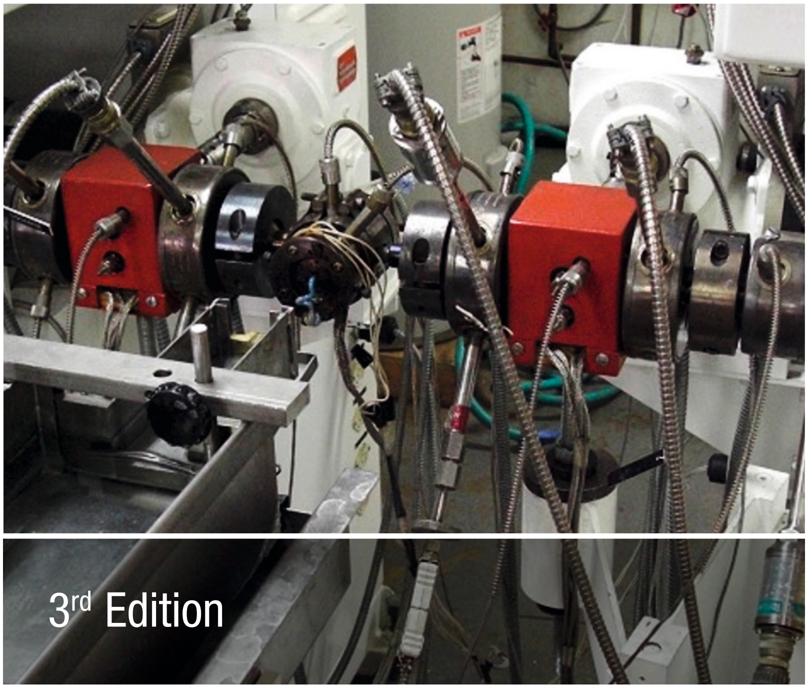
Chris Rauwendaal

Understanding Extrusion



3rd Edition

HANSER

Rauwendaal

Understanding Extrusion

Chris Rauwendaal

Understanding Extrusion

3rd Edition

HANSER

Hanser Publishers, Munich

Hanser Publications, Cincinnati

The Author:

Dr. Chris Rauwendaal, 10556 Combie Road PMB 6677, Auburn, California 95602, USA

Distributed in the Americas by:
Hanser Publications
6915 Valley Avenue, Cincinnati, Ohio 45244-3029, USA
Fax: (513) 527-8801
Phone: (513) 527-8977
www.hanserpublications.com

Distributed in all other countries by:
Carl Hanser Verlag
Postfach 86 04 20, 81631 Munich, Germany
Fax: +49 (89) 98 48 09
www.hanser-fachbuch.de

Cataloging-in-Publication Data is on file with the Library of Congress

Editor: Dr. Julia Diaz-Luque
Production Management: Jörg Strohbach
Coverconcept: Marc Müller-Bremer, www.rebranding.de, Munich
Coverdesign: Stephan Rönigk
Typesetting: Kösel Media GmbH, Krugzell
Printed and bound by Kösel GmbH, Krugzell
Printed in Germany

ISBN: 978-1-56990-698-9
E-Book ISBN: 978-1-56990-699-6

Preface to the Third Edition

The first edition of Understanding Extrusion was published in 2000 and the second edition in 2010. Since the second edition was issued several important developments have taken place. As a result, it makes sense to have a third edition of Understanding Extrusion.

Most of the new material is incorporated in Chapter 2. Topics included in this chapter are interpretation of extrusion process data, dimensional variation by melt temperature fluctuations, efficient extrusion, and more. Chapters 7 and 8 have also been extended and now cover topics such as analysis of shrink void formation and grooved barrel extruder technology.

I would like to thank Dr. Mark Smith for his encouragement to work on this third edition. I also want to thank my wife Sietske for her continued support and for putting up with me despite these time-consuming projects.

Chris Rauwendaal

September 2018

Contents

1 Extrusion Machinery

In this chapter we will discuss extrusion machinery, including:

- a description of an extruder
- different types of extruders
- components of an extruder

1.1 What is an Extruder?

To describe what an extruder is, we first need to define some related terms. First, to extrude is to push out. When a material is extruded, it is forced through an opening called the die. For instance, when we squeeze toothpaste from a tube, we extrude toothpaste. As the material flows through the die, it acquires the shape of the die flow channel. A machine that is used to extrude a material is called an extruder. Many different materials can be extruded, including clays, ceramics, food, metals, and of course, plastics. Definition

The main function of an extruder is to develop sufficient pressure in the material to force the material through the die. The pressure necessary to force a material through the die depends on the geometry of the die, the flow properties of the material, and the flow rate. Basically, an extruder is a machine capable of developing pressure. In other words, an extruder is a pump. A plastics extruder is a pump for plastic materials. However, this is not to be confused with a plasticating extruder, which is a machine that not only extrudes but also plasticates, or melts, the material. A plasticating extruder is fed with solid plastic particles and delivers a completely molten plastic to the die. On the other hand, a machine that extrudes molten plastic without melting it is called a melt-fed extruder. Function

Extruders are the most common machines in the plastics processing industry. Extruders are not only used in extrusion operations; most molding operations also use an extruder, for instance, injection molding and blow molding. Essentially every plastic part has gone through an extruder at one point or another; in many cases, more than once.

1.2 Different Types of Extruders

In this section we will discuss:

- single screw extruders
- twin screw extruders
- ram extruders

1.2.1 Single Screw Extruders

Extruder types

In the plastics industry, there are three main extruder types: the screw extruder, which is the most common one, the ram extruder, and the drum or disk extruder, which is the least common. In a screw extruder a screw rotates in a cylinder; the rotation of the screw creates a pumping action, see Figure 1.1.

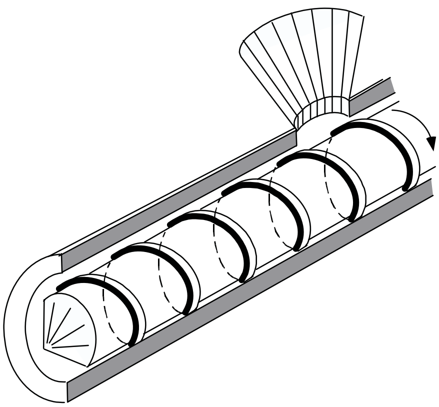


Figure 1.1
A single screw extruder

1.2.2 Twin Screw Extruders

A screw extruder can have one screw or more than one screw. An extruder with one screw is called a single screw extruder; it is the most common machine in the plastics processing industry. An extruder with more than one screw is called a multi-screw extruder. The most common multi-screw extruder is the twin screw extruder with its two screws.

1.2.2.1 Co-Rotating Twin Screw Extruders

Screw rotation

There are several types of twin screw extruders. In most twin screw extruders, the screws are located side by side. If both screws rotate in the same direction, the extruder is called a co-rotating twin screw extruder, see Figure 1.2.

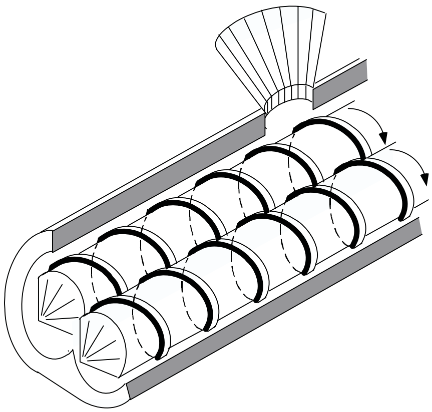


Figure 1.2
A co-rotating twin screw extruder

1.2.2.2 Counter-Rotating Twin Screw Extruders

If the screws of a twin screw extruder rotate in opposite directions, it is called a counter-rotating twin screw extruder. Twin screw extruders can run at high or low speed, depending on the application. High speed extruders run at around 200 to 500 rpm, sometimes even higher; they are primarily used in compounding. Low speed extruders run at about 10 to 40 rpm and are used mostly in profile extrusion applications.

Most twin screw extruders for profile extrusion are counter-rotating extruders. This is because counter-rotating extruders tend to have better conveying characteristics than co-rotating extruders. Most twin screw extruders have parallel screws, but some extruders have conical screws, where the screws are not parallel, see Figure 1.3.

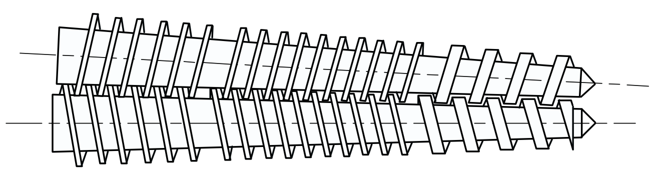


Figure 1.3 Conical twin screw extruder

Degree of intermeshing

Another distinguishing feature of twin screw extruders is the extent to which the screws intermesh. The screws can be fully intermeshing, see Figure 1.4a, partially intermeshing, see Figure 1.4b, and non-intermeshing, see Figure 1.4c.

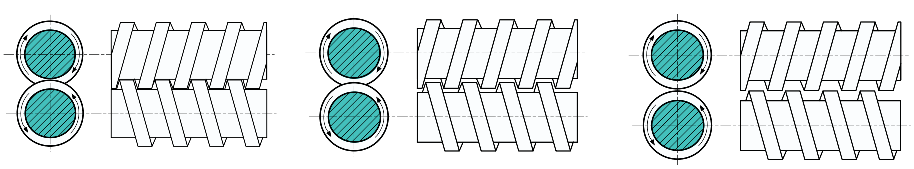


Figure 1.4 **(a)** Fully intermeshing counter-rotating screws; **(b)** partially intermeshing counter-rotating screws; **(c)** non-intermeshing (tangential) counter-rotating screws

Length-to-diameter ratio

Most twin screw extruders are intermeshing. The advantage of non-intermeshing twin screw extruders is that they can be very long yet avoiding problems with metal-to-metal contact between the screws. The length-to-diameter (L/D) ratio can be 100:1 and higher. The L/D of intermeshing twin screw extruders is generally limited to values less than 50:1. A disadvantage of current non-intermeshing twin screws is that they have limited dispersive mixing capability; however, new dispersive mixing technology described in Chapter 5 may negate this limitation.

1.2.3 Ram Extruders

In a ram extruder, a reciprocating piston forces the material forward and through the die, as shown in Figure 1.5.

High pressure, low melting capacity

Ram extruders have very good conveying characteristics and can develop very high pressures. The drawback of ram extruders is that they have low melting capacity. Therefore, they are not used very often for normal plastics. There are some unusual plastics, however, that are often processed on a ram extruder, such as the so-called "intractable" plastics that cannot be processed on normal extruders. Examples of such plastics are PTFE (poly-tetra-fluoro-ethylene) and ultra high molecular weight (UHMW) polyethylene. These plastics do not melt like normal plastics and are formed by sintering. Continuous products can be made on a ram extruder, although the line speeds are quite low – typically in the range of 25 to 75 cm per hour (10 to 30 inches per hour).

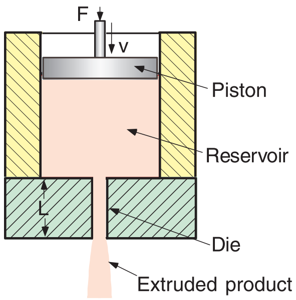


Figure 1.5
Schematic of a ram extruder

1.3 Components of an Extruder

In this section we will discuss:

- the extruder screw
- the extruder barrel
- the feed throat
- the feed hopper
- barrel heating and cooling
- the breaker plate
- the screen pack
- the extrusion die
- the extruder drive
- the reducer
- gear pumps
- instrumentation and control

1.3.1 The Extruder Screw

The heart of the extruder is the extruder screw. This is a long cylinder with a helical flight wrapped around it, see Figure 1.6. The screw is very important because conveying, heating, melting, and mixing of the plastic are mostly determined by the screw. The stability of the process and the quality of the extruded product are very much dependent on the design of the screw. The screw rotates in a cylinder that fits closely around it.

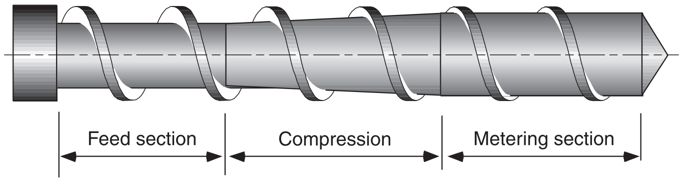


Figure 1.6 A single flighted extruder screw

1.3.2 The Extruder Barrel

The cylinder is called the extruder barrel. The barrel is a straight cylinder usually equipped with a bimetallic liner; this liner is a hard, integral layer with high wear resistance. In most cases, the wear resistance of the barrel should be better than that of the screw. The reason is that the screw is much easier to rebuild and replace than the barrel. Bimetallic barrels usually cannot be rebuilt.

Functions

The barrel may have a vent opening through which volatiles can be removed from the plastic, see Figure 1.7, a process called devolatilization. An example is the removal of moisture from a hygroscopic plastic. An extruder with a vent port should use a special screw geometry to keep the plastic melt from coming out of the vent port; such a screw is called a “two-stage screw,” see Figure 1.7.

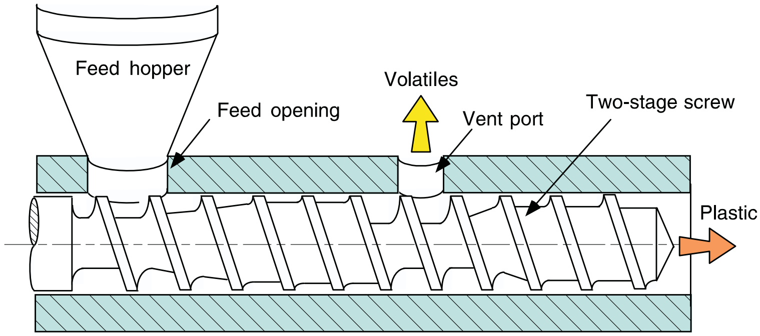


Figure 1.7 A vented extruder barrel with a two-stage screw

1.3.3 The Feed Throat

Material intake

The feed throat is connected to the barrel; it contains the feed opening through which the plastic material is introduced to the extruder. The feed throat usually has water-cooling capability because we have to be able to keep the feed throat temperature low enough to keep the plastic particles from sticking to the wall. To improve the intake capability of the feed throat, the feed opening can be offset as shown in Figure 1.8 and have an elongated shape. The length of the feed opening should be about 1.5 times the diameter of the barrel and the width about 0.7 times the diameter.

Some extruders do not have a separate feed throat, but the feed opening is machined right into the extruder barrel. There are both advantages and disadvantages to such a setup. The advantages are lower cost, fewer parts, and no problems with alignment of the barrel to the feed throat. Disadvantages are that it is more difficult to create a thermal barrier between the hot barrel and the cold feed throat region and good cooling of the feed throat region is more difficult.

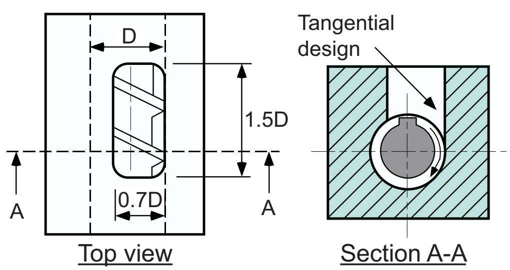


Figure 1.8 Preferred geometry for feed opening in the feed throat

1.3.4 The Feed Hopper

The feed throat is connected to the feed hopper and the extruder barrel. The feed hopper holds the plastic pellets or powder and discharges the material into the feed throat. The hopper should be designed to allow a steady flow of material. Steady flow is best achieved with a circular hopper with a gradual transition in the conical section of the hopper, see Figure 1.9.

Conveying material

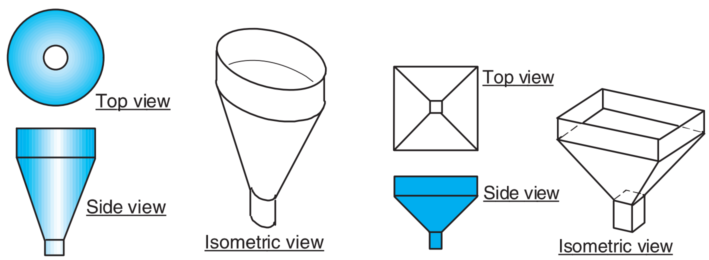


Figure 1.9 Good hopper design (left) and bad hopper design (right)

For difficult bulk materials, special devices can be used to promote steady flow through the hopper; such as vibrating pads, stirrers, wipers, and even crammer screws to force the material to the discharge, see Figure 1.10.

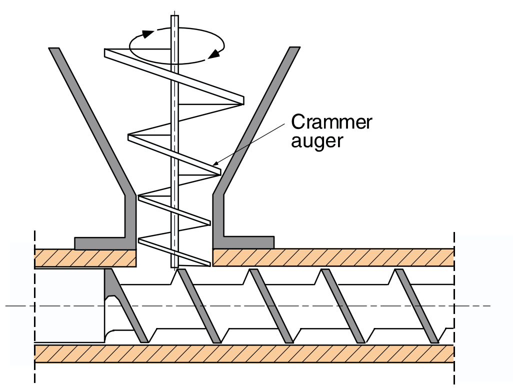


Figure 1.10 Example of crammer feeder

1.3.5 Barrel Heating and Cooling

The extruder barrel has both heating and cooling capability. Heating is usually done with electrical band heaters located along the length of the extruder. The heaters can be mica insulated heaters, ceramic heaters, or cast-in heaters. In cast-in heaters, the heating elements are cast in a semi-circular block of aluminum or bronze; these heaters provide good heat transfer. Aluminum cast heaters can heat up to 400 °C, while bronze cast heaters have a maximum operating temperature of about 550 °C. Other types of heating can be used, such as induction heating,

Various heating methods

radiation heating, and fluid heating. Induction and radiation heating are not commonly used; fluid heating is used in rubber extrusion and on some older plastic extruders.

Most extruders have at least three temperature zones along the length of the barrel. Long extruders may have eight temperature zones or more. Each zone has its own heating and cooling capability and at least one temperature sensor to measure the zone temperature. The temperature is usually measured in the barrel. The die may have one or several temperature zones, depending on its complexity. Some dies have more than ten temperature zones. Dies have heating capability, but usually do not have cooling.

Cooling methods

The barrel has to be cooled if the internal heat generation in the plastic raises the barrel temperatures above the setpoint. This is likely to occur when extruding high viscosity plastics and when running at high screw speeds. Cooling on single screw extruders is usually done with air. Blowers are placed under the extruder barrel and temperature zones are partitioned, so that one blower cools only one temperature zone, see Figure 1.11.

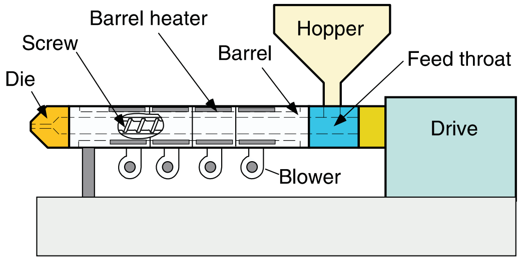


Figure 1.11 Extruder with barrel heaters and blowers for cooling

Water cooling can be used as well, particularly if large amounts of heat must be removed. The extrusion process normally runs best when the screw supplies most of the energy needed in the process, so that little additional heating or cooling needs to be done through the barrel. As a result, air cooling is sufficient for most extrusion operations using single screw extruders. Since water cooling removes heat more quickly, it can be more difficult to maintain good temperature control with water cooling. Oil cooling can be used as well; in fact, oil can be used both for heating and cooling.

Barrel vs. plastic temperature

With barrel cooling, it is important to realize that even if the temperature is at its setpoint, the actual melt temperature is above the setpoint. With barrel cooling on, the heat flows from the plastic through the barrel to the outside. In this situation, the highest temperature occurs in the plastic. Even if the barrel temperature is at setpoint, the plastic temperature can be substantially higher. Therefore, barrel cooling should be minimized if possible.

1.3.6 Screw Heating and Cooling

The screw of an extruder is usually neither heated nor cooled; such a screw is called a "neutral screw." However, it is possible to either heat or cool the screw by coring the screw (making it hollow) and circulating a heat transfer fluid through the hollow section, see Figure 1.12.

Temperature control of the screw

The screw can also be heated by a cartridge heater. The heater's electrical power has to be supplied through a slip ring assembly at the drive end of the screw. If the cartridge heater is equipped with a temperature sensor, the power to the heater can be controlled to maintain a constant temperature.

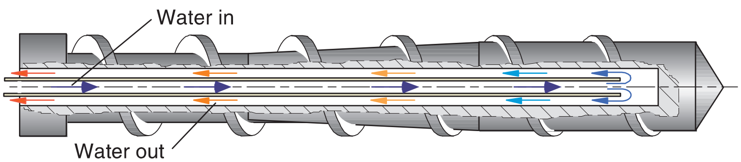


Figure 1.12 Circulating a heat transfer fluid through the screw

1.3.7 The Breaker Plate

The breaker plate is located at the end of the barrel. It is a thick metal disk with closely spaced holes as shown in Figure 1.13.

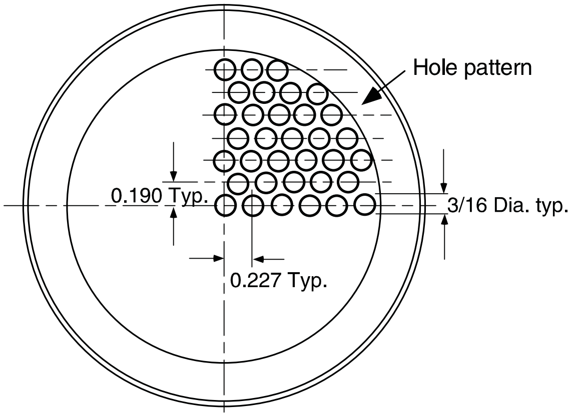


Figure 1.13 Example of a breaker plate

The main purpose of the breaker plate is to support a number of screens, located just ahead of the breaker plate. The screens are used to trap contaminants so they do not end up in the extruded product. Usually, several screens are stacked together starting with a coarse screen followed by increasingly finer screens and then a coarse screen again right up against the breaker plate. The plastic melt thus flows

Trap for contaminants

through screens with increasingly smaller openings. The last coarse screen acts merely as a support for the finer screens. The collection of screens is called the screen pack.

1.3.8 The Screen Pack

Mesh rating

The screen pack is not only used to trap contaminants; in some cases the restriction of the screen pack is increased to increase mixing in the extruder. This works to some degree; however, the mixing can be improved more efficiently by adding mixing sections to the extruder screw, as discussed in Chapter 5. The most common filters are wire mesh screens. The mesh number of the screen represents the number of wires per inch (25 mm). The higher the mesh, the more wires per inch and the smaller the openings of the screen.

Figure 1.14 shows the relationship between the mesh value of the screen and the micron rating. The micron rating indicates what size particles the screen is able to trap. The higher the mesh, the lower the micron rating and, therefore, the finer the screen. A typical screen pack can consist of a 20-mesh screen, followed by a 40-, 60-, and 80-mesh screen with a final 20-mesh screen for support against the breaker plate.

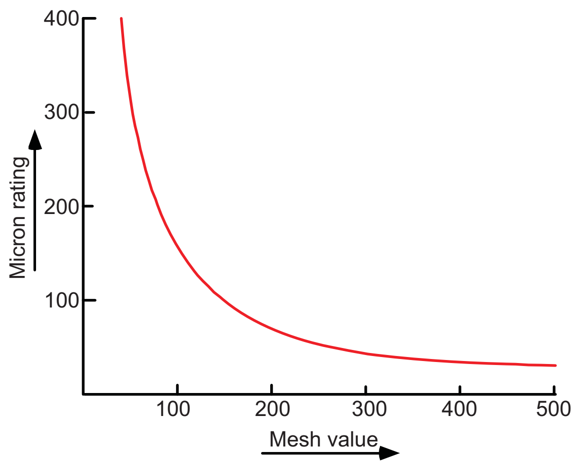


Figure 1.14 The micron rating vs. the mesh value for wire mesh screens

Filter materials

There are a number of different filter materials. Wire screens are the most common. Several types of wire screens are available, such as the square mesh with plain weave and the square mesh with Dutch twill. There are also depth filtration media, such as sintered metal powder and random metal fibers. Advantages and disadvantages of different filter materials are shown in Table 1.1.

Other filter materials used in some cases are plates with small holes and filters made of sand. Plates with small holes are useful in filtering out coarse contaminants and, for that reason, are used for pre-filtration. Sand is inexpensive and because of the large volume, sand filters can operate for long periods before they have to be changed. A drawback of sand is that the filtration action is not uniform. Also, the run-in period for sand filters can be long and the installation is complicated.

Filter performance

Table 1.1 Comparison of Different Filter Media

	Wire mesh square weave	Wire mesh Dutch twill	Sintered metal powder	Random metal fibers
Gel capture	Poor	Fair	Good	Very good
Contaminant capacity	Fair	Good	Fair	Very good
Permeability	Very good	Poor	Fair	Good
Price	Low	Fair	High	High

1.3.8.1 Screen Changers

Fast screen exchange

In some cases, screens have to be replaced at short intervals, for instance, every two hours. This may happen when the plastic contains a substantial level of contaminants. In such a situation, it can be advantageous to use a screen changer, which is a device that allows a quick change of the screens. Some screen changers allow the extruder to keep running while the screens are changed; these are called continuous screen changers. Screen changers are useful when pressure increases rapidly at the screens. Screen changers can be manual or automatic. In many automatic screen changers, the screens are changed when the pressure drop across the screens reaches a preset value.

Types of screen changers

There are various types of screen changers, including manual screen changers, hydraulic screen changers, semi-continuous screen changers, screen changers with a continuous moving screen, and rotary type screen changers. Manual screen changers are used on smaller extruders, up to about 90 mm or 3.5″. They use a slide plate design with two circular screen blocks; one is in the melt flow at all times. When the pressure builds up to a certain level, the operator uses a hand lever to insert a new screen block.

Hydraulic screen changers use a hydraulic ram to push the block containing a new screen into the melt stream, see Figure 1.15. They can be used with larger extruders. Semi-continuous screen changers allow the screen to be changed without affecting the melt flow. In most units, trapped air is prevented from going into the melt stream by a bleed valve. Even if the entrapped air can be eliminated completely, there may still may a pressure spike when a new screen is moved into position.

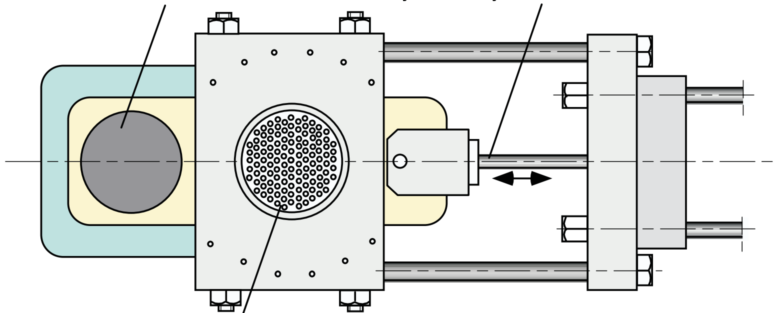


Figure 1.15 Typical slide plate screen changer

Continuously moving screen

In screen changers with a continuously moving screen, a continuous band of screen material passes across the melt flow at a speed determined by the pressure difference across the screen. The rotary screen changer uses a moving wheel with 10 to 16 kidney-shaped cavities containing the screens. Each cavity moves slowly through the melt stream. This is similar to the continuously moving screen, except that in the rotary screen, the screen itself is not continuous because of the webs between the cavities. The webs, however, are relatively thin, so that at any given time at least 90% of the channel is occupied by the screen. Rotary screen changers use separate screen inserts that are changed by the operator. The advantage of the screen changer with the continuously moving screen and the rotary screen is that pressure disturbances during screen changes are minimized.

1.3.9 The Extrusion Die

Dies for various extrusion products

The die is placed at the discharge end of the extruder. Its function is to mold the flowing plastic into the desired shape of the extruded product. Dies can be categorized by the shape of the product that they produce. Annular dies are used to make tubing, pipe, and wire coating. Slit dies are used to make flat film and sheet. Circular dies are used to make fiber and rod. Profile dies are used to make shapes other than annular, circular, or rectangular. Dies are also named by the product that they produce. So, we talk about tubing dies, flat film dies, blown film dies, etc.

Die flow channel

The inlet channel of the die is usually designed to match the exit of the extruder. If the die entrance does not match the extruder exit, an adapter can be used between the extruder and the die. The three main elements of the die flow channel are the inlet channel, the manifold, and the land region, see Figure 1.16.

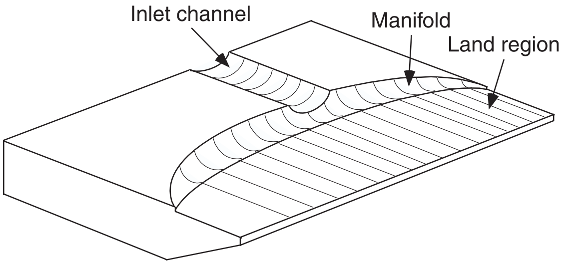


Figure 1.16 The three main elements of an extrusion die

The flow channel of the die should be designed such that the plastic melt achieves a uniform velocity across the die exit. The shape of the land region of the die corresponds to the shape of the extruded product. An example of an inline tube or pipe die is shown in Figure 1.17. The material flows into the die from the extruder; then it flows around a torpedo.

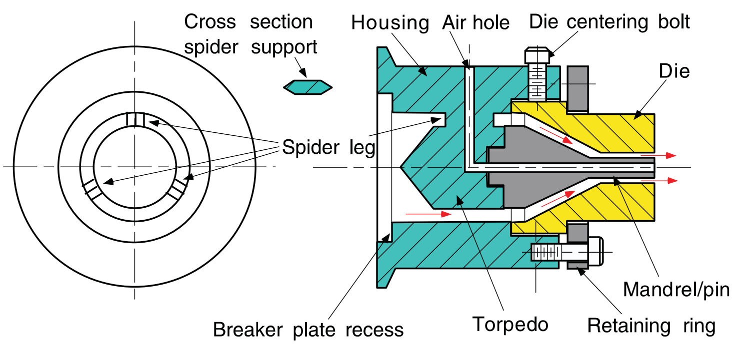


Figure 1.17 Example of inline tubing or pipe die

The torpedo is supported by spider legs that have a streamlined shape to achieve smooth flow around the support legs. From the torpedo, the plastic melt flows to the tip and die, where it is shaped into an annulus, so that a tube-shaped product emerges.

Size and shape of the extruded product

The size and shape of the land region are not exactly the same as the extruded product. There are several reasons for this: drawdown, cooling, swelling, and relaxation. These factors are discussed in more detail in Chapter 5. Because of the several variables affecting the size and the shape of the extruded plastic, it is often difficult to predict how exactly the size and shape of the plastic changes once it leaves the die. As a result, it is also difficult to predict how the die flow channel should be shaped to achieve the desired shape of the extruded product. This is an important reason why die design is still largely based on experience rather than on engineering calculations. With the advent of improved numerical techniques and commercial die flow analysis software, this situation is improving; however, die design is still often a trial and error process.