TECHNICAL WHITEPAPER

Melt Extrusion: The Basic Process

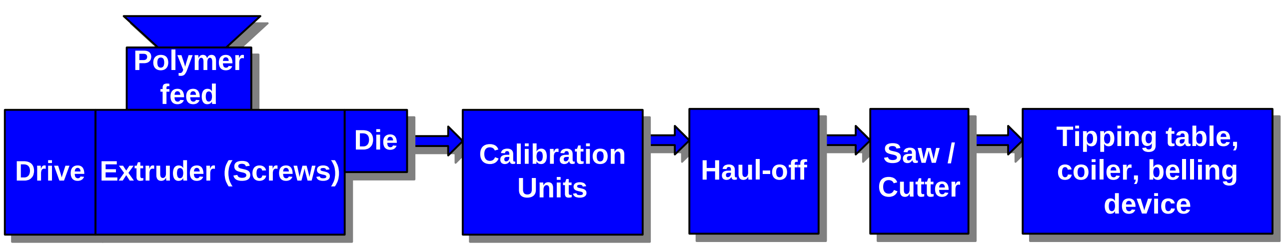
Introduction

Extrusion is used in all methods of polymer processing as either the main method of forming or as the method of transporting and metering the molten plastic before it is formed. The extrusion process is not difficult to visualize and we use it every day when we extrude toothpaste onto our toothbrush. This is analogous to ram extrusion that is used in many applications, but most processing of plastics uses screw extrusion and the best model for this is the meat grinder. The grinder takes in large lumps of meat and uses a screw to reduce the size of the meat, mix it all up, and then extrude the result out as a fine stream of meat through the die at the face of the meat grinder. The very simplicity of these examples might imply that extrusion is simple, but extrusion is as much art as it is science and in many cases it is the last 'black art' of polymer processing. This Newsletter introduces the basics of extrusion and hopefully will throw a little light on what is possible to achieve with this remarkable process.

While extrusion is used for processes as varied as wire coating and film blowing, this Newsletter will concentrate on profile extrusion, one of the largest volume areas of extruded products.

The extrusion line

The components of the extrusion line are relatively similar regardless of the type of extruder. A typical layout is shown diagrammatically below.



The basic components of an extrusion line

A typical extrusion line consists of the material feed hopper, basic extruder (drive, gearbox and screws), the extrusion die, the calibration units, the haul-off, the saw (or other cutting device), and finally the treatment devices for final finishing and handling.

The hopper holds the raw plastic material (in either powder or granule form) and continuously feeds this into the extruder, which has a heated barrel containing the rotating screw. This screw transports the polymer to the die head and simultaneously the material is heated, mixed, pressurized and metered. At the die the polymer takes up the approximate shape of the article and is then cooled either by water or air to give the final shape. As the polymer cools it is drawn along by haul-off devices and either coiled (for soft products) or cut to length (for hard products).

The components in detail

The extruder motor is electrical in operation and connected to the extrusion screw via a gearbox and drive belt system. The screw is pushing resin out of the extruder under high pressure where Newton's law states there must be an equal reaction of the screw driving backwards in the machine. A high load thrust bearing is used to support the rearward force on the screw. The polymer feed to the screw is from the feed hopper, and the feed may be by gravity, metering screw or simple conveying spiral. The feed must be consistent to avoid too much air being drawn into the extruder throat.

The extruder barrel and screw are of high strength steels and are protected from wear and corrosion by a variety of hardening and coating treatments such as nitriding and hard chroming. The barrel and screw are usually zoned from three to seven sections which are individually heated and cooled depending on the material and process parameters. In many cases there is no great need for heating because of the shear heating that takes place as the material is moved along the extruder barrel and in some cases the extruder barrel needs to be cooled to prevent overheating of the material. The multiple functions of the extruder screw are given in more detail below.

The melted polymer moves from the front of the screw to a die channel, which forms the basic shape of the desired product. The calibration units stabilize the form of the output to the detailed shape while the polymer is being cooled. Providing the dragging force to overcome the frictional forces in the calibrators, the haul-off pulls the profile through the calibrators and feeds the material to the saw/cutter that cuts the profile to the desired length. Additional operations may be performed in the line or at the end of the line depending on the final product requirements.

Major advances have taken place in all components of the extrusion line in the past decade but perhaps the most important has been in the output rates possible and in the command and control segments of the extruder. The advances in output rates have been driven by the demands of processors and the improved control systems have resulted from the availability of low cost computer processing power.

The functions of the extruder screw

The extruder screw has the following basic functions:

- Bring the feedstock into the extruder and to move the material along the screw while at the same time compressing it and removing volatile gases.
- Soften the melt by heating it (both from internally generated shear forces and additional externally applied heat if required).
- Mix the melt and produce a homogeneous melt without impurities.

- Meter the melt into the die area.
- Apply the constant pressure (free of pulsation) required to force the material through the die.

These functions, at least for the single screw extruder, are generally achieved at different sections of the extrusion screw as the material progresses along the barrel are shown below:

The major functions of the extruder screw

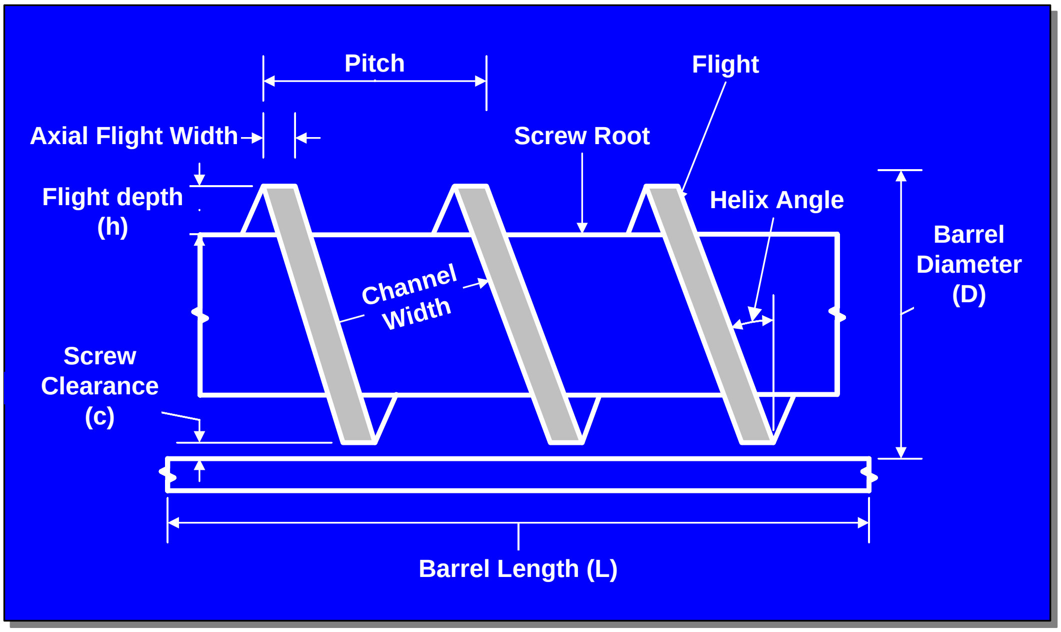
A twin-screw extruder carries out the same functions but they often take place simultaneously.

Key dimension of extruders

The detailed design of an extruder screw is extremely complex in order to perform all the functions required of it. It is useful to understand the main features of the extruder screw in order to understand the process.

In absolute terms probably the most referenced number for extruder specifications is the barrel L/D ratio (barrel length/barrel diameter), as this defines many of the operating characteristics. The L/D ratio is a major factor in the effectiveness of the extruder and of the types of material that it can process. For most extruder types the L/D ratio has increased as technology has advanced. The limitation of high L/D ratios is the torque available from the motor (longer screws mean higher friction), and the capacity of the thrust bearings of the extruder. As advances have been made in these areas, the L/D ratios have steadily increased from approximately 15 in the early 1960s to 30-35 at present.

It is also important to realize that an extruder screw will not have constant dimensions along the length of the screw. The dimensions will change depending on the particular function being carried out by the screw at that stage. As an example, the flight depth will generally decrease in the metering area to provide an accurate material feed rate to the die area. The ratio of depth of the feed section flights to the metering section flights is called the screw compression ratio. Common compression ratios in extruders range from 2 to 4:1. Some of the key dimensions of the extruder screw are shown below.



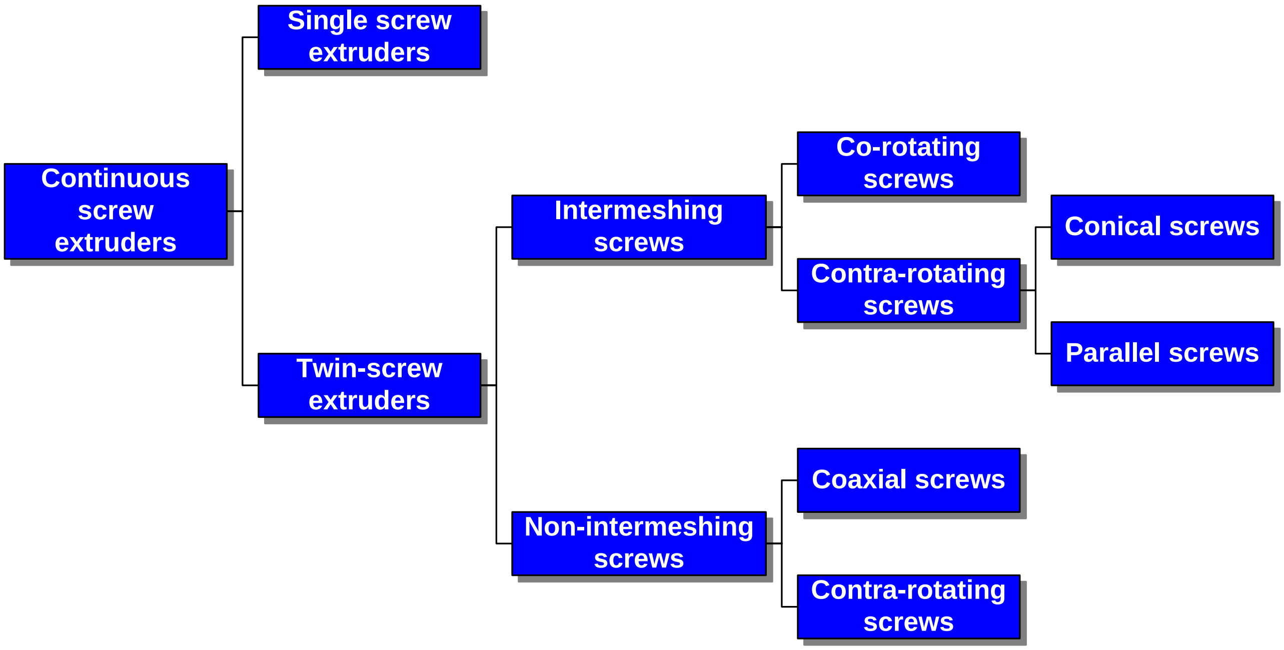
The key dimensions of an extruder screw

Basic extruder types

The basic extruder is available in many different versions depending on the material being processed and the application.

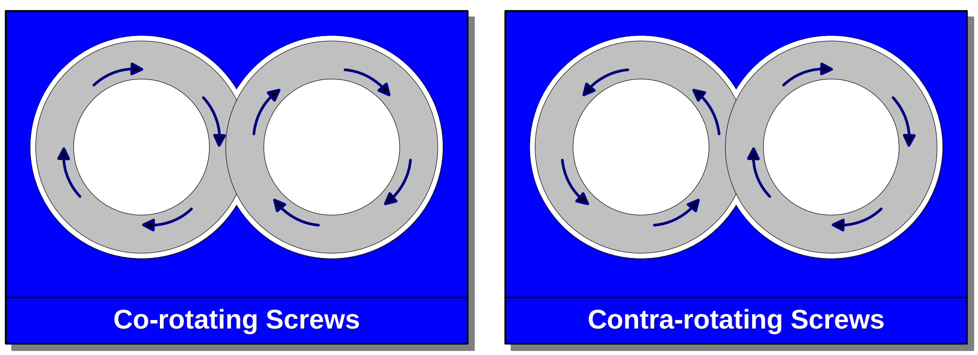
Single screw extruders are generally used for simple extrusions using granules and pre-prepared compounds. The single screw extruder can be regarded as the most basic form of extruder that simply melts and forms the material.

Twin-screw extruders provide excellent mixing of the material as well as being a forming process, and are widely used to process powder blends that need to be thoroughly mixed as well as being melted and formed. The twin-screw extruder is available in a wide variety of formats depending on the manufacturer, and all have been developed to meet specific market needs. The range of formats is shown below.



The main types of extruder

The two main types of screw machines, co-rotating and contra-rotating, have different screw rotations in the barrels and these are shown below.



The development of the conical screw extruder was driven by the need for large thrust bearing at the rear of the machine. This is achieved by using a larger diameter screw at the rear of the extruder, allowing for the use of a larger thrust bearing, and therefore greater output before thrust bearing failure can occur.

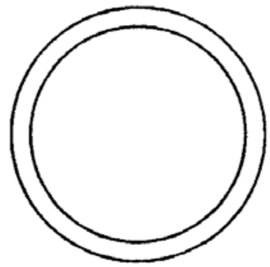
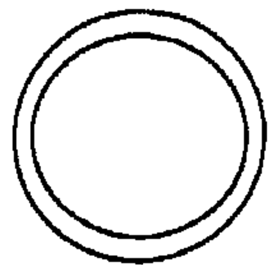
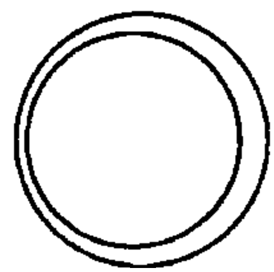
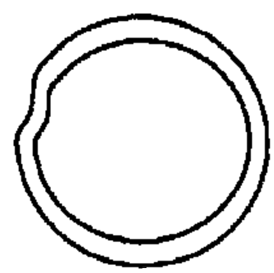
The advantages and limitations of extrusion for product design

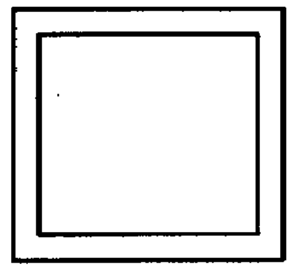
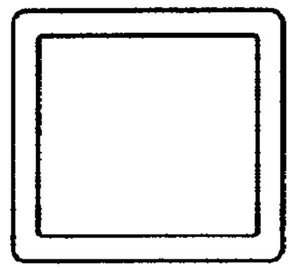
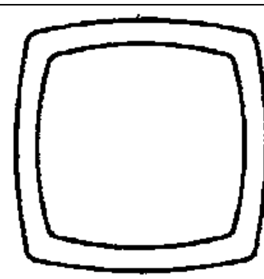
Whichever type of extruder is used, the process has some common features that designers need to understand. These considerations are listed below with some explanatory notes where applicable.

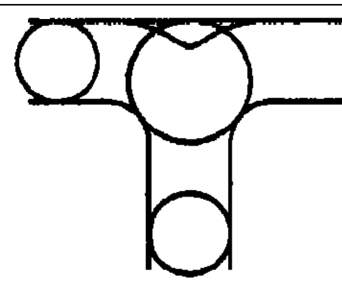
Feature	Result	Notes
Equipment Cost	High	
Tooling Cost	Moderate	
Cycle Time	Continuous	Production rates can be high for tubing (many meters per minute) or low for complex profiles (less than a meter per minute).
Economic Quantity	>5000 m	Extrusion equipment and die costs are high and the minimum economic length is also generally high, i.e. 200,000 cable holders of 10 mm long may appear as a large order but the total extrusion length is only about 2200 m (allowing for the saw cut). Injection molding may well be cheaper and provide more design options. There may also be a minimum order quantity to cover setting up production.
Tolerances and precision	Good	Extrusion can produce excellent repeatability but achievable tolerances may be more difficult. Critical areas should be noted and the producers' advice on achievable tolerances sought. Tolerances of less than +/- 0.01 mm are not generally realistic. The addition of tighter tolerances increases the cost of the product.
Wall Thickness Control	Yes	Good within the achievable tolerances.
Open-ended Hollows	No	Extrusion can generally only produce products that have a constant cross-section.
Enclosed Hollows	No	Extrusion can generally only produce products that have a constant cross-section.
Very Small Items	No	Extrusion can generally only produce products that have a constant cross-section.
Complicated/Intricate Shapes	Yes	Complicated and intricate shapes are easily possible provided they have a constant cross-section.
Large Enclosed Volumes	No	
Inserts	No	
Molded-in Holes	No	
Threads	No	

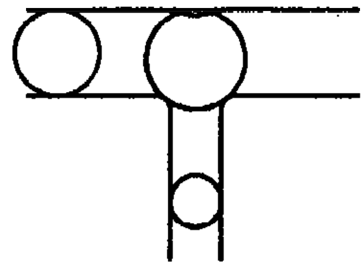
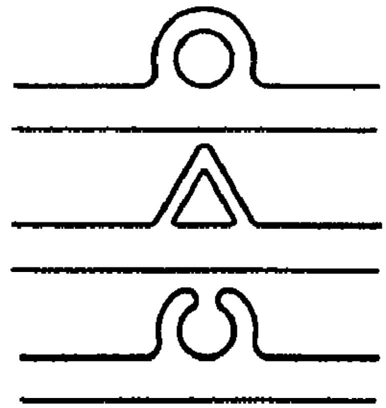
Designing extrusions for production

The design of extruded profiles is not complex but product designers need to be aware of some simple potential problems in order to produce designs that are both economical and easy to manufacture. The table below gives some guidelines for good tubing product design practice.

Wall thickness and stability	
This is the desired output but variations can occur during production even with a simple tube.	
This illustrates a potential concern with thin walled tubes. The haul-off can deform and flatten the section because of the pressure necessary to grip the output. Forming the haul-off belts to mirror the form of the section thus increases the surface area contact and can reduce deformation.	
The wall thickness may vary around the section if the center pin of the die is incorrectly set. This may cause excessive shrinkage in the area that is thickest. Bending of the profile will also occur because the thick and thin sections will cool at different rates. Concentricity is a key measure of tubing accuracy.	
If a tube suffers from lack of concentricity then the grip of the haul-off can locally and uncontrollably deform the tube.	

Squares and rectangles	
The internal and external corners are shown as sharp but this condition is not always desired or always possible to achieve. The plastic melt will not reliably fill sharp corners as it flows through the die and the resulting corners will vary in sharpness.	
This illustrates a more acceptable result, with small internal radii, slightly larger external radii, and straight sides. The wall thickness should be constant or as near constant as possible to avoid shrinkage and bending of the section (in length).	
Convex (or concave) sides can result from die swell after the plastic exits the die head. To counteract this, the calibrator must pre-form the section in the opposite direction. This condition is very difficult to predict so a certain amount of testing is necessary as with all extrusion tooling.	

Internal walls and chambers	
This illustrates sinkage: a concern encountered with thick internal walls meeting thick outer walls. Where the two walls meet there is a large mass of material. This larger mass of material will shrink more than the thinner areas and create a sink mark along the length of the extrusion.	

The thickness of the internal wall needs to be reduced to keep it in proportion with the outer wall. If the inner wall thickness is less than 2/3 of the outer wall thickness then any sink marks will be minimized.	
Areas within the chambers - Areas within the chambers are difficult to control.	
A screw port of this shape is easy to produce but will not be sufficiently strong to retain screw. Two solutions are explained below. Solution 1: This will add sufficient strength to the port, but manufacturing the die is more complicated. Solution 2: This shows the best solution with strong screw port and simpler die manufacture.	

Potential applications for extrusion

The limiting factors listed may appear restrictive in some instances, but the amount of extruded profile in daily use proves that good design can provide economical and useful applications in all areas of activity. The initial design constraint of a constant cross section is overcome in many applications by fabrication techniques such as cutting, drilling, welding, and stamping, and by innovative processing techniques such as co-extrusion of soft and hard polymers, multiple color extrusion, and in-line application of decorative foils or adhesive tapes. The following are examples of industrial applications.

Fluid Transfer

Fluoropolymer tubing produced in a melt extrusion is utilized in fluid handling applications for various reasons. The primary benefits are clarity, UV resistance, flexibility, and chemical resistance. PFA and FEP tubing are used in down-hole sampling to retrieve ground water for analysis, as it doesn’t allow traceables or leachables to contaminate the samples. Other fluid applications include the transfer of deionized water, chemicals, and other harsh elements that cannot penetrate or break down fluoropolymer tubing. These melt-processable extrusions are also easily formed into retractable coils and other bend-sets to allow end-users to save space and work around tight configurements. Other industries such as semiconductor, biotech, and pharmaceutical prefer PFA and FEP for these reasons.

Mechanical

Fluoropolymer tubing produced in a melt extrusion is utilized in various mechanical applications due to properties such as low friction, light weight, and high temperature characteristics. Insulation is critical in various advanced applications, and fluoropolymer tubing and heat shrinkable tubing are utilized for the required high performance parameters. Standard tubing, convoluted tubing, roll covers, and other heat shrinkable products are used for insulation of wiring, cable bundling, food and beverage roll covering, and fiber optics.

Summary

Extrusion is a key forming process in plastics processing and enables designers to produce a wide range of products to good tolerances. Without plastic extrusions our lives would simply not be the same. At Zeus we specialize in custom tubing extrusions that are capable of meeting extraordinary customer specifications. Through a continuing investment in Research and Development combined with technological process improvements, Zeus has developed a portfolio of capabilities unsurpassed in the world. Products such as our ultra-thin Sub-Lite-Wall® tubing has wall thicknesses down to .001" and tolerances of +/-.0005" (0.13mm). Other products include Bump tubing (ID and OD varies along the length of the extrusion), seamless Lay-Flat® tubing, and PEEKshrink™, PEEK heat-shrink tubing. Please visit us at www.zeusinc.com for full details about our unique products.

How Zeus Can Help

With a technical inside and outside sales force backed up with engineering and polymer experts, Zeus is prepared to assist in material selection and can provide product samples for evaluation. A dedicated R&D department staffed with PHD Polymer chemists and backed with the support of a world-class analytical lab allows Zeus an unparalleled position in polymer development and customization.

Since 1966 Zeus has been built upon the core technology of precision extrusion of high temperature plastics. Today, with a broad portfolio of engineered resins and secondary operations, Zeus can provide turnkey solutions for development and high-volume supply requirements.

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