1.1 Basic Process

The extruder is indisputably the most important piece of machinery in the polymer processing industry. To extrude means to push or to force out. Material is extruded when it is pushed through an opening. When toothpaste is squeezed out of a tube, it is extruded. The part of the machine containing the opening through which the material is forced is referred to as the extruder die. As material passes through the die, the material acquires the shape of the die opening. This shape generally changes to some extent as the material exits from the die. The extruded product is referred to as the extrudate.

Many different materials are formed through an extrusion process: metals, clays, ceramics, foodstuffs, etc. The food industry, in particular, makes frequent use of extruders to make noodles, sausages, snacks, cereal, and numerous other items. In this book, the materials that will be treated are confined to polymers or plastics.

Polymers can be divided into three main groups: thermoplastics, thermosets, and elastomers. Thermoplastic materials soften when they are heated and solidify when they are cooled. If the extrudate does not meet the specifications, the material can generally be reground and recycled. Thus, the basic chemical nature of a thermoplastic usually does not change significantly as a result of the extrusion process. Thermosets undergo a crosslinking reaction when the temperature is raised above a certain temperature. This crosslinking bonds the polymer molecules together to form a three-dimensional network. This network remains intact when the temperature is reduced again. Crosslinking causes an irreversible change in the material. Therefore, thermosetting materials cannot be recycled as can thermoplastic materials. Elastomers or rubbers are materials capable of very large deformations with the material behaving in a largely elastic manner. This means that when the deforming force is removed, the material completely, or almost completely, recovers. The emphasis of this book will be on thermoplastics; only a relatively small amount of attention will be paid to thermosets and elastomers.
Materials can be extruded in the molten state or in the solid state. Polymers are generally extruded in the molten state; however, some applications involve solid-state extrusion of polymers. If the polymer is fed to the extruder in the solid state and the material is melted as it is conveyed by the extruder screw from the feed port to the die, the process is called plasticating extrusion. In this case, the extruder performs an additional function, namely melting, besides the regular extrusion function. Sometimes the extruder is fed with molten polymer; this is called melt fed extrusion. In melt fed extrusion, the extruder acts purely as a pump, developing the pressure necessary to force the polymer melt through the die.

There are two basic types of extruders: continuous and discontinuous or batch type extruders. Continuous extruders are capable of developing a steady, continuous flow of material, whereas batch extruders operate in a cyclic fashion. Continuous extruders utilize a rotating member for transport of the material. Batch extruders generally have a reciprocating member to cause transport of the material.

### 1.2 Scope of the Book

This book will primarily deal with plasticating extrusion in a continuous fashion. Chapters 2, 3, and 4 deal with a description of extrusion machinery. Chapter 5 will briefly review the fundamental principles that will be used in the analysis of the extrusion process. Chapter 6 deals with the polymer properties important in the extrusion process. This is a very important chapter, because one cannot understand the extrusion process if one does not know the special characteristics of the material to be extruded. Understanding just the extrusion machinery is not enough. Rheological and thermal properties of a polymer determine, to a large extent, the characteristics of the extrusion process. The process engineer, therefore, should be a mechanical or chemical engineer on the one hand, and a rheologist on the other hand. Since most engineers have little or no formal training in polymer rheology, the subject is covered in Chapter 6, inasmuch as it is necessary for the analysis of the extrusion process.

Chapter 7 covers the actual analysis of the extrusion process. The process is analyzed in discrete functional zones with particular emphasis on developing a quantitative understanding of the mechanisms operational in each zone.

The theory developed in Chapter 7 is applied to the design of extruder screws in Chapter 8 and to the design of extruder dies in Chapter 9. Chapter 10 is devoted to twin screw extruders. Twin screw extruders have become an increasingly important branch of the extrusion industry. It is felt, therefore, that any book on extrusion cannot ignore this type of extruder. Troubleshooting extruders is covered in Chapter 11.
This is perhaps the most critical and most important function performed in industrial operation of extruders. Extrusion problems causing downtime or off-spec products can become very costly in a short period of time: losses can often exceed the purchase price of the entire machine in a few hours or a few days. Thus, it is very important that the process engineer can troubleshoot quickly and accurately. This requires a solid understanding of the operational principles of extruders and the basic mechanisms behind them. Therefore, the chapter on troubleshooting is a practical application of the functional process analysis developed in Chapter 7.

The final chapter of the book, Chapter 12 on modeling and computer simulation was added in the fourth edition. This chapter was written by Paul Gramann, Bruce Davis, and Tim Osswald; three workers who have made substantial contributions to the development of this branch of polymer processing. Computer aided engineering (CAE) is now an integral part of extrusion engineering and a current book on extrusion would not be complete without dealing with this important subject.

The book is therefore divided in four main parts. The first part deals with the hardware and/or mechanical aspects of extruders: this is covered in Chapters 2, 3, and 4. The second part deals with the process analysis: this is covered in Chapters 5, 6, and 7. The third part deals with practical applications of the extrusion theory: this is covered in Chapters 8, 9, 10, and 11. Part four is the chapter on modeling and computer simulation. Parts I, II, and IV can be studied independently; Part III, however, cannot be fully appreciated without studying Part II.

### 1.3 General Literature Survey

Considering the fact that there are already several books on extrusion of polymers, the question can be asked why the need for another book on extrusion. The three most comprehensive books written on extrusion as of the early 1980s were the books by Bernhardt [1], Schenkel [2], and Tadmor [5]. The book by Bernhardt is on polymer processing, but has a very good chapter on extrusion. It is well written and describes extrusion theory and its practical applications to screw and die design. Because of the age of the book, however, the extrusion theory is incomplete in that it does not cover plasticating—this theory was developed later by Tadmor [5]—and devolatilization theory.

The book by Schenkel [2] is a translation of the German text “Kunststoff Extruder-Technik” [3], which is an extension of the original book “Schneckenpressen fuer Kunststoffe” [4]. This book is very complete: dealing with flow properties of polymers, extrusion theory, and design of extrusion equipment. The emphasis of Schenkel’s book is on the mechanical or machinery aspects of extruders. As in Bernhardt’s
book, the book by Schenkel suffers from the fact that it was written a long time ago, in the early 1960s. Thus, the extrusion theory is incomplete and new trends in extrusion machinery are absent. The book by Tadmor [5] is probably the most complete theoretical treatise on extrusion. From a theoretical point of view, it is an outstanding book. It is almost completely devoted to a detailed engineering analysis of the extrusion process. Consequently, relatively little attention is paid to extrusion machinery and practical applications to screw and die design. In order to fully appreciate this book, the reader should possess a significant degree of mathematical dexterity. The book is ideally suited for those who want to delve into detailed mathematical analysis and computer simulation of the extrusion process. The book is less suited for those who need to design extruder screws and/or extruder dies, or those who need to solve practical extrusion problems.

Another book on extrusion is “Plastics Extrusion Technology” edited by Hensen et al. [44]. This is quite a comprehensive book dealing in detail with a number of extrusion processes, such as compounding, pipe extrusion, profile extrusion, etc. The book gives good information on the various extrusion operations with detailed information on downstream equipment. This book is an English version of the two-volume German original, “Kunststoff-Extrusionstechnik I und II” [45, 46]. Volume I, Grundlagen (Fundamentals), covers the fundamental aspects such as rheology, thermodynamics, fluid flow analysis, single- and twin-screw extruders, die design, heating and cooling, etc. Volume II, Extrusionsanlagen, covers various extrusion lines; this is the volume translated into English.

Another important addition to the extrusion literature is the book on twin screw extrusion by White [47]. This book has an excellent coverage of the historical development of various twin screw extruders. It also discusses in some detail recent experimental work and developments in twin screw theory. This book covers intermeshing and non-intermeshing extruders, both co- and counter-rotating extruders. Another extrusion process, which has been gaining interest and is being used more widely, is reactive extrusion. A good book on this subject was edited by Xanthos [48]; it covers applications, review, and engineering fundamentals of reactive extrusion.

Statistical process control in extrusion is covered by a book by Rauwendaal [49]; an updated version of this book also covering injection molding and pre-control was published in 2000 [56]. Mixing in extrusion processes is covered by a book edited by Rauwendaal [50]. It covers basic aspects of mixing and mixing in various extrusion machinery, such as single screw extruders, twin screw extruders, reciprocating screw extruders, internal mixers, and co-rotating disk processors. Another book on mixing is the book edited by Manas-Zloczower and Tadmor [51]. This book covers four major sections: mixing mechanisms and theory, modeling and flow visualization, material considerations, and mixing practices. The book on mixing in polymer processing [54] by Rauwendaal covers the basics of mixing and a comprehensive
description of mixing machinery. This book is written as a self-study guide with questions at the end of each chapter.

In order not to duplicate other texts on extrusion, this book will emphasize new trends and developments in extrusion machinery. The extrusion theory will be covered as completely as possible; however, the mathematical complexity will be kept to a minimum. This is done to enhance the ease of applying theory to practical cases and to make the book accessible to a larger number of people. A significant amount of attention will be paid to practical application of the extrusion theory to screw and die design and solving extrusion problems. After all, practical applications are most important to practicing polymer process engineers or chemists.

Various other books on extrusion have been written [6–22, 52]. These books generally cover only specific segments of extrusion technology: e.g., screw design, twin screw extrusion, etc., or provide only introductory material. Thus, it is felt that a comprehensive book on polymer extrusion with recent information on machinery, theory, and application does fulfill a need. There are several books on the more general subject of polymer processing [24–36], in addition to the book by Bernhardt [7] already mentioned. Many of these give a good review of the field of polymer processing, some emphasizing the general principles involved in process analysis [24–33] or machine design [34], while others concentrate more on a description of the process machinery and products [35, 36]. Since the field of polymer processing is tremendously large, books on the subject inevitably cover extrusion in less detail than possible in a book devoted exclusively to extrusion.

The book “Understanding Extrusion” [55] is a very much-simplified and abbreviated version of “Polymer Extrusion” without any equations in the main body of the text. Even though the mathematical level of Polymer Extrusion is at approximately the bachelors engineering level, the mathematics is too much for people who are not interested in the engineering details. Understanding Extrusion became an immediate best seller, indicating that a non-engineering level book on extrusion can attract a wide readership. This book is the basis of a computer based interactive training program on extrusion, ITX®.


Chung’s book “Extrusion of Polymers” [57] covers some of the same material as Polymer Extrusion, however, it does not cover die design, troubleshooting, and modeling and computer simulation. As such, the book is limited in scope; it also suffers from the fact that most references are from before 1980. The book “Screw Extrusion: Technology and Science” [58] was edited by White and Potente. This book has a broad scope and multiple contributors; it covers fundamentals, single screw extru-
A recent book on extrusion is the book “Analyzing and Troubleshooting Single-Screw Extruders” [60] by Campbell and Spalding. The authors claim that this is the first book that focuses on the actual physics of the process-screw rotation physics. This claim is not entirely correct considering that the 4th edition of this book already examined this issue in detail, see Section 7.4.3.5.

### 1.4 History of Polymer Extrusion

The first machine for extrusion of thermoplastic materials was built around 1935 by Paul Troester in Germany [37]. Before this time, extruders were primarily used for extrusion of rubber. These earlier rubber extruders were steam-heated ram extruders and screw extruders; with the latter having very short length to diameter (L/D) ratios, about 3 to 5. After 1935, extruders evolved into electrically heated screw extruders with increased length. Around this time, the basic principle of twin screw extruders for thermoplastics was conceived in Italy by Roberto Colombo of LMP. He was working with Carlo Pasquetti on mixing cellulose acetate. Colombo developed an intermeshing co-rotating twin screw extruder. He obtained patents in many different countries and several companies acquired the rights to use these patents. Pasquetti followed a different concept and developed and patented the intermeshing counter-rotating twin screw extruder.

The first detailed analyses of the extrusion process were concerned with the melt conveying or pumping process. The earliest publication was an anonymous article [38], which is often erroneously credited to Rowell and Finlayson, who wrote an article of the same title in the same journal six years later [39]. Around 1950, scientific studies of the extrusion process started appearing with increased frequency. In the mid-fifties, the first quantitative study on solids conveying was published by Darnell and Mol [40]. An important conference in the development of extrusion theories was the 122nd ACS meeting in 1953. At this symposium, members of the Polymers Department of E. I. DuPont de Nemours & Co. presented the latest developments in extrusion theory [41]. These members, Carley, Strub, Mallouk, McKelvey, and Jepson were honored in 1983 by the SPE Extrusion Division for original development of extrusion theories. In the mid-sixties, the first quantitative study on melting was published by Tadmor [42], based on earlier qualitative studies by Maddock [43]. Thus, it was not until about 1965 that the entire extrusion process, from the feed hopper to the die, could be described quantitatively. The theoretical work since this time has concentrated, to a large extent, on generalizing and extending the
extrusion theory and the development of numerical techniques and computer methods to solve equations that can no longer be solved by analytical methods.

As a result, there has been a shift in the affiliation of the workers involved in scientific extrusion studies. While the early work was done mostly by investigators in the polymer industry, later workers have been academicians. This has created something of a gap between extrusion theoreticians and practicing extrusion technologists. This is aggravated by the fact that some workers are so concerned about the scientific purity of the work, which is commendable in itself, that it becomes increasingly unappealing to the industrial process engineer who wants to apply the work. One of the objectives of this book is to bridge this gap between theory and practice by demonstrating in detail how the theory can be applied and by analyzing the limitations of the theory.

Another interesting development in practical extrusion technology has been the concept of feed-controlled extrusion. In this type of extrusion, the performance is determined by the solids conveying zone of the extruder. By the use of grooves in the first portion (close to the feed port) of the extruder barrel, the solids conveying zone is capable of developing very high pressures and quite positive conveying characteristics (i.e., throughput independent of pressure). In this case, the diehead pressure does not need to be developed in the pumping or melt conveying zone; it is developed in the solids conveying zone. The feed zone overrides both the plasticating and the melt conveying (pumping) zone.

Thus, the extruder becomes solids conveying or feed controlled. This concept has now become an accepted standard in Western Europe, particularly in Germany. In the U.S., this concept has been met with a substantial amount of reluctance and skepticism. For the longest time, the few proponents of the feed-controlled extrusion were heavily outnumbered by the many opponents. As a consequence, only a small fraction of the extruders in the U.S. have been equipped with grooved barrel sections. However, there does seem to be a trend towards increasing acceptance of this concept. This is especially true in the blown film industry where the use of very high molecular weight polyethylene has led many processors to use grooved feed extruders.

One approach to making the grooved feed extruder more attractive is to make it adjustable. This can eliminate many of the disadvantages of current grooved feed extruders. The grooved feed section can be made adjustable by changing the depth of the grooves while the machine is operating. This makes the grooved feed extruder more versatile and allows a greater degree of control of the extrusion process. Adjustable grooved feed extruders are discussed in Chapter 7.

When a single screw extruder is used for demanding mixing and compounding operations it is often preferred that the extruder is starve fed rather than flood fed. Flood feeding often results in higher pressures inside the extruder and this can lead to an agglomeration of powdered fillers. When this occurs it may be difficult or
impossible to disperse the agglomerates formed in the extruder. With starve feeding the pressures inside the extruder are lower and can be controlled by adjusting the feed rate and/or the screw speed. As a result, there is less risk of agglomeration using starve feeding.

Around 2000, a new generation of mixing devices was developed to generate strong elongational flow to improve mixing, particularly dispersive mixing. It has long been known that elongational mixing is more effective than shear mixing. However, this knowledge was not translated into actual mixing devices until recently. These new mixing devices, such as the CRD mixer discussed in Chapter 7, use the same type of mixing mechanism active in high-speed co-rotating twin screw extruders. As a result, when these mixers are used in single screw extruders the mixing action can be comparable to that of twin screw compounders. In fact, these mixers are now successfully used in twin screw extruders as well.

The advent of effective new mixers for single screw extruders has improved the capabilities of conventional single screw extruders. An interesting application may be long single screw extruders (30 to 60D) with multiple downstream ports for compounding and direct extrusion. When such machines are starve fed they can be used in many applications now serviced by twin screw extruders. Because single screw extruders are considerably less expensive to purchase and to operate, this approach can offer substantial cost savings. This approach represents a significant departure from conventional extrusion technology; as a result, it may take some time before it is widely accepted in the extrusion industry. However, when a new technology makes technical and economic sense and it works, then sooner or later it will be adopted.

Very high speed single screw extruders have been commercially available since about 2005–2010. This is one of the most significant developments in single screw extrusion over the past several decades. These relatively small extruders (50–75 mm) that run at screw speeds as high as 1,000 to 1,500 rpm and achieve output rates about an order of magnitude above the rate of conventional extruders.

References
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38. N.N., Engineering, 114, 606 (1922)
44. F. Hensen, W. Knappe, and H. Potente (Eds.), “Plastics Extrusion Technology,” Carl Hanser Verlag, Munich (1988)
PART I
Extrusion Machinery
Extruders in the polymer industry come in many different designs. The main distinction between the various extruders is their mode of operation: continuous or discontinuous. The latter type extruder delivers polymer in an intermittent fashion and, therefore, is ideally suited for batch type processes, such as injection molding and blow molding. As mentioned earlier, continuous extruders have a rotating member, whereas batch extruders have a reciprocating member. A classification of the various extruders is shown in Table 2.1.

### 2.1 The Single Screw Extruder

Screw extruders are divided into single screw and multi-screw extruders. The single screw extruder is the most important type of extruder used in the polymer industry. Its key advantages are relatively low cost, straightforward design, ruggedness and reliability, and a favorable performance/cost ratio. A detailed description of the hardware components of a single screw extruder is given in Chapter 3.

The extruder screw of a conventional plasticating extruder has three geometrically different sections; see Fig. 2.1.

This geometry is also referred to as a “single stage.” The single stage refers to the fact that the screw has only one compression section, even though the screw has three distinct geometrical sections! The first section (closest to the feed opening) generally has deep flights. The material in this section will be mostly in the solid state. This section is referred to as the feed section of the screw. The last section (closest to the die) usually has shallow flights. The material in this section will be mostly in the molten state. This screw section is referred to as the metering section or pump section. The third screw section connects the feed section and the metering section. This section is called the transition section or compression section. In most cases, the depth of the screw channel (or the height of the screw flight) reduces in a linear fashion, going from the feed section towards the metering section, thus causing a compression of the material in the screw channel. Later, it will be shown that this compression, in many cases, is essential to the proper functioning of the extruder.
The extruder is usually designated by the diameter of the extruder barrel. In the U.S., the standard extruder sizes are 3/4, 1, 1-1/2, 2, 2-1/2, 3-1/2, 4-1/2, 6, 8, 10, 12, 14, 16, 18, 20, and 24 inches.

Obviously, the very large machines are much less common than the smaller extruders. Some machines go up in size as large as 35 inches. These machines are used in specialty operations, such as melt removal directly from a polymerization reactor. In Europe, the standard extruder sizes are 20, 25, 30, 35, 40, 50, 60, 90, 120, 150, 200, 250, 300, 350, 400, 450, 500, and 600 millimeters. Most extruders range in size from 1 to 6 inches or from 25 to 150 mm. An additional designation often used is the length of the extruder, generally expressed as length to diameter (L/D) ratio. Typical L/D ratios range from 20 to 30, with 24 being very common. Extruders used for extraction of volatiles (vented extruders, see Section 2.1.2) can have an L/D ratio as high as 35 or 40 and sometimes even higher.

<table>
<thead>
<tr>
<th>Table 2.1 Classification of Polymer Extruders</th>
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<tr>
<td><strong>Screw extruders</strong> (continuous)</td>
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<tr>
<td>Single screw extruders</td>
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<tr>
<td>- Melt fed</td>
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<tr>
<td>- Plasticating</td>
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<td>- Single stage</td>
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<tr>
<td>- Multi stage</td>
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<tr>
<td>- Compounding</td>
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<td>Multi screw extruders</td>
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<td>- Twin screw extruders</td>
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<td>- Gear pumps</td>
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<tr>
<td>- Planetary gear extruders</td>
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<tr>
<td>- Multi (&gt;2) screw extruders</td>
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<tr>
<td><strong>Viscous drag extruders</strong></td>
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<td>Spiral disk extruder</td>
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<td>Drum extruder</td>
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<td>Diskpack extruder</td>
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<td>Stepped disk extruder</td>
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<td><strong>Elastic melt extruders</strong></td>
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<td>Screwless extruder</td>
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<tr>
<td>Screw or disk type melt extruder</td>
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<tr>
<td><strong>Reciprocating extruders</strong> (discontinuous)</td>
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<tr>
<td>Ram extruders</td>
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<tr>
<td>- Melt fed extruder</td>
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<tr>
<td>- Plasticating extruder</td>
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<tr>
<td>- Capillary rheometer</td>
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<tr>
<td>Reciprocating single screw extruders</td>
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<tr>
<td>Plasticating unit in injection molding machines</td>
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<tr>
<td>Compounding extruders such as the Kneader</td>
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2.1 Basic Operation

The basic operation of a single screw extruder is rather straightforward. Material enters from the feed hopper. Generally, the feed material flows by gravity from the feed hopper down into the extruder barrel. Some materials do not flow easily in dry form and special measures have to be taken to prevent hang-up (bridging) of the material in the feed hopper.

As material falls down into the extruder barrel, it is situated in the annular space between the extruder screw and barrel, and is further bounded by the passive and active flanks of the screw flight: the screw channel. The barrel is stationary and the screw is rotating. As a result, frictional forces will act on the material, both on the barrel as well as on the screw surface. These frictional forces are responsible for the forward transport of the material, at least as long as the material is in the solid state (below its melting point).

As the material moves forward, it will heat up as a result of frictional heat generation and because of heat conducted from the barrel heaters. When the temperature of the material exceeds the melting point, a melt film will form at the barrel surface. This is where the solids conveying zone ends and the plasticating zone starts. It should be noted that this point generally does not coincide with the start of the compression section. The boundaries of the functional zones will depend on polymer properties, machine geometry, and operating conditions. Thus, they can change as operating conditions change. However, the geometrical sections of the screw are determined by the design and will not change with operating conditions. As the material moves forward, the amount of solid material at each location will reduce as a result of melting. When all solid polymer has disappeared, the end of the plasticating zone has been reached and the melt conveying zone starts. In the melt-conveying zone, the polymer melt is simply pumped to the die.

As the polymer flows through the die, it adopts the shape of the flow channel of the die. Thus, as the polymer leaves the die, its shape will more or less correspond to the cross-sectional shape of the final portion of the die flow channel. Since the die exerts a resistance to flow, a pressure is required to force the material through the die. This is generally referred to as the diehead pressure. The diehead pressure is determined by the shape of the die (particularly the flow channel), the temperature...
of the polymer melt, the flow rate through the die, and the rheological properties of
the polymer melt. It is important to understand that the diehead pressure is caused
by the die, and not by the extruder! The extruder simply has to generate sufficient
pressure to force the material through the die. If the polymer, the throughput, the
die, and the temperatures in the die are the same, then it does not make any differ-
ence whether the extruder is a gear pump, a single screw extruder, a twin screw
extruder, etc.; the diehead pressure will be the same. Thus, the diehead pressure is
carried by the die and by the flow process, taking place in the die flow channel. This
is an important point to remember.

2.1.2 Vented Extruders

Vented extruders are significantly different from non-vented extruders in design
and in functional capabilities. A vented extruder is equipped with one or more open-
ings (vent ports) in the extruder barrel, through which volatiles can escape. Thus,
the vented extruder can extract volatiles from the polymer in a continuous fashion.
This devolatilization adds a functional capability not present in non-vented extrud-
ers. Instead of the extraction of volatiles, one can use the vent port to add certain
components to the polymer, such as additives, fillers, reactive components, etc. This
clearly adds to the versatility of vented extruders, with the additional benefit that
the extruder can be operated as a conventional non-vented extruder by simply plug-
ging the vent port and, possibly, changing the screw geometry.

A schematic picture of a vented extruder is shown in Fig. 2.2.

![Figure 2.2 Schematic of vented extruder](image)

The design of the extruder screw is very critical to the proper functioning of the
vented extruder. One of the main problems that vented extruders are plagued with
is vent flow. This is a situation where not only the volatiles are escaping through the
vent port, but also some amount of polymer. Thus, the extruder screw has to be
designed in such a way that there will be no positive pressure in the polymer under
the vent port (extraction section). This has led to the development of the two-stage
The devolatilization capability of single screw extruders of conventional design is limited compared to twin screw extruders. Twin screw extruders can handle solvent contents of 50% and higher, using a multiple-stage extraction system, and solvent content of up to 15% using single-stage extraction. Single screw vented extruders of conventional design usually cannot handle more than 5% volatiles; this would require multiple vent ports. With a single vent port, a single screw vented extruder of conventional design can generally reduce the level of volatiles only a fraction of one percent, depending, of course, on the polymer/solvent system.

Because of the limited devolatilization capacity of single screw extruders of conventional design, they are sometimes equipped with two or more vent ports. A drawback of such a design is that the length of the extruder can become a problem. Some of these extruders have a L/D ratio of 40 to 50! This creates a problem in handling the screw, for instance when the screw is pulled, and increases the chance of mechanical problems in the extruder (deflection, buckling, etc.). If substantial amounts of volatiles need to be removed, a twin screw extruder may be more cost-effective than a single screw extruder. However, some vented single screw extruders of more modern design have substantially improved devolatilization capability and deserve equal consideration; see Section 8.5.2.

### 2.1.3 Rubber Extruders

Extruders for processing elastomers have been around longer than any other type of extruder. Industrial machines for rubber extrusion were built as early as the second half of the nineteenth century. Some of the early extruder manufacturers were John Royle in the U.S. and Francis Shaw in England. One of the major rubber extruder manufacturers in Germany was Paul Troester; in fact, it still is a producer of extruders. Despite the fact that rubber extruders have been around for more than a century, there is limited literature on the subject of rubber extrusion. Some of the handbooks on rubber [1–5] discuss rubber extrusion, but in most cases the information is very meager and of limited usefulness. Harms’ book on rubber extruders [13] appears to be the only book devoted exclusively to rubber extrusion. The few publications on rubber extrusion stand in sharp contrast to the abundance of books and articles on plastic extrusion. Considering the commercial significance of rubber extrusion, this is a surprising situation.
The first rubber extruders were built for hot feed extrusion. These machines are fed with warm material from a mill or other mixing device. Around 1950, machines were developed for cold feed extrusion. The advantages of cold feed extruders are thought to be:

- Less capital equipment cost
- Better control of stock temperature
- Reduced labor cost
- Capable of handling a wider variety of compounds

However, there is no general agreement on this issue. As a result, hot feed rubber extruders are still in use today.

Cold feed rubber extruders, nowadays, do not differ too much from thermoplastic extruders. Some of the differences are:

- Reduced length
- Heating and cooling
- Feed section
- Screw design

There are several reasons for the reduced length. The viscosity of rubbers is generally very high compared to most thermoplastics; about an order of magnitude higher [5]. Consequently, there is a substantial amount of heat generated in the extrusion process. The reduced length keeps the temperature build-up within limits. The specific energy requirement for rubbers is generally low, partly because they are usually extruded at relatively low temperatures (from 20 to 120°C). This is another reason for the short extruder length. The length of the rubber extruder will depend on whether it is a cold or hot feed extruder. Hot feed rubber extruders are usually very short, about 5D (D = diameter). Cold feed extruders range from 15 to 20D. Vented cold feed extruders may be even longer than 20D.

Rubber extruders used to be heated quite frequently with steam because of the relatively low extrusion temperatures. Today, many rubber extruders are heated like thermoplastic extruders with electrical heater bands clamped around the barrel. Oil heating is also used on rubber extruders and the circulating oil system can be used to cool the rubber. Many rubber extruders use water cooling because it allows effective heat transfer.

The feed section of the rubber extruders has to be designed specifically to the feed stock characteristics of the material. The extruder may be fed with either strips, chunks, or pellets. If the extruder is fed from an internal mixer (e.g., Banbury, Shaw, etc.), a power-operated ram can be used to force the rubber compound into the extruder. The feed opening can be undercut to improve the intake capability of the extruder. This can be useful, because the rubber feed stock at times comes in relatively large particles of irregular shape. When the material is supplied in the form of
a strip, the feed opening is often equipped with a driven roll parallel to the screw to give a “roller feed”. Material can also be supplied in powder form. It has been shown that satisfactory extrusion is possible if the powder is consolidated by “pill-making” techniques. Powdered rubber technology is discussed in detail in [6].

The rubber extrusion technology appears to be considerably behind the plastics extrusion technology. Kennaway, in one of the few articles on rubber extrusion [8], attributes this situation to two factors. The first is the frequent tendency of rubber process personnel to solve extrusion problems by changing the formulation of the compound. The second is the widespread notion that the extrusion behavior of rubbers is substantially different from plastics, because rubbers crosslink and plastics generally do not. This is a misconception, however, because the extrusion characteristics of rubber and plastics are actually not substantially different [9].

When the rubber is slippery, as in dewatering rubber extruders, the feed section of the barrel is grooved to prevent slipping along the barrel surface or the barrel I.D. may be fitted with pins. This significantly improves the conveying action of the extruder. The same technique has been applied to the thermoplastic extrusion, as discussed in Section 1.4 and Section 7.2.2.2.

The extruder screw for rubber often has constant depth and variable decreasing pitch (VDP); many rubber screws use a double-flighted design; see Fig. 2.3. Screws for thermoplastics usually have a decreasing depth and constant pitch; see Fig. 2.1.

Another difference with the rubber extruder screw is that the channel depth is usually considerably larger than with a plastic extruder screw. The larger depth is used to reduce the shearing of the rubber and the resulting viscous heat generation. There is a large variety of rubber extruder screws, as is the case with plastic extruder screws. Figure 2.4 shows the “Plastiscrew” manufactured by NRM.

Figure 2.5 shows the Pirelli rubber extruder screw. This design uses a feed section of large diameter, reducing quickly to the much smaller diameter of the pumping section. The conical feed section uses a large clearance between screw flight and barrel wall. This causes a large amount of leakage over the flight and improves the batch-mixing capability of the extruder.
Figure 2.5
The Pirelli rubber extruder screw

Figure 2.6 shows the EVK screw by Werner & Pfleiderer [14]. This design features cross-channel barriers with preceding undercuts in the flights to provide a change in flow direction and increased shearing as the material flows over the barrier or the undercut in the flight. A rather unusual design is the Transfermix [10–13] extruder/mixer, which has been used for compounding rubber formulations. This machine features helical channels in both, the screw and barrel; see Fig. 2.7.

Figure 2.6
The EVK screw by Werner & Pfleiderer

Figure 2.7 The Transfermix extruder

By a varying root diameter of the screw the material is forced in the flow channel of the barrel. A reduction of the depth of the barrel channel forces the material back into the screw channel. This frequent reorientation provides good mixing. However, the machine is difficult to manufacture and expensive to repair in case of damage.

Another rubber extruder is the QSM extruder [7, 15–20]. QSM stands for the German words “Quer Strom Misch,” meaning cross-flow mixing. This extruder has
adjustable pins in the extruder barrel that protrude all the way into the screw channel; see Fig. 2.8.

![Figure 2.8 The QSM extruder (pin barrel extruder)](image)

The screw flight has slots at the various pin locations. The advantages of this extruder in rubber applications are good mixing capability with a low stock temperature increase and low specific energy consumption. This extruder was developed by Harms in Germany and is manufactured and sold by Troester and other companies. Even though the QSM extruder has become popular in the rubber industry, its applications clearly extend beyond just rubber extrusion. In thermoplastic extrusion, its most obvious application would be in high viscosity, thermally less stable resins: PVC could possibly be a candidate, although dead spots may create problems with degradation. However, it can probably be applied wherever good mixing and good temperature control are required.

Another typical rubber extrusion piece of hardware is the roller die. A schematic representation is shown in Fig. 2.9.

![Figure 2.9 The roller die used in rubber extrusion](image)

The roller die (B.F. Goodrich, 1933) is a combination of a standard sheet die and a calender. It allows high throughput by reducing the diehead pressure; it reduces air entrapment and provides good gauge control.