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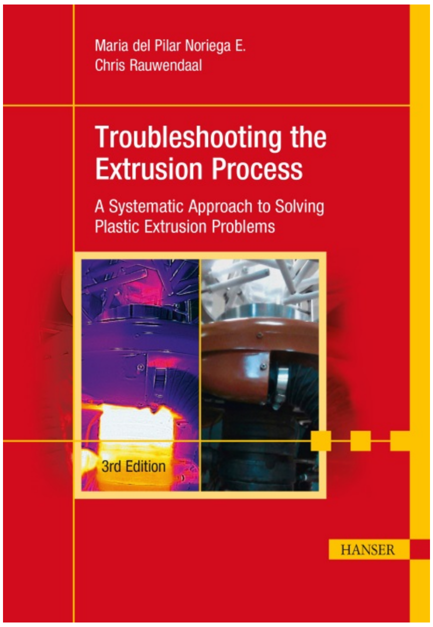

Sample Pages

Troubleshooting the Extrusion Process

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Preface

One of the greatest challenges in actual extrusion operations is efficient and rapid problem-solving. Extrusion problems often result in downtime and/or out-of-spec product, and this can be very costly. However, because of the nature of the extrusion process, it is often quite difficult to determine the cause of the problem and find the proper solution, particularly if it must be done quickly. Despite the industrial importance of extrusion troubleshooting, no book currently deals exclusively with this topic. This book is an attempt to rectify this situation.

Both authors have worked in extrusion for many years and have been involved in numerous troubleshooting projects. Although it is impossible to discuss all possible extrusion problems, it is possible to discuss the main categories and to develop a systematic and methodical approach to solving extrusion problems. In this book, the authors frequently use flow charts and fishbone charts to allow systematic troubleshooting.

The authors added a substantial amount of new material to this third edition, including:

- Chapter 1: new section on collection and interpretation of extrusion process data
- Chapter 2: data acquisition systems section substantially expanded and updated with cloud-based DAS and systems that can automatically detect machine problems; new sections on rotational rheometry and the smartphone
- Chapter 3: new sections covering how screw design can affect extruder performance and melt temperature variation; additionally, barrel temperature profiles for many polymers from LDPE to PEEK
- Chapter 4: ten new case studies
- Appendix 3: new section with information on barrel temperature optimization for PP and HDPE for a 2.5-inch (63.5 mm) extruder and a description of recent research on automatic optimization of extruder barrel temperatures conducted at the department of Kunststofftechnik Paderborn, University of Paderborn, Germany by Verena Resonnek

- Appendix 4 (new): process signal analysis using Fast Fourier Transform

The authors welcome feedback from readers, along with additional material on extrusion troubleshooting. This will allow more information to be incorporated into future editions of this book.

Contents

3 Systematic Troubleshooting

3.1 Upsets versus Development Problems

This chapter will primarily focus on upsets, problems that occur in an existing extrusion line for an unknown reason. If the extrusion line had been running fine for a considerable period of time, then it is clear that there must be a solution to the problem. Thus, the objective of troubleshooting is to find the cause of the upset and eliminate it. On the other hand, there may be no solution to a development problem. Solving a development problem involves establishing a condition that has not been achieved before. If it is physically impossible to establish the desired condition, then, clearly, there is no solution to the problem. A functional analysis of the process should make it possible to determine the bounds of the conditions that can be realized in practice.

3.2 Machine-Related Problems

In machine-related problems, mechanical changes in the extruder cause a change in extrusion behavior. These changes can affect the drive system, the heating and cooling system, the feed system, the forming system, or the actual geometry of the screw and the barrel. The main components of the drive are the motor, the reducer, and the thrust-bearing assembly. Drive problems manifest themselves as variations in rotational speed and/or the inability to generate the required torque. Problems in the reducer and thrust bearings are often associated with clear audible signals of mechanical failure. If the problem is suspected to be the drive, make sure that the load conditions do not exceed the drive capacity.

3.2.1 The Drive System

Older motor drive systems generally consist of a direct current (DC) brush motor, a power conversion unit (PCU), and operator controls. A frequent problem with the motor itself is worn brushes; these should be replaced at regular intervals as recommended by the manufacturer. The manufacturer's recommendations should also be followed in troubleshooting an extruder drive. A typical troubleshooting guide for a DC motor is shown in Table 3.1.

Table 3.1 Troubleshooting Guide for DC Motor

Problem	Possible cause	Action
Motor will not start	Low armature voltage	Make sure motor is connected to proper voltage
	Weak field	Check for resistance in the shunt field circuit
	Open circuit in armature or field	Check for open circuit
	Short circuit in armature or field	Check for short circuit
Motor runs too slow	Low armature voltage	Check for resistance in armature circuit
	Overload	Reduce load or use larger motor
	Brushes ahead of neutral	Determine proper neutral position for brush location
Motor runs too fast	High armature voltage	Reduce armature voltage
	Weak field	Check for resistance in shunt field circuit
	Brushes behind neutral	Determine proper neutral position for brush location
Brushes sparking	Brushes worn	Replace
	Brushes not seated properly	Reseat brushes
	Incorrect brush pressure	Measure brush pressure and correct
	Brushes stuck in holder	Free brushes, make sure brushes are of proper size
	Commutator dirty	Clear commutator
	Commutator rough or eccentric	Resurface commutator
	Brushes off neutral	Determine proper neutral position for brush location
	Short circuit in commutator	Check for shorted commutator, and check for metallic particles between commutator segment
	Overload	Reduce load or use larger motor
	Excessive vibration	Check driven machine for balance
Brush chatter	Incorrect brush pressure	Measure and correct
	High mica	Undercut mica
	Incorrect brush size	Replace with proper size
Bearings hot	Belt too tight	Reduce belt tension
	Misaligned	Check alignment and correct
	Bent shaft	Straighten shaft
	Bearing damage	Inspect and replace

3.2.2 The Feed System

The most important component of the feed system in a flood-fed extruder is the feed hopper and its stirrer and/or discharge screw. A mechanical malfunction of this system can be determined by visual inspection. If the feed hopper is equipped with a discharge screw (crammer feed), the speed of the discharge screw should be checked for unusual variation. For proper functioning, the drive of a crammer feeder should have a torque feedback control to ensure constant feeding and to avoid overfeeding.

Many extruders have square feed hoppers with rapid compression in the converging region. Extruder manufacturers often choose this geometry because of the ease of manufacture, but this hopper geometry does not promote steady flow. When flow instabilities occur in a feed hopper, the extruder operator will often hit the hopper with a heavy object to get the flow going again. As a result, hoppers that cause flow problems often show signs of abuse such as surface damage, dents, scrapes. Such damage is a strong indication of poor feed hopper design.

3.2.3 The Heating and Cooling System

The heating and cooling system exercises a certain degree of control of the polymer melt temperature. However, stock temperature deviations do not necessarily indicate a heating or cooling problem because heat is transferred directly to (or removed from) the barrel and only indirectly to (or from) the polymer. It is actually the barrel temperature that is controlled. The local barrel temperature, as measured with a temperature sensor, determines the amount of barrel heating or cooling.

The stock temperature is generally controlled by changing the setpoint of the temperature zones along the extruder. However, due to the slow response of the melt temperature to changes in heat input, only very gradual stock temperature changes can be effectively controlled by setpoint changes. Rapid stock temperature fluctuations (cycle times less than about five minutes) usually cannot be reduced via a melt temperature control system. Such fluctuations are indicative of conveying instabilities in the extrusion process and can only be effectively reduced by eliminating the cause of the conveying instability.

The heating system can be checked by changing the setting to a much higher temperature, for instance 50 °C above the regular setting. The heater should turn on at 100% power, and the measured barrel temperature should begin rising in about one to two minutes. If the heater does not turn on at full power, the barrel temperature measurement is in error, or there is a problem with the electronic circuit of the temperature controller. If the heater turns on at full power but the temperature does not start to rise within two to four minutes, either the barrel temperature measurement is incorrect, or there is poor contact between the heater and barrel. The cooling system can be checked similarly by changing the setting to a much lower temperature, for instance 50 °C below the regular setpoint. If the cooling does not turn on at full capacity, the barrel temperature measurement is in error, or there is a problem in the circuit of the temperature controller. If the cooling turns full on at full capacity but the temperature does not start to drop within two to four minutes, either the barrel temperature is incorrect or the cooling device is inoperable. This checkout procedure is summarized in Table 3.2.

Table 3.2 Heating and Cooling System Check

Heating system: Increase setpoint of temperature zone by 50 °C	
Heater turns on full blast and the barrel temperature rises in about 2 minutes	Heating system normal
Heater turns on full blast but the barrel temperature does not change	Poor contact of heater to barrel, insufficient heating capacity, temperature sensor failure
Heater output does not change	Heater failure, controller bad
Cooling system: Reduce setpoint of temperature zone by 50 °C	
Cooling on full blast and the barrel temperature drops in about 2 minutes	Cooling system normal
Cooling on full blast but the barrel temperature does not change	Temperature sensor failure, insufficient cooling capacity, cooling system not functioning at all
Cooling output does not change	Cooling system bad, controller bad

If a substantial amount of cooling is required to maintain the desired stock temperature, this is generally a strong indication of excessive internal heat generation by frictional and viscous dissipation. Internal heat generation can be reduced by lowering the screw speed or by changing the screw design. The main screw design variable that affects viscous heating is the channel depth. Increasing the channel depth will reduce shear rates and viscous heating. Mechanical changes in the forming system are tied to the extrusion die and downstream equipment. These elements can be subjected to simple visual inspection to detect mechanical changes. Changes in the geometry of the screw and/or the barrel are often caused by wear. Because wear is a very important element in the performance of extrusion machinery, it will be discussed in detail in Section 3.2.5.

3.2.4 How Screw Design Can Affect Extruder Performance

One possible cause of a number of extrusion problems is poor screw design. It is helpful to have some rudimentary knowledge of screw design so that a problem caused by poor screw design can be recognized. Screw design is a very large topic and we will not go into the details of screw design. For a detailed discussion on screw design, the reader is referred to the Polymer Extrusion book [176]. However, it is important to have an understanding of some of the main screw design issues.

The screw is the heart of the extruder. The screw performs the following functions:

- Feeding of the plastic particles (usually pellets)
- Conveying of the plastic
- Heating of the plastic
- Melting of the plastic
- Mixing of the plastic
- Degassing of the plastic (in vented extruders)
- Pressure development

Functional Zones of the Extruder

The main functional zones of the extruder are feeding, solids conveying, melting, and melt conveying in the extruder and melt conveying in the die. These zones have to be in balance for the extruder to achieve stable extrusion conditions. The balancing of the functional zones occurs by the pressures that develop over the length of the extruder. For instance, if the solids-conveying rate is higher than the melting rate, the pressure at the end of the solids-conveying zone will increase as shown in Figure 3.1.

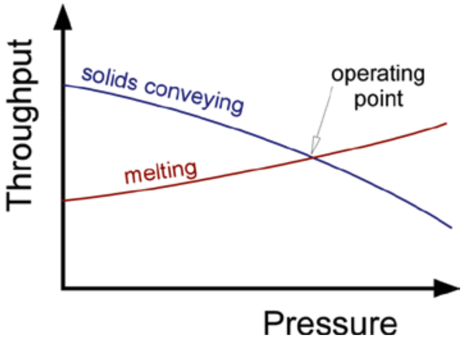

Figure 3.1 Throughput versus pressure solids conveying and melting – stable conditions

The pressure shown in Figure 3.1 is the pressure at the end of the solids-conveying zone; this is also the pressure at the start of the melting zone. An increase in this pressure will reduce the solids-conveying rate and increase the melting rate. When the solids-conveying rate equals the melting rate, the two zones are balanced. This is where the solids-conveying characteristic curve intersects with the melting characteristic curve. This point is called the operating point.

We have unstable conditions when solids conveying cannot reduce to the point where the solids-conveying rate equals the melting rate; this situation is shown in

Table 3.9 Comparison of Various Distributive Mixers

Mixers	Pressure drop	Dead spots	Barrel wiped	Operator-friendly	Machining cost	Splitting reorientation
Pins	Medium	Yes	Partial	Good	Low	Medium
Dulmage	Low	No	Partial	Good	Medium	Good
Saxton	Low	No	Fully	Good	Medium	Good
CTM	High	Yes	Partial	Poor	Very high	Good
TMR	High	Few	Fully	Medium	High	Good
CRD	Low	No	Fully	Good	Medium	Good
Axon	Low	No	Fully	Good	Low	Medium
Double-wave	Low	No	Fully	Good	High	Low
Pulsar	Low	No	Fully	Good	Medium	Low
Stratablend	Low	Few	Fully	Good	Medium	Low

3.4.2.7 Dispersive Mixing Sections

The following characteristics are desirable for dispersive mixing:

- The mixing section should have regions where the material is subjected to high stresses, preferably elongational stresses.
- The high stress regions should be designed in such a way that the exposure to high shear stresses occurs only for a short time, while exposure to elongational stresses is maximized.
- All fluid elements should pass through the high stress regions many times to achieve efficient dispersive mixing action.
- All fluid elements should pass through the high stress regions the same number of times for uniform mixing.

There are several types of dispersive mixing sections: blister rings, fluted mixing sections, and planetary gear extruders.

Blister Ring

The blister ring is simply a circumferential shoulder on the screw with a small clearance between the ring and the barrel (Figure 3.60). All material must flow through this small gap where it is exposed to high shear stresses. Since no forward drag flow occurs in the blister ring, relatively high pressure drops occur across the blister ring. The stress level in the gap is not uniform; therefore, the mixing action is not uniform.

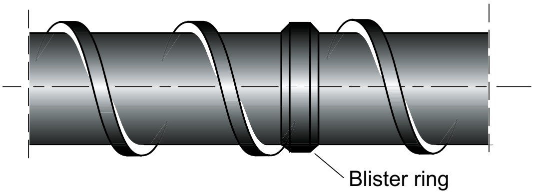

Figure 3.60 Blister ring

Fluted Mixing Sections

These mixers have inlet and outlet flutes separated by barrier flights. The material must pass through the narrow gap of the barrier flights to exit from the mixer, and this is where the mixing action takes place. One of the earliest fluted mixers was the Egan mixing section developed by Gregory and Street in which the flutes have a helical orientation (Figure 3.61).

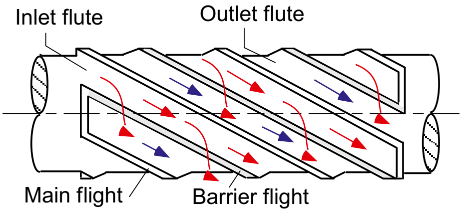

Figure 3.61 Egan mixing section

Another fluted mixer is the Union Carbide mixer (UC mixer) developed by LeRoy and popularized by Maddock, which has straight flutes (Figure 3.62). Because of the straight flutes, the LeRoy mixer has no forward pumping capability and thus, tends to have a high pressure drop. It is typically machined with a ball mill, and as a result, the flutes have a semicircular cross section. This tends to result in inefficient streamlining at the entry and exit of the flutes. Despite these shortcomings, the LeRoy mixer is probably the most commonly used mixer in single-screw extruders.

It is important to design mixing sections with a low pressure drop. This is particularly true for dispersive mixers. A high pressure drop reduces output, increases melt temperatures, increases residence time, and increases the chance of degradation. Higher melt temperatures reduce melt viscosity and the stresses in the melt in the mixing section, and therefore reduce dispersive mixing. Because a high pressure drop causes high temperatures, a high pressure drop should be avoided.

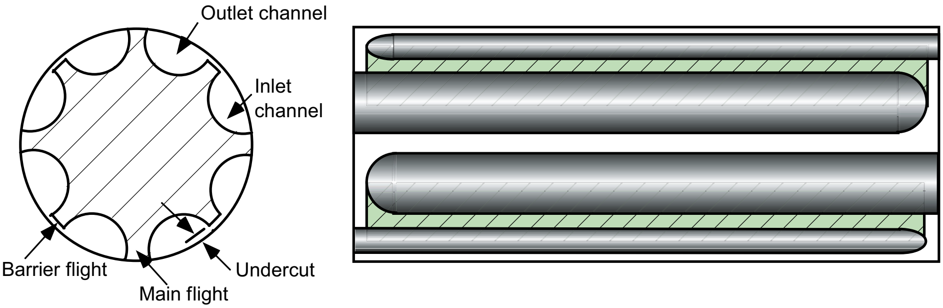

Figure 3.62 LeRoy mixing section

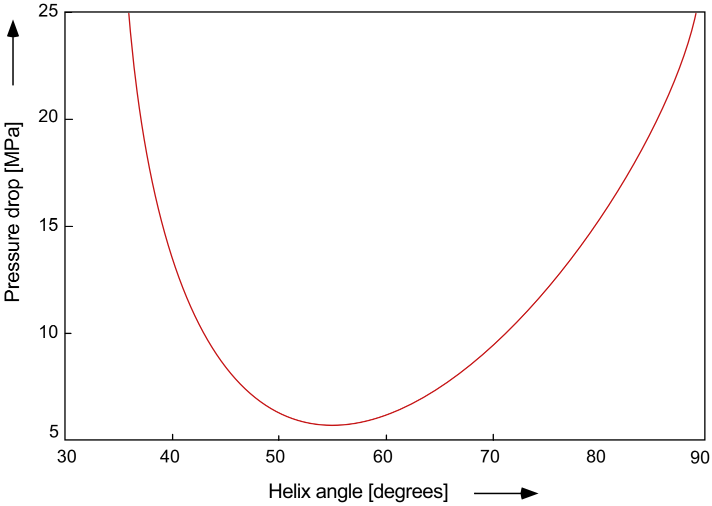

Figure 3.63 Pressure drop versus helix angle for a Newtonian fluid

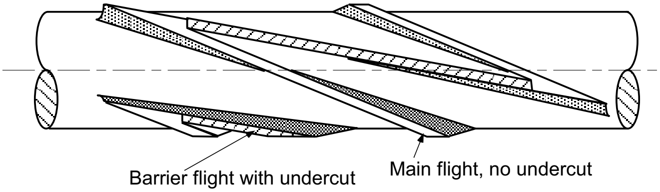

Figure 3.64 Zorro mixing section

The strong influence of helix angle on pressure drop is illustrated graphically in Figure 3.63. Clearly, a 90° helix angle (as in the LeRoy or Maddock mixer) is not a good choice in terms of pressure drop. Likewise, a 30° helix angle (as in the Egan mixer) is not a good choice either. The optimum helix angle is approx. 50°, and less than 50° for non-Newtonian fluids. The optimum helix angle depends on the degree of non-Newtonian behavior, and for typical plastics, the optimum angle is approx. 45°.

To promote good streamlining, the helix angle of the barrier flight can be made larger than the main flight, as shown in Figure 3.64. This makes the entry channel wide at the entrance and the exit channel wide at the exit. To minimize hangup, the channels should taper to zero depth at the end of the entry channels and at the beginning of the exit channels. The geometry of this Zorro mixing section is shown in Figure 3.64.

Planetary Gear Mixers

Planetary gear mixers have six or more planetary screws that revolve around the circumference of the main screw. The planetary barrel section must have helical grooves corresponding to the helical flights on the planetary screws. The planetary barrel section is generally separate, with a flange-type connection to the other barrel section (Figure 3.65). These machines are commonly used in Europe, but not commonly used in the United States. Some of the benefits of planetary gear mixers are:

- Good homogeneity of the melt at low temperature level
- Uniform shear exposure
- High output per screw revolution
- Low production cost per unit throughput
- Self-cleaning action for easy material change
- Good dispersive and distributive mixing of various additives

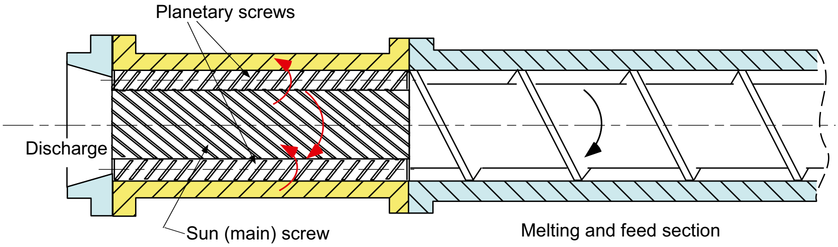

Figure 3.65 Schematic of planetary gear mixer

These characteristics make the planetary gear extruders well suited for foam extrusion and processing of heat-sensitive materials, such as rigid and flexible PVC. They are also used to process blends (e.g., PVC and ABS), powder coatings, epoxy, polyester, acrylic, polyurethane, and chlorinated polyethylene.

The Chris Rauwendaal Dispersive (CRD) Mixer

Current dispersive mixers have two important drawbacks. First, they rely mostly on shear stresses to disperse materials rather than on elongational stresses; and second, the material passes over the high stress region only once. New mixing technology developed by Rauwendaal eliminates the disadvantages of existing dispersive mixers [133–139]. The CRD mixer uses a slanted pushing flight flank to create a wedge-shaped lobal region (Figure 3.66).

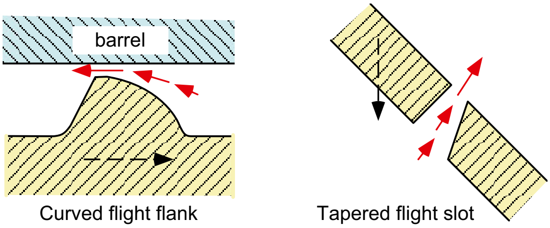

Figure 3.66 Wedge-shaped regions in CRD mixer

The flights in the CRD mixer are slotted to improve the distributive mixing capability; the slots are not straight but tapered. As a result, the fluid accelerates as it passes through the slots and thus is exposed to elongational flow. Therefore, the fluid is exposed to elongational stress as it flows over the mixing flights, and again when it passes through the slots in the flights. It is important to incorporate good distributive mixing in a dispersive mixing element to randomize the fluid. This ensures that all fluid elements are exposed to the mixing action several times.

The wedge shape creates strong elongational flow. The CRD mixer uses multiple mixing flights with a relatively large flight clearance to ensure that all fluid elements pass through the high stress region several times. Figure 3.67 shows a CRD5 mixer which has four flights with tapered slots. One out of four flight segments is a wiping flight section. The wiping flight sections are staggered in such a way that the mixer completely wipes the barrel.

Because of the large clearances of the mixing flights, wiping flights are used to avoid a stagnant film at the barrel surface and improve pumping. The wiping flights can be continuous flights, as in the CRD8 mixer, or wiping flight segments, as in the CRD5. The CRD8 mixer (Figure 3.68) has eight flights, six mixing flights and two wiping flights. All the flights are slotted to provide the best possible mixing action. Mixers with separate wiping flights are easier to manufacture than mixers that have wiping segments along the mixing flights. Good wiping action is important in maintaining good heat transfer characteristics in the mixing section.

in the extrudate or in the final product. In this case, two dispersive mixers could be used without problems because of the low melt viscosity (high melt index) of the polymer. Low melt viscosity raises little concern regarding an increase in temperature due to viscous dissipation.

Table 4.7 Data of New Mixing Screw

Diameter, mm	60
Total length, *L*/*D*	30
Feed zone:	
Channel depth, mm	12
L/*D*	10
Barrier melting zone:	
L/*D*	14
Dispersive mixing zone:	
Channel depth, mm	8
L/*D*	4
Distributive mixing zone:	
Channel depth, mm	8
L/*D*	2

■ 4.5 Plastic Film with Poor Transparency

4.5.1 Description of the Problem

This case involved a PP film manufactured in a cast film line. The mono-layer was made of homopolymer PP (natural). The film was extruded on a 120-mm single-screw extruder with L/D = 28. The polymer stream flowed into a feed block, and from there to a cast film die. The extrusion line was fully instrumented.

The film exhibited a serious appearance problem, in this case poor transparency. The film looked opaque throughout the entire roll. The extruder operating conditions are shown in Table 4.8. The extrusion line had a melt temperature probe at the discharge end of the extruder barrel, just before the screen pack. Melt temperature, measured only at this one location, was 225 °C. The screw design was also checked and its geometry is shown in Table 4.9. The screw geometry indicates a screw design intended for processing polyolefins. The screw compression ratio of 4 is relatively high for polypropylene.

Table 4.8 Operating Conditions of 120-mm Extruder

Screw rotation speed, rpm	170
Extruder back pressure, bar	200
Barrel temperature profile, °C	225 (= feed zone), 225, 215, 215, 215, 215, 215 (= screw tip)
Temperature of polymer granules, °C	30
Melt temperature, °C	225
Output, kg/h	650

Table 4.9 Screw Geometry

Diameter, mm	120
Total length, *L/D*	28
Feed zone:	
Channel depth, mm	21.3
L/D	7
Compression zone:	
L/D	8
Metering zone:	
Channel depth, mm	5.3
L/D	11
Mixing zone:	
Channel depth, mm	20
L/D	2

The first issue was to take into account all the variables related to film transparency in a semi-crystalline material such as PP.

4.5.2 Analysis of the Problem

The problem was visualized based on the fishbone diagram in Figure 4.8, and the variables were checked one by one. Crystallization is a major concern in this case. Therefore, optical microscopy was used to examine the type of crystals occurring in the film under different operating conditions for the extruder and with different cooling rates.

Film manufactured under one specific set of operating conditions was cut to allow examination of the film cross section. A micrograph was taken at 500 × magnification with transmitted and polarized light as illumination (see Figure 4.9). A Leica optical microscope, Laborlux 12 Pol S, equipped with polishing and microtome capability was used for the examination. Transmitted, reflected, and polarized light can be used with this microscope.

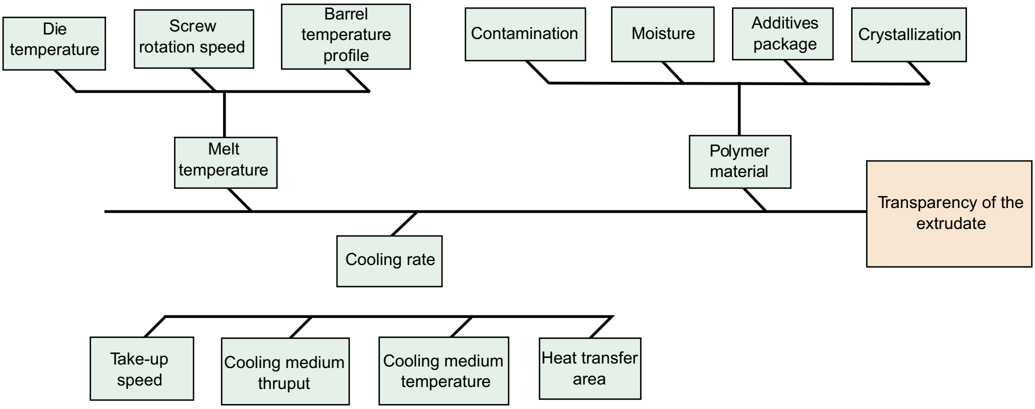

Figure 4.8 Fishbone chart of transparency problem

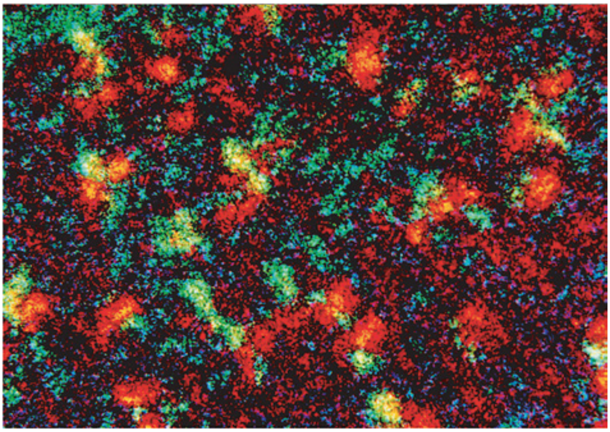

Figure 4.9 Optical micrograph of spherulites in a polypropylene film

The micrograph shows the type of crystals or spherulites in the film. It is possible to observe both amorphous and crystalline regions. Several micrographs of film manufactured at different operating conditions were obtained.

4.5.3 Solution

Crystallization was confirmed as the key variable affecting film transparency based on the micrographs at different line operating conditions. Transparency was better at higher cooling rates and lower chill roll temperatures. The lower limit for

Figure 4.53
Maillefer type dispersive mixer

The melt homogeneity of the polymer blend and the film color were verified by means of optical microscopy and color spectrometer. Agglomerates and striations disappeared and the expected output was obtained for the required production program.

4.19 Instability of Formation at the Die

4.19.1 Description of the Problem

This problem concerned the single-screw extrusion of a PP blend comprised of recycled post-consumer PP and virgin PP material for industrial strapping and banding. The extruder operated with a smooth barrel surface in the feed section. The extrusion line manufactured heavy duty strapping tapes from PP blends in different compositions and colors. The recycled post-consumer PP content in the blend varied between approximately 40 and 60%, depending on product requirements.

The problem presented the following characteristics:

- the extrusion process was unstable,
- instability of formation at the die was noticeable,
- presence of inhomogeneities, e. g., agglomerates visible for several blend compositions, especially at higher amounts of recycled PP, and
- variations in mechanical resistance of the tapes.

These tapes were produced in 0.5 mm and 0.8 mm thickness and 13 mm width. A simultaneous extrusion of two tapes was required (e. g., two-cavity die). A subsequent drawing process was necessary to achieve the desired mechanical strength and stiffness of the tapes.

A minimum extruder output of 60 kg/h was considered. A melt temperature below 220 °C was a condition for a successful subsequent drawing process (e. g., drawing ratio 10 : 1).

The performance of an extrusion line is strongly dependent on the interaction between extruder and extrusion die, in particular when using a conventional extruder with a smooth barrel. With regard to the design of an extrusion die, following key criteria should be taken into account [172]:

- The pressure drop is an important parameter, because it is related directly to output and melt temperature difference.
- Ensuring that the melt emerges from the die at the same average rate all across the outlet cross section.
- The surface of the extrudate and/or the interfaces of the melt layers should remain smooth at operating conditions (e. g., within the processing window). Flow anomalies and/or stagnations should be avoided along the die length.

4.19.2 Analysis of the Problem

This tape extrusion case presented an interaction of extruder and extrusion die, where the operation of the main components, screw and die, suffered from a deficient design. In addition, there was a source of visible inhomogeneities of various types caused by recycled post-consumer PP.

The solution was visualized based on the problem tree showed in Figure 4.54, considering each one of the potential causes. A problem tree is a problem analysis tool that illustrates the cause and effect relationship of problem(s) using a hierarchical tree diagram.

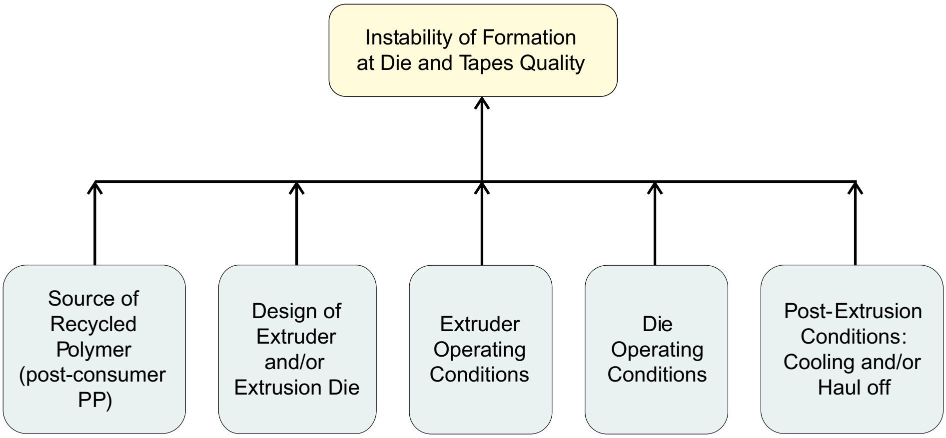

Figure 4.54 Problem tree for instability of formation at die

Setup and operating conditions were checked; it was discovered that the melt temperatures were too high (above 240 °C), affecting extrudate cooling and other post-extrusion processes. The original screw (*D* = 63.5 mm, *L*/*D* = 30.9) was a conventional screw with square pitch and a compression ratio of 2.8 : 1. This screw had an inefficient mixer for dispersion of agglomerates located at the end of the compression zone. Figure 4.55 shows the geometry of the original screw.

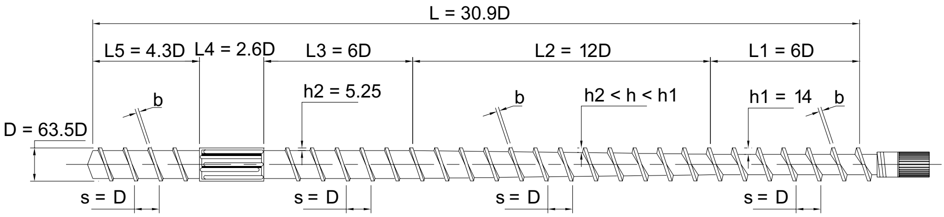

Figure 4.55 Original 63.5-mm screw

A capillary rheometer was used to obtain complete viscosity curves at three temperatures. Measurements for a polymer blend comprising recycled post-consumer PP were carried out at 200, 220, and 240 °C. Figure 4.56 presents the corrected viscosity curves at three temperatures for a specific PP blend composition. These viscosity curves were strongly affected by the content of recycled PP.

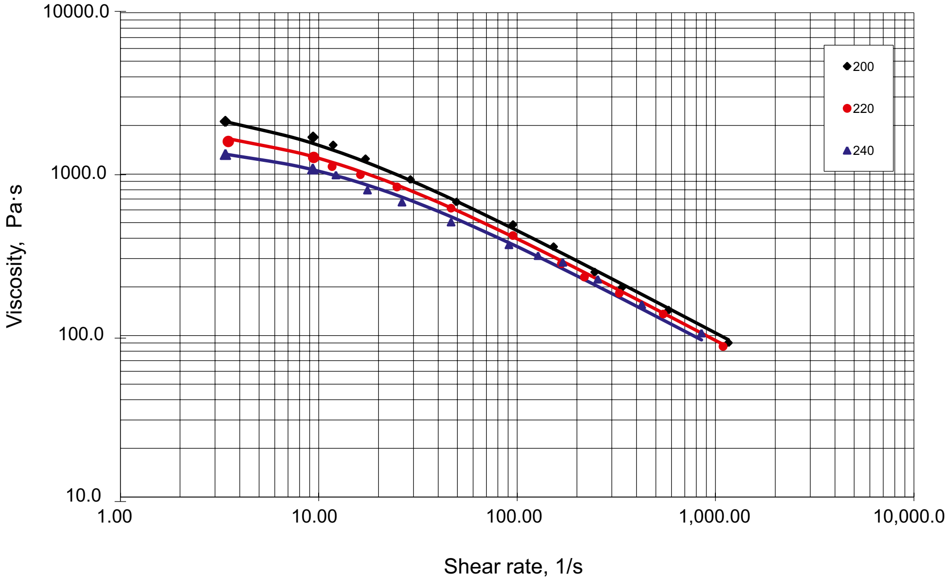

Figure 4.56 Viscosity curves of blend with recycled PP content

4.19.3 Solution

The solution was visualized based on previous information, computer simulations, extrusion line trials, IR thermography, and the problem tree shown in Figure 4.54. Each of the causes was analyzed, focusing on a new screw design suitable for a new two-cavity die.

The newly designed single-screw needed to achieve 60 kg/h output and sufficient mixing to avoid the presence of inhomogeneities or agglomerates caused by recycled PP. Therefore, a variable pitch screw was designed ($D = 63.5$ mm, $L/D = 30.9$), including a 4D dispersive mixer of Maillefer type and a 2D distributive mixer of Saxton type. Figure 4.57 shows the new optimized design delivering, both in simulations and final trials, a higher output of 60 kg/h at 112 rpm. A uniform rate of molten material could be conveyed to the extrusion die.

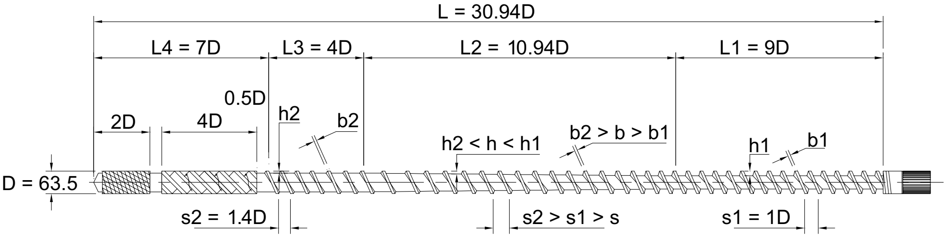

Figure 4.57 New 63.5-mm variable pitch screw

The new two-cavity die was designed to achieve the same 60 kg/h output with a 2.3 mm die gap for manufacturing both tape sizes (0.5 mm and 0.8 mm thickness and 13 mm width). Figure 4.58 shows the calculated pressure drop along the die length. A pressure drop of approx. 65 bar was predicted and obtained in final trials with small deviations. A low melt temperature increase (less than 5 °C) was observed because of low viscous dissipation.

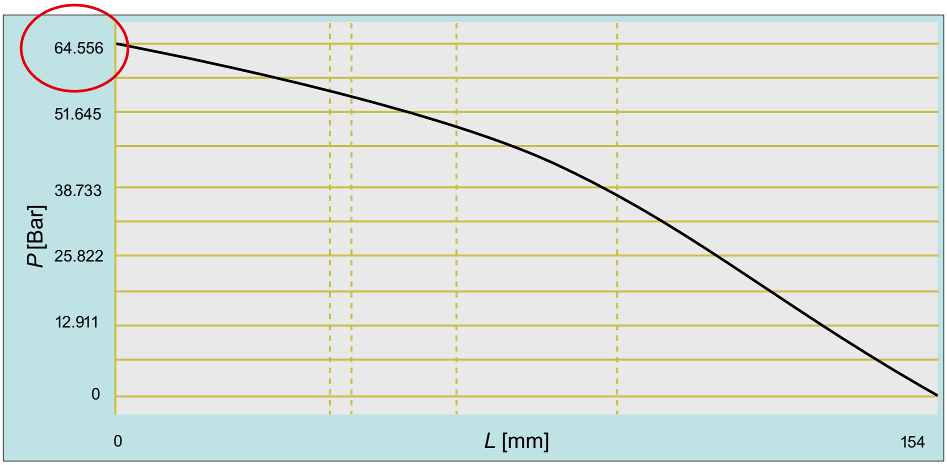

Figure 4.58 Calculated pressure drop along the die length

Figure 4.59 provides important information with regard to flow front velocity at the die exit. It shows that the melt front velocity was the same for the two die cavities. The simultaneous and uniform tape extrusion was a requirement in this case. The final trials showed a successful uniform extrusion of tapes.

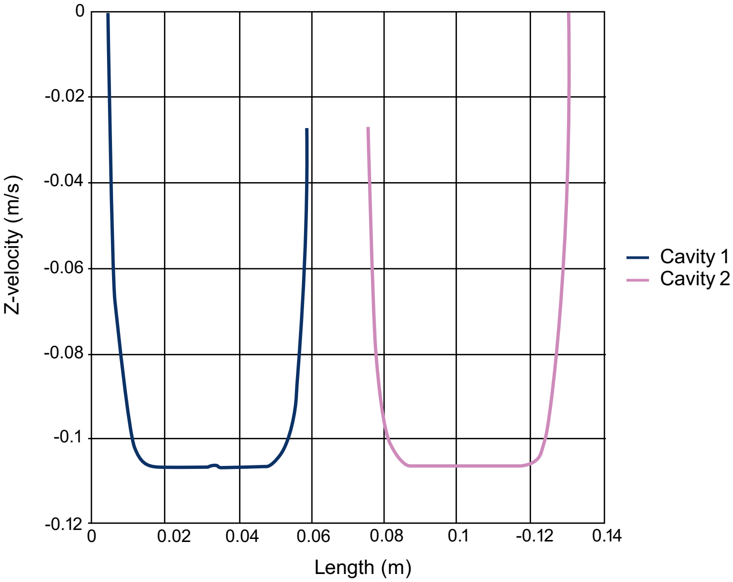

Figure 4.59 Flow front velocity for two-cavity die

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