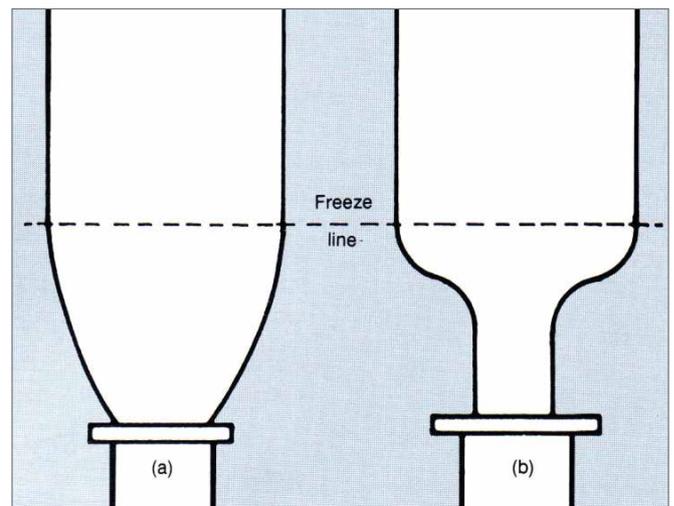


Figure 38: Typical Bubble Shapes

Such a bubble shape would produce a film with well-balanced shrink properties in the machine and transverse directions. In practice, it can be difficult to achieve this stalk-shaped bubble with LDPE rich films, but high blow-up ratios, large freeze line distances, high extruder output rates and high melt temperatures may help. Bubble stability and potential for film blocking must be considered.

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Other Extrusion Variables

Raising the freeze line for fixed blow-up ratio and film gauge gives a decrease in the TD shrink. MD shrink tends to decrease at higher freeze lines to give more balanced shrink properties, but such conditions are limited by bubble stability and blocking considerations. However it is important that the freeze line height is uniform around the bubble, otherwise poor gauge control and a wide shrink range will result.

Increasing the film thickness with all other variables constant lowers the MD shrinkage with a small increase in TD shrinkage. For thinner films, it may be necessary to reduce the die gap to achieve the required TD shrinkage, with perhaps a small reduction in MD shrinkage.

Increases in the output rate and melt temperature have only small effects in improving the balance of shrinkage.

Choice of Polymer for Shrink Film

A polyethylene film polymer that gives a fairly strong, stiff melt (i.e. good melt strength) is advantageous for shrink wrapping because it can withstand high temperatures without holing, and thus can be used over a wide working shrink temperature range. Because of the nature of the shrink film application, the film must also exhibit good mechanical properties.

Alkathene LDPE polymers of density about 0.920 to 0.922 g/cm³ and MFI between 0.3 and 3.5 g/10 min have been found to give excellent performance for shrink film applications, with MFI's at the lower end of the range being preferred, as higher TD shrink can then be expected (see Figure 37).

LLDPE and HDPE polymers are generally unsuitable for use in shrink film on their own. The wider die gaps and the faster relaxation of the melt result in a lower MD orientation level for a given film thickness. However blends of *Alkathene* LDPE with either *Alkatuff* LLDPE, *Alkamax* mLLDPE or *Alkatane* HDPE polymers can be used to obtain improved toughness and puncture resistance, leading to the possibilities for down gauging.

Blends containing LLDPE or HDPE polymers will have significantly reduced shrink properties compared to pure LDPE films. If high shrinkage is required, then the extrusion conditions must be altered as described above, i.e. a higher blow-up ratio or a narrower die gap may be required.

SURFACE PROPERTIES OF POLYETHYLENE FILMS

The surface characteristics of polyethylene film are of critical importance in determining the ability of the film to be processed in converting equipment, and to perform in intended end use applications.

Most film is converted through printing, laminating, sealing, bag-making, wrapping or packaging equipment. While it is important for the film to have the desired optical and mechanical properties to meet end use requirements, it must also have the right surface properties for handling and processing through this equipment.

The important properties which affect how the film processes through converting and packaging equipment are:

- Coefficient of friction (or slipperiness)
- Blocking
- Antistatic behaviour
- Heat sealability

Heat sealability is discussed later in the section on 'Film Conversion'.

The optical properties and aesthetic appearance of polyethylene films are largely dependent on the nature of the surface, and this has been discussed earlier in the section 'Optical Properties of Polyethylene Film'. The receptivity of the film surface to printing inks and adhesives has been discussed earlier under 'Treatment of Polyethylene Film'.

Coefficient of Friction

The coefficient of friction (COF) is a measure of the ease with which the surface of one material will slide over another. Films which are slippery and move easily over other surfaces have a low coefficient of friction or 'high slip'.

The frictional properties of polyethylene film are important for a number of reasons, e.g. good roll formation during film extrusion, ease of passing over rollers and between surfaces in printing, bag-making and packaging machines, and ease of handling packages in transit and by retailers and consumers. Reasonably high slip is required for ready conversion by these processes. However, too much slip will cause telescoping of film rolls during handling. For heavy duty sacks, low slip properties are required in order to prevent any tendency for stacked sacks to slip.

The coefficient of friction of polyethylene film is measured from the force required to slide a sled covered with film across another piece of flat film at a constant rate (ASTM D1894).

Addition of Slip-Promoting Additives

Polyethylene film which does not contain any additives has a high coefficient of friction, above about 0.8. Small quantities of slip-promoting additives such as oleamide and erucamide are normally incorporated into film formulations at levels between 300 ppm and 1,000 ppm, to achieve coefficients of friction of less than 0.35. Medium slip films have a coefficient of friction of about 0.25, high slip films about 0.10 to 0.20.

Alkathene LDPE, *Alkatuff* LLDPE and *Alkamax* mLLDPE polyethylene film grades incorporate a slip additive to give the most useful slip level for the intended application. If a higher slip level is desired, then additional additive can be incorporated by blending a slip additive masterbatch into the film polymer at the time of film extrusion.

Mode of Action of Slip Additives

Slip additives act by migrating, or “blooming”, to the surface of the film after extrusion and forming a layer which gives the desired slip characteristics. A considerable amount of the additive has migrated to the surface in the first hour; normally the migration is complete and the equilibrium slip level reached about 24 hours after extrusion (see Figure 39). However there are some factors that can alter the rate of migration and the time required to reach the equilibrium COF. Some examples are ambient temperature, film formulation and winding tension.

This layer of additive has a severe inhibiting effect on corona treatment and for this reason treatment should be performed in-line when much less additive is present on the surface. High levels of slip additive can have other deleterious effects, namely, the need for extra treatment power, poor printability and inferior heat sealing.

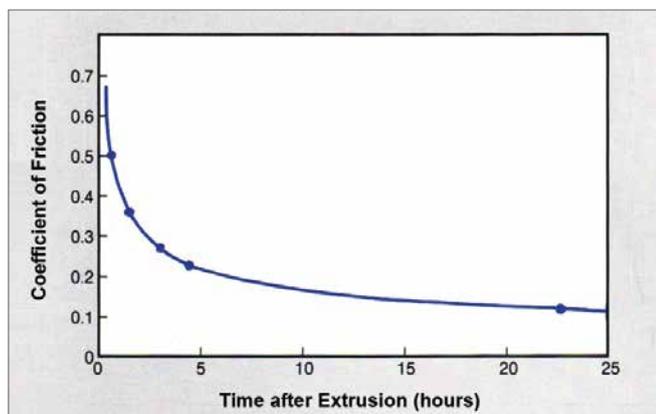


Figure 39: Kinetic Coefficient of Friction at Various Time after Film Extrusion with 900 ppm Erucamide (Film Thickness 50 micron)

Factors Affecting COF

The film thickness is an important parameter to consider when designing a film to achieve a desired COF. An example of this is shown in Figure 40. It can be seen that thinner films require a higher concentration of slip additive to achieve low COFs. This occurs because thinner films contain less slip additive available to migrate to the surface.

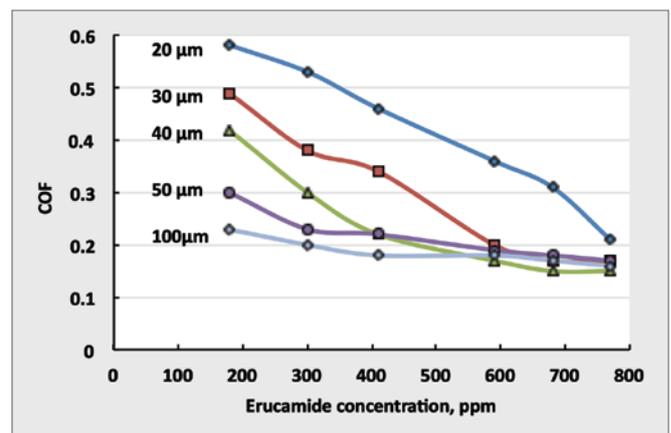


Figure 40: Effect of Slip Additive Concentration and Film Gauge on COF. (LLDPE/LDPE Blend)

Other factors that may have significant effects on the COF include the following:

- The type of slip additive. For example, oleamide typically results in a higher COF than erucamide
- Antiblocking additives (see next section) also act to reduce the COF
- In general, HDPE will have a lower COF than LDPE or LLDPE
- Grades with lower melt index will typically have a lower COF
- Excessive corona treatment can increase the COF

Blocking

Blocking is the tendency for the opposite faces of films in intimate contact to stick or adhere to each other, making separation difficult during subsequent handling operations. The use of blocked films in some automatic packaging machinery is virtually impossible.

Blocking is caused by the presence of low molecular weight components in the polymer which exude to the surface of the film immediately after extrusion. When the film is flattened in the nip rolls, wound tightly on the reel, or under pressure in any way, these low molecular weight materials on the two surfaces are forced into contact and blocking is likely to occur.

Blocking can be measured as the force required to separate a given area of blocked film in the direction normal to the film.

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Factors Affecting Blocking

The extent of blocking for any film formulation depends on a number of factors which relate to the extrusion of the film. It is a function of the nip roll pressure and the temperature of the film at the nip rolls. Hence blocking will become worse with increased nip roll pressure, higher extrusion temperature, higher output rate or linear film speed, higher ambient temperature, and insufficient air cooling applied to the bubble, e.g. from a high freeze line distance and low nip roll height.

High winding tension can exacerbate the blocking on the film roll, especially at high ambient temperatures or in an unfavourable storage environment. Excessive or reverse-side corona discharge treatment often contributes to blocking, especially with high gloss films under pressure.

Films which have a very smooth, high gloss surface show a greater tendency towards blocking. Typically, films produced from metallocene LLDPE have a lower tendency to block than films produced from LLDPE, which in turn have a lower tendency to block than films produced from LDPE. Films with higher stiffness (higher density) show a lower tendency to block.

Excessive corona treatment can increase the adhesion between film layers, increasing the tendency to block.

Use of Antiblocking Additives

It is normal practice to incorporate finely-divided inorganic fillers such as silica as antiblocking additives in polyethylene film formulations, at levels generally between 0.15% and 0.3%. These additives act by imparting a micro-roughness to the film surface, thereby decreasing the area of contact that is possible. Unlike slip additives, these additives do not migrate to the film surface; they are dispersed throughout the film, with a proportion present on the surface.

These additives are very effective in reducing the blocking tendency. However they also cause a worsening of the optical properties (higher haze value), and may reduce the mechanical performance of the film.

As these additives are not migratory, the thickness of the film has limited influence on the blocking tendency. In some film formulations, slip additives can assist with reducing the blocking tendency of the film. However, for sensitive applications, antiblocking additives will be necessary.

Antistatic Performance

Polyethylene films have a very high surface resistivity and are hence non-conductors of electric currents. With the continual passage of polyethylene films over rollers during the fabrication and conversion processes, considerable static charges build up and these charges tend to accumulate on the film because of its poor conductivity. During use of polyethylene film, friction between the film and other surfaces will also generate static charges. These electrostatic charges can create considerable problems, such as sparking in hazardous environments, possible discomfort to operators, poor bag stacking in bag-making operations, and dust pick-up during end use.

Every endeavour should be made during processing and conversion of the films to remove the static charges, by earthing all rotating machine parts, increasing the relative humidity of the surrounding air, ionising the air or using 'tinsel' conductors in immediate proximity to the film (see Australian Standard AS1020: The Control of Undesirable Static Electricity).

Use of Antistatic Additives

Antistatic additives can be incorporated into the film formulation to help reduce the static problem. These additives act by migrating to the surface of the film where they absorb moisture from the air and so form a conducting layer. This layer tends to dissipate the electrostatic charge once it is formed. Because of the important effect of moisture, antistatic additives are most effective in high humidity environments.

It should be noted that in effective antistatic films the surface resistivity is only reduced from above 10^{16} ohms to the order of 10^8 to 10^{11} ohms. In critical areas such as the wrapping of electronic components and the mattress covering sheets for operating theatres, antistatic films are not satisfactory; semi-conducting films should be used in these applications.

Alkathene LDJ226 is formulated with an antistatic additive, to give static protection where required by the end use. Film manufacturers can also incorporate an additive via an antistatic masterbatch blended with the polymer at the time of extrusion.

At high addition levels above about 1,000 ppm, antistatic additives because of their migratory nature can cause problems with heat sealing by raising the minimum seal temperature, and this is especially a problem if the film surface to be sealed has been corona discharge treated. They can also interfere with the corona treatment process when used at these high levels.

The measurement of the surface resistivity of the film is often used to assess its antistatic performance (ASTM D257). However a more effective procedure is to measure the rate of decay of the static charge on a charged film; decay in a few seconds is indicative of a very effective antistatic film, negligible decay after 10 minutes indicates a non-antistatic film.

PERMEABILITY OF POLYETHYLENE FILMS

A key requirement in many polyethylene film packaging applications is for the film to provide a barrier against the transmission of various gases, vapours and liquids. This especially applies in food packaging where the package must prevent food components from escaping but must also protect the contents from contamination. In special cases, the film may have special transmission characteristics to help prolong the shelf-life of the food product.

Polyethylene is an excellent barrier to most liquids, although there are some organic chemicals such as ethers, hydrocarbons and chlorinated hydrocarbons which permeate through polyethylene film very rapidly. In addition, some essential oils diffuse through the film and evaporate from the surface.

The permeability of polyethylene to water vapour is very low; however the transmission rate is very dependent on both temperature and relative humidity, as is illustrated for 25 micron *Alkathene* LDPE film (MFI 7, density 0.917 g/cm³) in Figure 41. The effect of film thickness on the water vapour transmission rate of polyethylene film is shown in Figure 42.

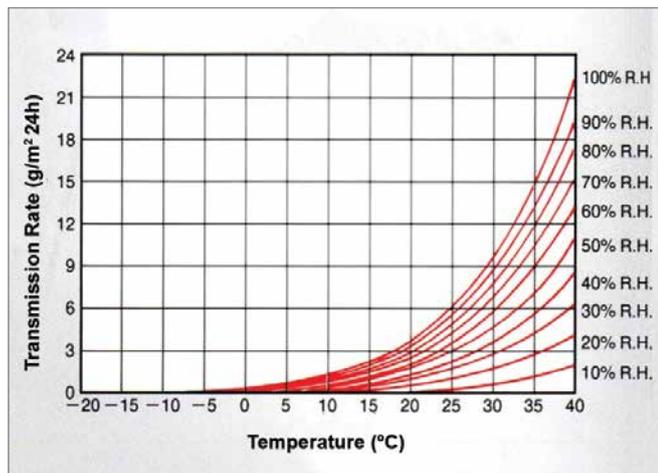


Figure 41: Water Vapour Transmission Rate of Polyethylene Film of MFI 7.0, Density 0.917 g/cm³ (Film Thickness 25 micron)

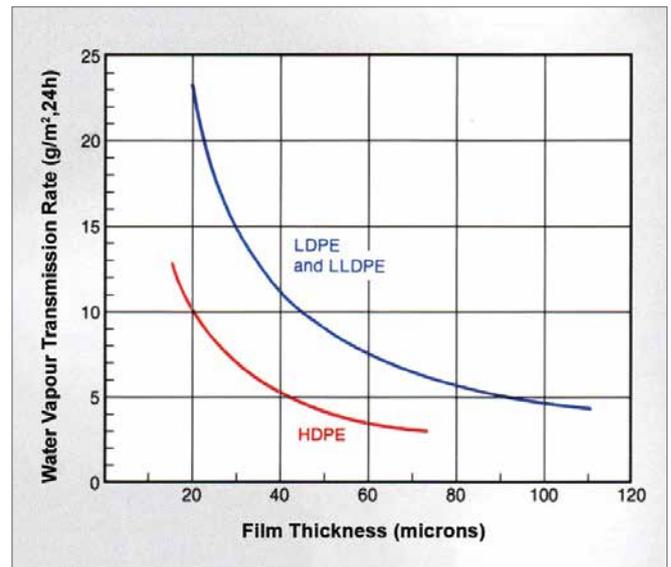


Figure 42: Effect of Film Thickness on Water Vapour Transmission Rate of Polyethylene Film (at 38°C, 90% R.H.)

The permeability of polyethylene film to gases and water vapour is chiefly a function of the density of the film, with higher crystallinity providing higher barrier properties and lower permeability. For applications requiring low transmission rates, the highest density HDPE is recommended. Lower permeability is also obtained with increased film thickness and at lower temperatures. Films made from *Alkatuff* LLDPE are expected to give gas and water vapour permeabilities about 15 to 20% lower than *Alkathene* LDPE films of the same density.

Typical transmission rates of several gases through polyethylene film compared with those through a number of other polymer films commonly used in packaging applications are shown in Table 5. Further details on the permeability of polyethylene are given in the publication *General Properties*.

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Table 5: Typical Gas and Water Vapour Transmission Rates of Polyethylene and Other Packaging Films

Film	Gas Transmission Rate (for 25 micron film at 20°C, 1 atm) (cm ³ /m ² , 24 h)			Water Vapour Transmission Rate (for 25 micron film at 38°C, 90% RH.) (g /m ² , 24 h)
	O ₂	N ₂	CO ₂	
Polyethylene LDPE (0.920 g/cm ³)	8500	3000	38000	18
Polyethylene HDPE (0.960 g/cm ³)	3000	650	9000	8
Ethylene Vinyl Acetate EVA Copolymer (18% VA)	12000	6200	45000	70
Ionomer	6500	–	6500	30
Polypropylene Biaxially oriented (BOPP)	1900	500	5500	6
Polypropylene PVdC coated BOPP	16	4	30	6
Polypropylene, cast	4200	750	10000	12
Polystyrene	3500	1000	17000	130
Cellulose Acetate	2500	–	16000	200
Regenerated cellulose*	660	–	1000	10
Polyvinylchloride, Plasticised PVC*	2000+	–	15000	27
Polyvinylchloride, Rigid PVC	250	–	750	50
Polyethylene Terephthalate PET	60	15	250	25
PA barrier resin	30	–	475	–
Polyvinylidene Chloride PVDC	15	3	50	3.5
Ethylene Vinyl Alcohol* (EVOH)	1.8	0.15	7	–

*Moisture dependent

BLEND OF LLDPE AND LDPE FOR FILM

Introduction

Important benefits can be achieved with the processability and end use properties of LDPE and LLDPE (including metallocene LLDPE) by blending the polymers together in various proportions. Such blends are widely used for the extrusion of polyethylene film for a range of applications.

Small quantities of LLDPE (less than 40%) blended into *Alkathene* LDPE give improved drawdown and similar processability to that of *Alkathene* LDPE when processed on conventional LDPE extrusion equipment; in addition, tensile properties, stiffness, puncture resistance and sealing properties of the film are enhanced.

With blends of LLDPE and a small amount (5 to 20%) of LDPE (linear-rich blends), processability of the LLDPE is considerably enhanced, optical properties are improved significantly and mechanical properties are modified slightly, including higher tear strength in the transverse direction.

Blends of LDPE and LLDPE show two major melting peaks when tested using the Differential Scanning Calorimeter (DSC). This indicates that the two polymers exist as separate phases within the blend. The relative sizes of the two peaks can often be used to estimate the composition of the blend.

Processing Properties

Blends of LDPE and LLDPE have shear viscosities intermediate between those of the two component polymers. This is illustrated in Figure 43 for blends of an MFI 2.5 *Alkathene* LDPE and an MFI 1.0 *Alkatuff* LLDPE. The blends have a lower shear viscosity at any shear rate than the base LLDPE polymer, and the log shear viscosity is approximately a linear function of the blend composition.

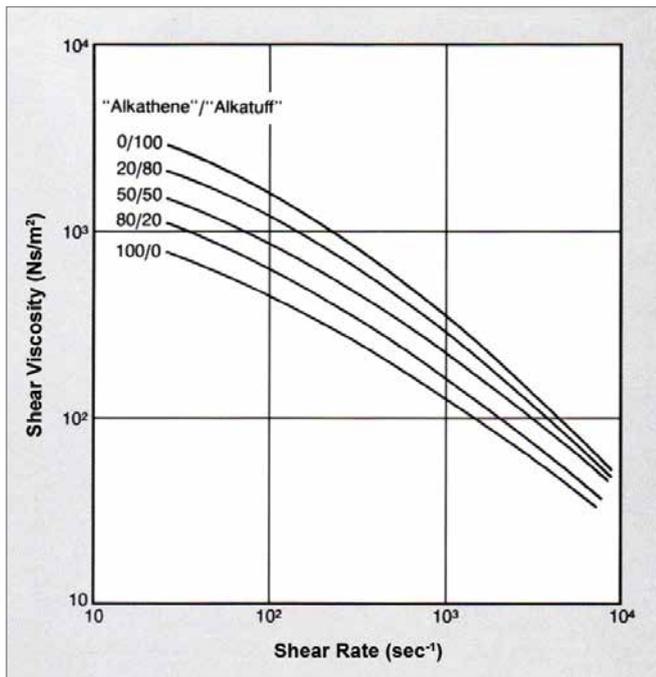


Figure 43: Shear Viscosity vs. Shear Rate for Blends of *Alkathene* LDPE (MFI 2.5, Density 0.922 g/cm³) and *Alkatuff* LLDPE (MFI 1.0, Density 0.920 g/cm³) at 190°C

This means that these blends will require less power to extrude than straight LLDPE, will give lower melt temperatures and lower pressure and, as a consequence, the output rate from any extruder will be less restricted. Extrusion may be possible without resorting to wide die gaps.

Addition of small amounts of LDPE to LLDPE gives significant increases in the extensional viscosity and imparts some strain-hardening characteristics. Such blends are less sensitive to disturbances than straight LLDPE and hence significantly decrease the tendency for bubble instability. LLDPE containing a small amount of LDPE will be less prone to show surface melt fracture effects than the straight polymer. This is one solution used in overcoming this extrusion problem.

In summary, significant processability benefits can be readily achieved with LLDPE or mLLDPE by using linear-rich blends containing, for example, 5 to 20% LDPE.

Physical Properties

The physical properties of a series of LDPE/LLDPE blends for blown film have been investigated. The blends evaluated were based on an MFI 0.45, density 0.922 g/cm³ *Alkathene* LDPE and contained various levels (20%, 40%, 60%, and 80%) of LLDPE. Three LLDPEs were used:

a butene-based copolymer made by the gas-phase process (MFI 1.0, density 0.920 g/cm³), a hexene-based (*Alkatuff* type) copolymer made by the gas-phase process (MFI 1.0, density 0.920 g/cm³) and an octene-based copolymer made by a solution process (MFI 1.0, density 0.921 g/cm³).

The effects of blending of these LLDPEs with the *Alkathene* LDPE on the mechanical properties of nominally 50 micron film were determined and these results are presented graphically in Figures 44 to 49. In general, the film properties of the blends with the higher alpha-olefin copolymer LLDPEs (hexene- and octene based) were quite similar and much superior to those obtained with the butene-based LLDPE blends.

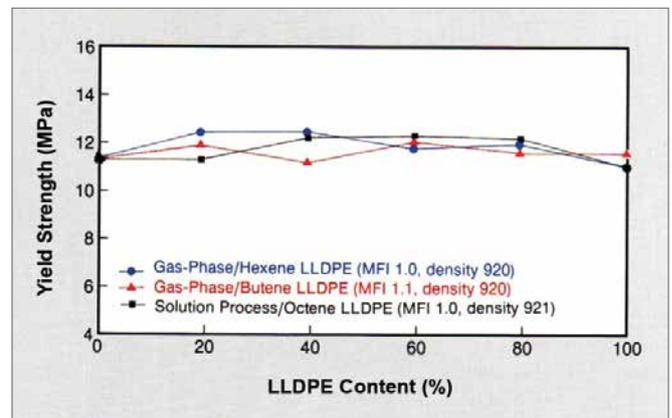


Figure 44: Yield Strength in Machine Direction for LDPE/LLDPE Film Blends, based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

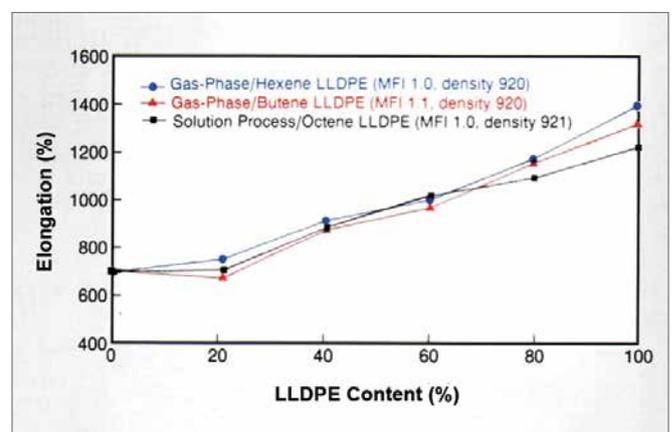


Figure 45: Elongation in Machine Direction for LDPE/LLDPE Film Blends (based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

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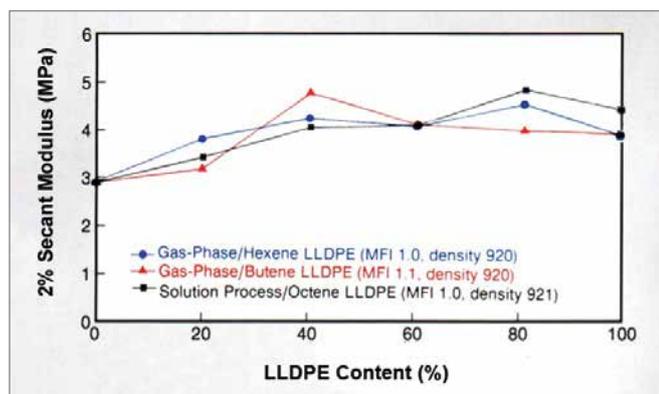


Figure 46: 2% Secant Modulus for LDPE/LLDPE Film Blends (based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

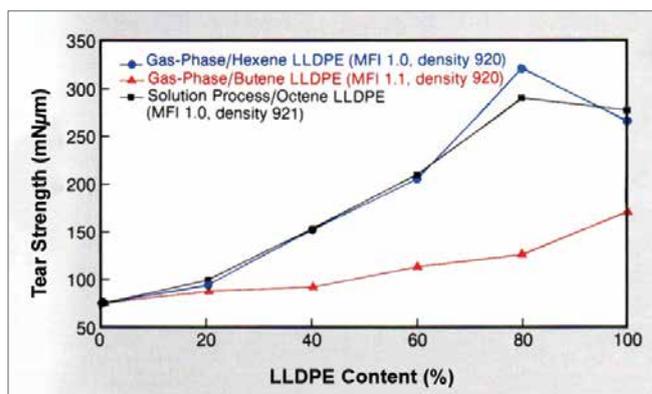


Figure 49: Transverse Direction Tear Strength for LDPE/LLDPE Film Blends (based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

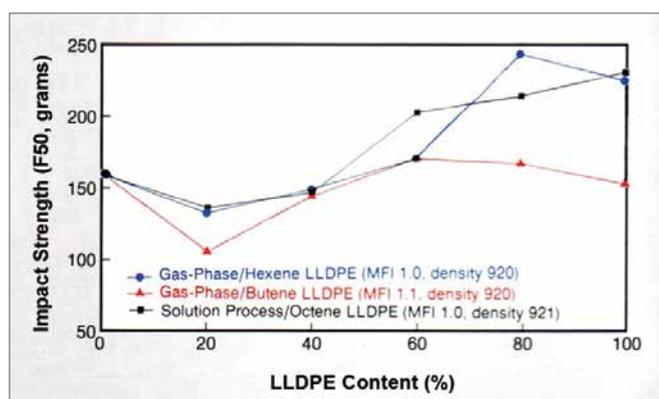


Figure 47: Impact Strength of LDPE/LLDPE Film Blends (based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

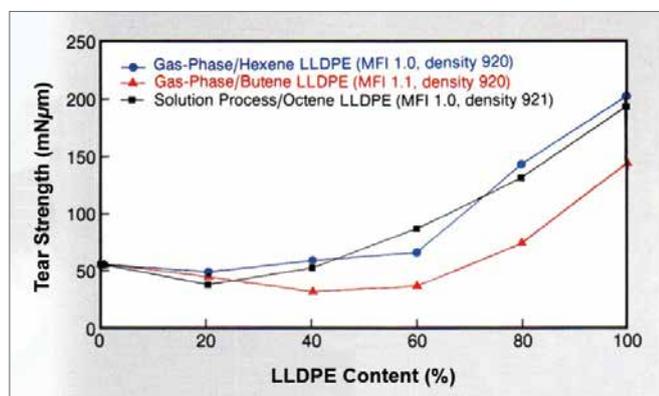


Figure 48: Machine Direction Tear Strength for LDPE/LLDPE Film Blends (based on MFI 0.45, Density 0.923 g/cm³ (Film Thickness 50 micron)

Tensile Properties: Yield strength in both the machine and transverse directions was relatively unaffected by the blending, as shown in Figure 44. There was a small yield strength benefit by adding about 20% LDPE to the LLDPE. Yield strength is essentially influenced by density and all the polymers used in this investigation had very similar densities.

Ultimate strength increased approximately linearly with the LLDPE content in the blends. The ultimate strength results demonstrated the poorer properties of the blends with the butene-based LLDPE.

Elongation increased roughly linearly with the LLDPE content, the increase being much greater (double) in the machine direction (see Figure 45) than in the transverse direction.

Film stiffness was assessed by measuring the 2% secant modulus. This property increased with increasing LLDPE content (see Figure 46).

Falling Dart Impact Strength: Addition of the LLDPE to the *Alkathene* LDPE grade significantly improved the impact strength of the film (see Figure 47).

Elmendorf Tear Strength: Small additions of LLDPE (about 20%) to the *Alkathene* LDPE grade gave small decreases in the MD tear strength but increases in the TD tear strength (see Figures 48 and 49).

Optical Properties: Addition of 20 to 40% *Alkathene* LDPE to the LLDPEs significantly improved their haze and gloss results.

Heat Sealing: Hot tack sealing measurements on these film blends using an IDM Hot Tack Tester (Figure 50) showed that the hot tack strength increased as the LLDPE content increased, with the linear-rich (80% LLDPE) blend performing quite well, especially at higher sealing temperatures.

Puncture Resistance: Blending LLDPE into conventional LDPE polymer results in a significant increase in puncture resistance.

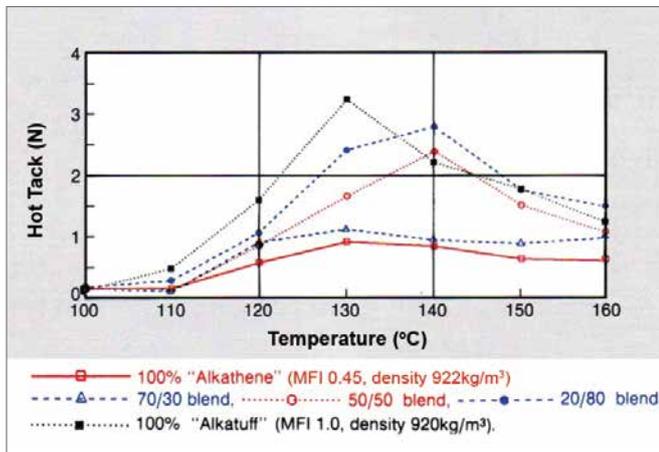


Figure 50: Hot Tack Sealing of *Alkathene* LDPE/*Alkatuff* LLDPE Blend Films (IDM Hot Tack Tester, Seal Pressure 275 kPa, Seal Time 0.5 sec, Delay Time 0.2 sec, Peel Speed 250 mm/sec, Film Thickness 50 micron)

3 FILM EXTRUSION AND CONVERSION

PART C. FILM CONVERSION

Introduction

Polyethylene film, following its production by blown or cast film extrusion, is either converted in-line, supplied as film-on-the-roll to a converter for further processing, or sold on-the-reel to the consumer for direct use. A number of different processes are involved in converting the film into a form required by the consumer. These converting processes include:

- Slitting
- Perforating
- Cutting
- Hole punching
- Embossing
- Printing
- Laminating
- Heat sealing
- Bag-making, wicketing
- Wrapping and packaging

Some converting operations may involve several processes. For example, form-fill-and-seal packaging involves forming and heat sealing printed sheet film into a tube, forming a bottom seal, filling the pouch or bag with product, heat sealing the top of the bag and at the same time cutting off the filled bag. In-line manufacture of open-mouth fertiliser sacks involves printing on one or both outer surfaces of layflat film, forming a bottom heat seal for the sack, cutting the sack to length, and possibly perforating or punching breather holes in the film.

Some converting characteristics depend on the polymer type.

- One difference in conversion performance occurs in operations that require some type of cutting or tearing. Because of the greater toughness and extensibility of LLDPE films, clean-cut edges during slitting and cutting are often more difficult to obtain than with LDPE films, unless tool sharpness is rigorously maintained.
- LLDPE films have inherently greater extensibility than conventional LDPE films. This means that careful attention must be given to avoid stretching the film at high web tensions during the conversion operation, especially if the film has been down-gauged.

- Stiffness is an important property for handling films in printing, bag-making and collating equipment. HDPE films have the greatest stiffness, followed by LLDPE then LDPE. Film gauge also influences the handling properties – thinner films will be more difficult to handle unless higher density polymers are used to compensate. HDPE and LLDPE films have higher melting points than LDPE films. In heat sealing processes higher sealing temperatures may be required.
- Despite this, the lower zero shear viscosity of LLDPE (particularly mLLDPE) can mean that it is easier to seal.
- Sealing pressure and dwell times can be reduced to account for the lower melt strength of LLDPE and HDPE.

Slitting, Perforating and Hole Punching

For many applications, slitting of the film at points across its width may be required to obtain narrower film webs. Slitting is normally accomplished using very sharp blade, or rotating cutters. Because of the greater toughness and elongation of LLDPE films, they require a very sharp blade, to ensure clean cutting and are not as tolerant to a blunt blade as LDPE films.

Several techniques are used successfully to overcome this cutting difficulty. Blades can be made of a hard metal or coated with a titanium alloy, either all over or on the cutting edge. In special circumstances a thin tungsten carbide coating on one side of the blade can be used to increase blade life significantly. Where the film can ride along the edge of the slitting blade: a 30 degree angle between the film and the cutting edge is desirable.

As with slitting, perforating and hole-punching operations on LLDPE films also require very sharp cutting edges to obtain clean cuts. This particularly applies to thin films. As the cutting edge wears, the LLDPE film will not perforate cleanly. Tools for punching holes or handle cut-outs in carry bags should be kept sharp; coating the outside surface of the male punch with tungsten carbide is effective for maintaining sharpness and extending the cutter life.

Film Embossing

Embossing is a procedure that is used to alter physically the surface structure of a film, by imprinting a geometrical pattern into the film, under the action of heat and pressure. The embossing is performed to improve the aesthetic qualities, surface characteristics or final properties of the film. With micro-embossing, softness and textile-like characteristics can be created.

During the embossing process, heat and pressure are applied to the film. The simplest method is to pass the film through a heated nip system which incorporates a hot roller carrying the embossing pattern. An alternative technique is to feed a hot film into the nip of a cold embossing roller system. The film is preheated to a temperature close to the melting point, and then passed between the nips of an engraved steel roll and a rubber covered roll to impress the pattern in the film. The processes can be carried out in-line or out-of-line.

Printing of Polyethylene Films

In many packaging applications, polyethylene film is printed, often in several colours, as a means of either brand identification, enhancing sales appeal, imparting details about the contents of the package, or providing instructions regarding their use.

The surface of polyethylene film is highly non-polar and inert and consequently is not receptive to the printing of inks, lacquers, coatings, etc. For this reason, all film surfaces which are to be subsequently printed are treated by electrical corona discharge treatment (see the section 'Treatment of Polyethylene Film'). This treatment oxidises the surface, increases the polarity, and allows the printing ink to bond to the surface with good adhesion.

It is accepted practice that films for normal printing applications with solvent-based inks should be treated to a dynes ink level of at least 38 to 40mN/m (dynes/cm).

Printing Inks

Information regarding inks for a particular printing application can best be supplied by the printing ink suppliers.

For flexographic and rotogravure printing the ink comprises essentially a pigment, a polymeric binder and an organic solvent. The pigment particles surrounded by the binder are dispersed in the solvent which spreads over the film surface on application. As the solvent evaporates, generally within a drying oven, it leaves a thin continuous coloured layer of pigment particles adhering to the surface of the polyethylene.

In flexography the choice of solvents is somewhat limited as they must not affect the rubber stereotypes; alcohols, alcohol/ketone mixtures and esters are normally used, but hydrocarbons are unsuitable. Because of environmental considerations, water-based inks are increasingly being used in place of the solvent-based systems.

Printing inks used with plastics films should provide a tough tenacious ink layer which is resistant to scuffing and flexing, does not affect the contents of the package, and is not itself affected by the package contents or the additives in the film. It is important that the ink is flexible as this is dictated by the film itself being flexible.

Lamination

Lamination Processes

Polyethylene films are frequently used as part of a multilayer film structure. The excellent sealing characteristics of polyethylene make it the most common sealing layer. These multilayer film structures can be produced by several different processes:

- By adhesive lamination, where individual films or layers are adhered together with adhesives
- By extrusion coating, where a single thin polymer web is extruded onto a substrate such as paper, aluminium foil or another polymeric film or laminate
- By thermal lamination, where heat and pressure are used to fuse the polymer surfaces of two films or laminates (without in-line adhesive application)
- By coating, with for example an emulsion, solution or lacquer
- By vapour metallisation, e.g. Aluminium coating onto polypropylene film

Adhesive lamination and extrusion coating are the two most common processes. Extrusion coating is described in the Extrusion Coating publication.

Adhesive Lamination

In the lamination process two or more dissimilar films or substrates are combined to create a composite laminated film structure. In most applications an aqueous or solvent based adhesive is used, either in a wet-bonding or a dry bonding process.

Wet-bonding is only applicable when one of the films is permeable to the water or solvent used in the adhesive, and is generally not successful with plastic films. In the dry-bonding process, the laminating film is treated with the adhesive and the solvent is driven off by heat before the film is bonded to the substrate by passing it through a nip roll (see Figure 51). Other bonding methods are hot melt bonding using a molten low melting point wax or copolymer as the adhesive, or thermal bonding in which a heat-sensitive laminating film and the substrate are combined in a heated nip.

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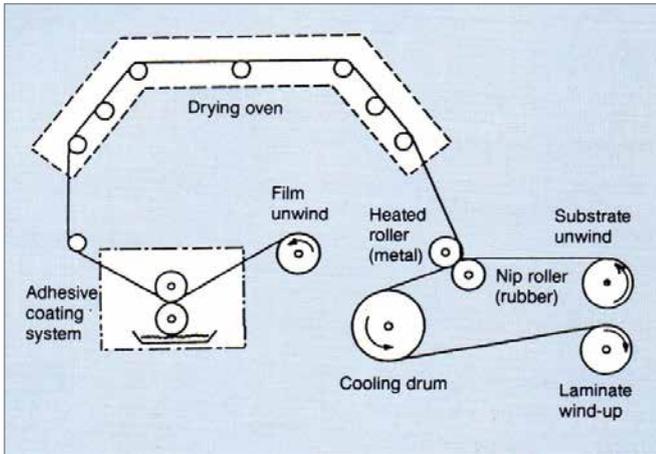


Figure 51: Adhesive Lamination Process

The substrate can be a non-polymer such as paper, aluminium foil or cardboard, or a polymer film such as biaxially-oriented polypropylene, polyester or polyamide.

The requirements for a lamination film are:

- High clarity, high gloss
- A low gel level
- Good roll geometry and uniform gauge
- Good sealing properties
- High level of corona treatment, about 42 mN/m (dynes/cm)
- Low additive level (since migrating slip additives tend to reduce adhesion with the substrate)
- Food contact approval

HEAT SEALING OF POLYETHYLENE FILMS

Introduction

One of the special advantages of polyethylene films is their ability to be heat sealed, i.e. to be fused together in narrow bands to form strong bags and packages. When two films are placed together and subjected to heat and pressure, a fusion bond is formed between them with a strength approaching that of the film itself.

Heat sealing is an important process in converting film to form a bag, package or sachet, and bag production rates depend largely on the 'sealability' of the film. Polyethylene films are easier to heat seal and give much stronger seal strength than most other packaging materials.

The Heat Sealing Process

The heat sealing process is illustrated diagrammatically in Figure 52. The two films to be sealed are clamped between two heated jaws or sealing bars for a fixed (dwell) time. Heat is conducted into the films, causing the polymer to melt and the molecules at the interface between the two films to become entangled. Once this fusion is completed the jaws are opened and the seal is cooled to below its melting point.

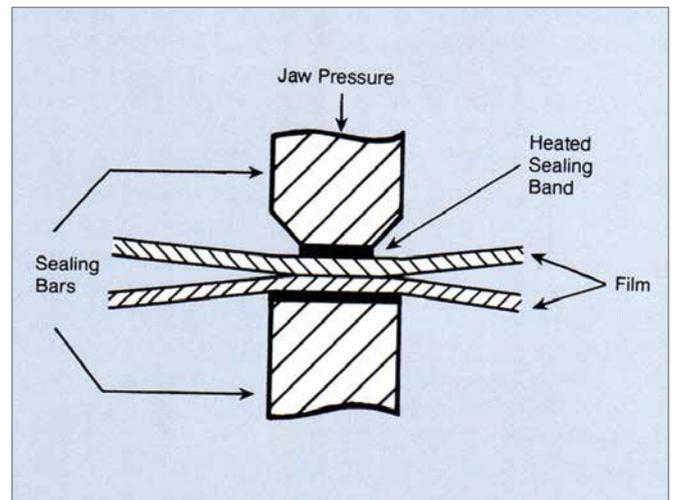


Figure 52: Diagram of Heat Sealing Process

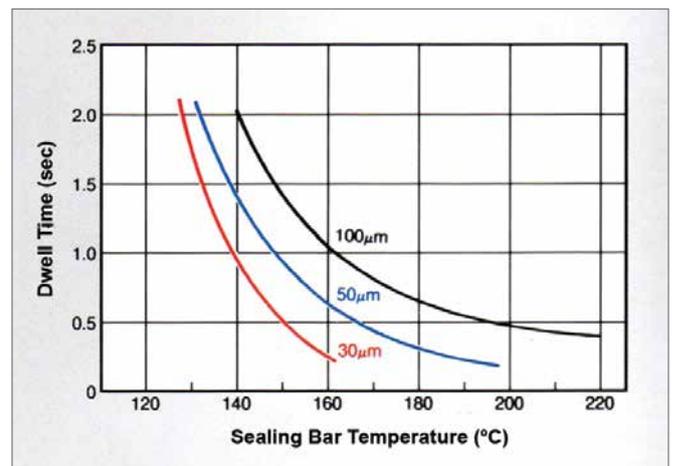


Figure 53: Relationships Between Required Dwell Time and Heat Sealing Temperature for LDPE Film of Various Thicknesses (Sealing Pressure 0.25 MPa)

The main sealing variables are temperature, dwell time and jaw pressure. Time and temperature are inter-related, as shown in Figure 53, since it is the amount of heat to fuse the films at their interface which is the critical requirement.

Types of Heat Sealing

There are several different methods of heat sealing. These are:

- **Hot jaw sealing:** The film is clamped between two heated sealing jaws, the upper jaw being moveable. Either the top or both sealing bands are temperature-controlled at the required set point. The sealing bands are covered with a thin non-stick tape to prevent the hot film sticking to the jaws. The pressure and the dwell time are controlled. This method is used for the formation of bottom (end) seals but can suffer from softening and thinning of the polymer adjacent to the seal.
- **Thermal impulse sealing:** In this method the electrical current to the sealing band only flows during the sealing dwell time and the film rapidly heats up above its melting point to form the seal. After a fixed time the current impulse ceases and the seal cools under pressure. This method overcomes some of the thinning problems with hot jaw sealing.
- **Hot wire or hot knife sealing:** A wire or thin wedge-shaped blade heated to 300 to 500°C is forced down onto the films to be joined, heating them very rapidly and cutting through them. The molten polymer on either side of the sealing element contracts to form a sealed bead. This method is widely used in many bag-making machines, including side-sealing machines, because of its high sealing speeds.

Determining the Seal Strength

Seal strength is calculated from the tensile force required to separate the two layers and break the seal, measured at ambient temperature. Seal energy which is the area under the tensile force vs. elongation graph is sometimes used.

When assessing the sealability of a film, the normal practice is to make seals over a range of temperatures covering the sealing range, for a fixed jaw pressure and sealing time. Each seal is then peeled apart on a tensile tester using 25 mm wide strips, and the sealing curve of seal strength vs. temperature plotted as shown in Figure 54.

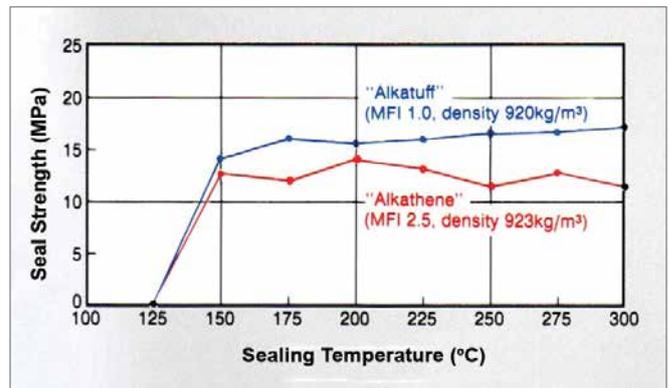


Figure 54: Heat Sealing Curves for Alkathene LDPE and Alkatuff LLDPE Films (Otto Brugger Heat Sealer, Dwell Time 0.5 sec, Pressure 0.2MPa, Film Thickness 50 micron)

This figure shows that at low temperatures below the melting point, no seal is formed. As the temperature is increased, a little melting occurs but the seal is easily delaminated or peeled apart (peel seal). Above the melting temperature of the polymer, effective fusion seals are made and good seal strengths obtained. At high temperatures or long sealing times, the seal may become distorted or wrinkled; eventually holes will occur in the seal area (burn-through), resulting in poor seals. The range of temperatures between that required to make a good fusion seal (the minimum seal temperature) and the burn through temperature is the sealing range.

Another useful measure is to compare the seal strength with the tensile strength of the film measured in the same direction, and expressed as a percentage or relative seal strength.

A comparison of the sealing curves for various polymers will indicate their comparative minimum sealing temperatures, seal strengths and sealing ranges. For good sealability, a high seal strength, a low minimum seal temperature and a wide sealing range are desirable. These properties lead to flexibility and short cycle times during the sealing operation.

Hot Tack

Another aspect of heat sealability is the hot tack performance. This is defined as the ability of the molten seal to withstand a load immediately after the sealing cycle. It is a critical property in vertical form-fill-and-seal packaging lines, when the bag is filled with its contents immediately after the bottom seal of the bag has been formed, while the seal is still hot. Since the contents can be heavy and line speeds high, excellent hot tack strength is required to withstand the load.

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Hot tack properties are determined by forming a seal on a loop of film with one end clamped in a load cell and the other to a piston system. After a fixed sealing dwell time and a short delay time, the sealing jaws open and the hot seal is immediately placed under load by the piston being activated. The hot tack strength is measured by the load cell. By repeating this test at different sealing temperatures, hot tack sealing curves of hot tack strength vs. temperature can be plotted (see Figure 55).

Hot tack strength increases with temperature above a minimum seal temperature and reaches a maximum as shown in Figure 55. Above the maximum, the hot tack strength decreases due to the decreasing melt strength of the molten seal.

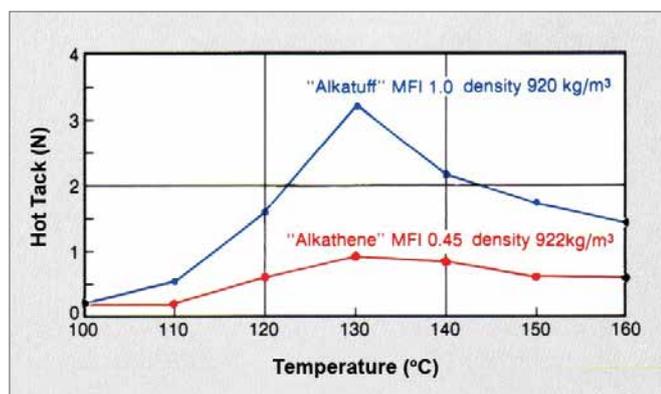


Figure 55: Hot Tack of *Alkathene* LDPE and *Alkatuff* LLDPE Films (IDM Hot Tack Testing, Seal Pressure 275 kPa, Seal Time 0.5 sec, Delay Time 0.2 sec, Peel Speed 250 mm/sec, Film Thickness 50 micron)

Factors Affecting Heat Sealability

Sealing Parameters

The parameters of the sealing process which influence the formation of a good seal are: sealing temperature, sealing dwell time, jaw or clamp pressure and cooling conditions. The inter-relationship between sealing temperature and dwell time is shown in Figure 53. Above the minimum sealing temperature, increasing the temperature has little effect on seal strength, provided it is below the burn through point (see Figure 53). Seal strength generally decreases as the pressure is raised, because of the effect of the molten polymer being squeezed away from the seal to give a thin section.

In production lines, sealing becomes more difficult at high line speeds because of the reduced dwell times.

Brittle heat seals, i.e. seals which fail in the film adjacent to the seal, can result because of the annealing effect on this portion of the film during the sealing operation.

Polymer Parameters

Heat sealability is affected by the polymer type, the MFI and the density of the polymer, and the additives present. The optimum polymer for an application will have the best balance of properties under the conditions applied.

- **Comonomer type:** In LLDPE, seal strength and hot tack strength increase as the length of the side chains increases. This means that the hexene- and octene based LLDPEs have better sealing properties than butene-based LLDPEs.
- **Polymer density:** As the density increases, the melting point and the heat of fusion also increase. Hence higher temperatures and longer times are required to form the seal, but seal strength will be higher. Hot tack strength decreases as density increases.
- **Polymer MFI:** Because the sealing operation occurs at very low shear rates of less than 1.0 sec^{-1} , the viscosity in this shear rate region (the zero shear viscosity) is a significant factor in determining the flow behaviour during sealing and hence the sealability. At any sealing temperature, higher MFI polymers have lower zero shear viscosities. The lower viscosities allow the polymer to flow more easily, including into gaps and creases, and thus they will be easier to seal. They will show a slightly lower minimum seal temperature and lower seal strengths. However, if the sealing pressure is too high, higher MFI polymers may be squeezed too much away from the seal, leading to thin sections that may fail. Lower MFI polymers have higher melt strength. This improves hot tack strength. The higher melt strength can also reduce any thinning that may occur adjacent to the seal if the film is loaded immediately after sealing.
- **Branching structure:** In metallocene LLDPEs, the side branches are distributed in a more controlled way. This allows an improved balance of viscosity and melt strength to be achieved. In particular, this improves the hot tack performance of these polymers.
- **Film additives:** At low additive levels, there is no effect on heat sealability. However very high levels of the migratory slip additives can have detrimental effects on the minimum sealing temperature and the seal strength, particularly in treated films.

Effect of Film Variables

- **Film thickness:** Heavier gauge film requires a higher sealing temperature or a longer sealing time than thinner film (see Figure 53). In gusseted film where four layers are to be sealed in part of the bag, higher temperatures are required but burn-through of the two layer part must be avoided. Film thickness has little effect on hot tack strength but thicker films will require a higher minimum seal temperature.
- **Corona treatment:** Excessive corona treatment or reverse-side treatment has a detrimental effect on heat sealability because of the interference in the melt fusion by the oxidised surface layer. The minimum sealing temperature rises significantly as the level of treatment increases (see Figure 56). This is particularly a problem in the side-sealing or hot-wire sealing of bags. The presence of slip additives can exacerbate this problem.
- **Film orientation:** This is an important variable which is not often recognised as having an influence on sealability. When heated, the film naturally tries to return to its original unstretched state in the vicinity of the heat seal. In film with unbalanced orientation in the machine and transverse directions, serious reductions in seal strength can be obtained. This effect applies particularly to side seals.
- **Film age:** There is some evidence that the sealability of film stored for long periods of time will deteriorate because of surface oxidation.
- **Creases:** These are the causes of many sealing weaknesses and failures, as the additional layers of film in a crease are much more difficult to seal. In general, stiffer films are less prone to forming creases during extrusion and converting; however the optimum stiffness will depend on the equipment. In some cases, higher MFI polymers will help seal through the creases, as they are able to flow more easily.

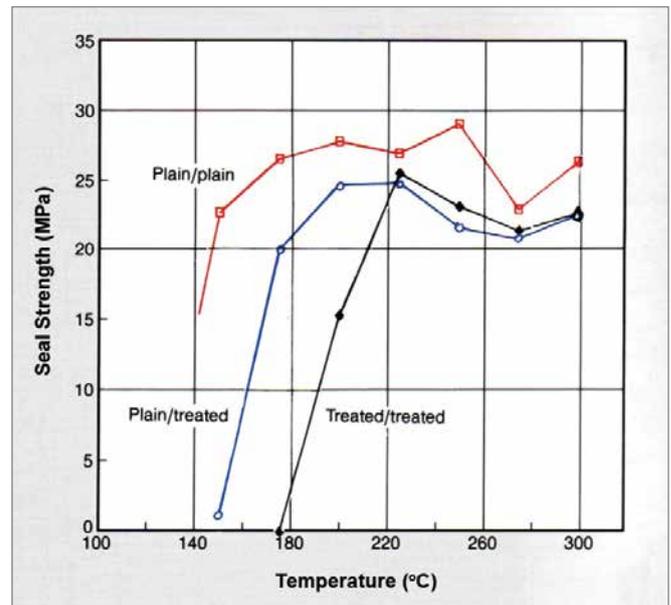


Figure 56: Effect of Treatment on Sealing Properties of MFI 2.5 LDPE Film (Otto Brugger Heat Sealer, Dwell Time 0.5 sec, Pressure 0.2 MPa, Film Thickness 37 micron)

Comparison of Alkathene LDPE, Alkatuff LLDPE and Alkamax mLLDPE Films for Heat Sealing

LLDPE films possess superior sealability to conventional LDPE films, having easier sealing, higher seal strengths and hot tack strengths, and excellent sealability through contaminated film surfaces. Typical sealing and hot tack curves comparing the sealability of *Alkathene* LDPE and *Alkatuff* LLDPE films are shown in Figures 54 and 55 respectively.

Alkatuff LLDPE and *Alkamax* mLLDPE films have about a 20°C higher melting point, a lower melt strength, a lower zero shear viscosity, a much lower film shrinkage and are frequently of thinner gauge than *Alkathene* LDPE films of similar MFI and density. These factors have a significant influence on the sealability of the two polymers.

A slightly higher minimum sealing temperature is required for *Alkatuff* LLDPE and *Alkamax* mLLDPE films. Because of their narrower molecular weight distributions and their flatter flow curves at low shear rates compared with *Alkathene* LDPE (see Figure 5), *Alkatuff* LLDPE and *Alkamax* mLLDPE have lower zero shear viscosities and consequently better flow during sealing for a given MFI and sealing temperature. This effect contributes to the easier sealing of *Alkatuff* LLDPE and *Alkamax* mLLDPE films. The zero shear viscosity decreases as the MFI and temperature increase.

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Seal strength is higher with *Alkatuff* LLDPE and *Alkamax* mLLDPE films because of the inherently higher tensile strength of the film itself (see Figure 54).

Figure 55 shows the superior hot tack strength of an *Alkatuff* LLDPE film compared with an *Alkathene* LDPE film with similar MFI and density. In addition, the good hot tack performance of the LLDPE film is retained over a range of temperatures, thus giving a wider operating window. Also, good hot tack strength is maintained even when sealing contaminated films. For *Alkamax* mLLDPE resins, the hot tack performance is further improved. Figure 57 shows an *Alkamax* mLLDPE resin has superior hot tack at lower sealing temperatures than a comparable standard LLDPE.

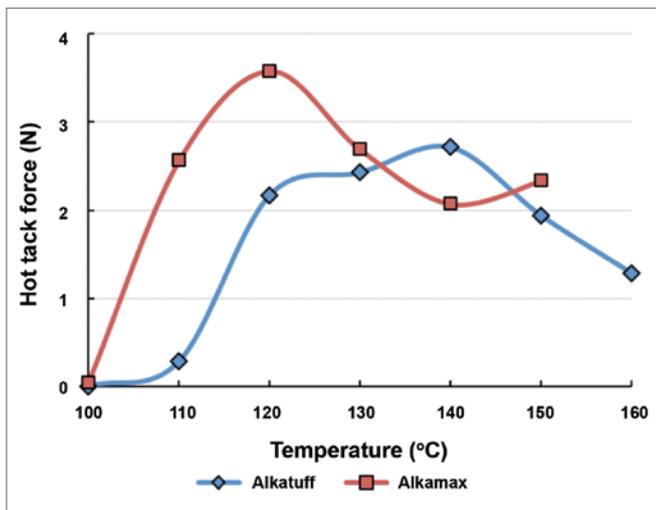


Figure 57: Hot Tack of *Alkamax* mLLDPE and *Alkatuff* LLDPE Films (IDM Hot Tack Testing, Seal Pressure 275 kPa, Seal Time 0.5 sec, Delay Time 0.2 sec, Peel Speed 250 mm/sec, Film Thickness 50 micron)

Good heat seals can be obtained in hot jaw sealing with LLDPE films by using a 10 to 20°C higher sealing temperature, but dwell time and jaw pressure can be reduced to account for the lower melt strength of the LLDPE. These conditions allow much faster cycling than with LDPE films.

In side-sealing operations under conditions normally used for LDPE films, slightly more knife build-up and some stringiness to the seals may occur with LLDPE films. Increasing the temperature of the hot knife eliminates build-up and gives better looking seals. Good seal integrity equivalent to or exceeding that of LDPE films is obtained. A sharper 0.4 mm radius knife, similar to those used for sealing polypropylene and high density polyethylene films, can provide better side-sealing performance.

Sealing through Contamination

In a number of applications, for example food packaging, the sealing area of the film can become contaminated with dust from the contents or coated with grease or liquid before the seal is made. This contamination makes sealing particularly difficult by interfering with the inter-fusion of the two films; sealing properties then deteriorate and the minimum sealing temperature is raised significantly.

LLDPE, including mLLDPE, films are less sensitive to sealing through contamination than LDPE films and for this reason LLDPE rich blends are widely used for applications where sealing can be difficult. Higher MFI grades can also help as the lower viscosity may allow the resin to flow around contamination more easily.

APPENDIX 1 – FILM EXTRUSION TROUBLESHOOTING GUIDE

Problem/Issue	Causes	Potential Solutions/Actions
Blocking	Insufficient bubble cooling	Optimise cooling air Reduce output rate
	Winding tension too high	Reduce winding tension
	Nip roller pressure too high	Reduce nip roller pressure
	Rolls exposed to excessive heat during storage or transport	Minimise heat exposure
	Antiblock level or type is not adequate	Increase level of antiblock Consider a different type of antiblock
	Formulation susceptible to blocking	Consider metallocene resins or higher density resins
Die lines or Die lip buildup	Melt temperature too high	Reduce extruder temperatures
	Die temperatures too high	Reduce die temperatures
	Insufficient process aid	Add process aid masterbatch
	Antiblock	Reduce level if possible. Check type of antiblock.
	Die lips scratched or dented	Repair or replace lip set
	Die lips misaligned	Ensure die lips are aligned and level
Gels or dark specks	Oxidation of resin during shutdown or startup	Cool extruder rapidly when shutting down (set temperatures to 100°C) Avoid long periods of heating while extruder idle Leave extruder full when shutting down Add antioxidant masterbatch when shutting down
	Extrusion temperatures not optimised	Optimise extrusion temperatures
	Extruder speed too slow or too fast for optimum extrusion	Alter formulation or equipment to achieve suitable extruder speeds
	Purging inadequate when changing formulations	Consider use of a purging compound
	Faulty thermocouple, or other fault in heating or cooling systems	Check heater controls, thermocouples, and cooling system
	Screenpack broken	Replace screenpack
	Screens too coarse	Use finer screen(s)
	Contamination	Eliminate sources of external contamination
	Moisture	Ensure resins are dry
	Buildup of oxidised material in equipment	Clean extruder screw and barrel. Clean die.
Incorrect COF /slip	Incorrect level of slip additive	Check dosing Consider type of slip additive
	Slip additive has not migrated to surface	Allow adequate time for additive to migrate Reduce winding tension
	Slip levels in each layer not optimised	Alter slip levels in each layer
	Slip additive absorbed by another layer	Consider non-migratory slip additive

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Problem/Issue	Causes	Potential Solutions/Actions
Low output	Unstable bubble	Refer to “Unstable bubble” section
	Extruder motor load too high	Increase extrusion temperatures Consider higher melt index resin(s) Regear extruder motor
	Head pressure too high	Change screenpack Increase extrusion temperatures Consider higher melt index resin(s) Increase die size or die gap
Melt fracture	Melt temperature too low	Increase extruder and/or die temperatures
	Die gap too narrow	Change die insert to a larger gap
	Insufficient process aid	Add or increase process aid masterbatch
	Formulation not optimum	Add or increase level of LDPE Consider a different grade of LLDPE
	Output rate too high	Reduce output rate
Poor optical properties	Melt temperature too low	Increase extruder and/or die temperatures
	Frost line too high	Reduce frost line height
	Output rate not optimum	Increase or reduce output rate
	Melt fracture	Refer to “Melt fracture” section
	Die gap too wide	Change die insert to a narrower gap
	Excessive level of antiblock or other additives	Optimise additive levels
	Formulation not optimum	Consider lower density resins Consider higher melt index resins Add or increase level of LDPE
Poor shrink properties	Incorrect blow-up ratio	Adjust die size or film width
	Incorrect resin or formulation for application	Adjust level of LLDPE/HDPE or alter grade of LDPE
	Poor gauge control	Minimise variation by centering die and optimising chilled air flow
	Frostline height not correct	Adjust chilled air flow or output rate
	Bubble shape not correct	Adjust chilled air flow or output rate
	Die lip gap not optimum	Replace die lip set
Poor sealing	Faulty sealing equipment	Ensure sealing equipment is well maintained
	Sealing temperature or dwell time too low	Increase sealing temperature or dwell time
	Sealing temperature too high	Reduce sealing temperature
	Sealing pressure too low or too high	Adjust sealing pressure Consider different type of sealing jaw or wire
	Gauge incorrect	Ensure target gauge is achieved
	Gauge variation	Minimise variation by adjusting die gaps and optimising chilled air flow
	Incorrect formulation	Ensure no errors occur in feeding or blending resins
	Excessive corona treatment	Reduce corona treatment level
	Formulation not optimum for conditions	Adjust formulation (will depend on failure type)

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Problem/Issue	Causes	Potential Solutions/Actions
Surging extruder	Feed throat cooling not working	Check cooling water flow
	Bridging or blockage in feed throat	Check feed throat
	Temperature profile not optimised	Optimise extruder temperatures
	Inconsistent resin blend	Ensure blenders are operating correctly
Unstable bubble	Cooling air flowrate not optimised	Adjust cooling air Ensure air ring type is suitable for formulation
	Melt strength too low	Reduce melt temperature Use material with lower MFI Add or increase level of LDPE
	Surging extruder	Refer to “Surging extruder” section
	High blow-up ratio	Increase die size
	Output rate too high	Reduce output rate

Disclaimer

The proposed solutions in this guide are based on conditions that are typically encountered in the manufacture of products from polyethylene. Other variables or constraints may impact the ability of the user to apply these solutions. Qenos also refers the user to the disclaimer at the beginning of this document.

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