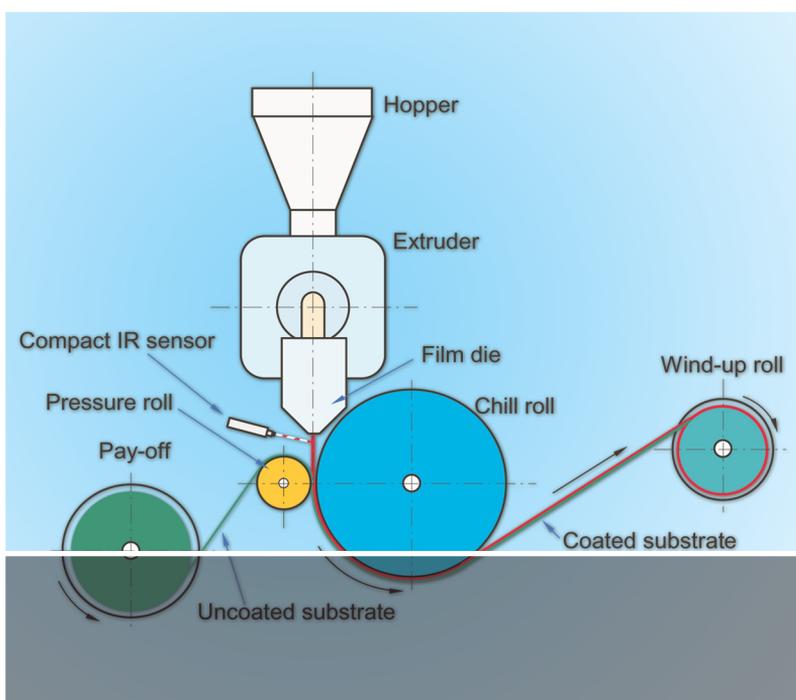


Chris Rauwendaal

# Polymer Extrusion



5<sup>th</sup> Edition

HANSER

Rauwendaal  
**Polymer Extrusion**



Chris Rauwendaal

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5<sup>th</sup> Edition

With contributions from

Paul J. Gramann, Bruce A. Davis, and Tim A. Osswald

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# Preface to the Fifth Edition

It has been twelve years since the fourth edition of Polymer Extrusion was published and twenty six years since the book was first published. Extrusion technology continues to advance; as a result, a fifth edition is needed to keep the Polymer Extrusion book up to date and relevant.

New material has been added throughout the book. The general literature survey has been updated since several books on extrusion have been published since 2001. A new theory for predicting developing melt temperatures has been incorporated into Chapter 7. This theory allows accurate prediction of changes in melt temperature along the length of the extruder; complete analytical solutions are presented to the relevant equations. As a result, melt temperatures can be predicted without having to resort to numerical techniques and computer simulation.

In Chapter 8, a new section on efficient extrusion of medical devices has been added. It covers good manufacturing practices in medical extrusion and automation. The effect of processing conditions and screw design on molecular degradation is covered in detail. Screw designs that minimize molecular degradation are discussed and explained.

In Chapter 11, the section on gels in extruded products has been expanded as this continues to be a problem experienced by many extrusion companies. There is also a new section on discolored specks in extruded products. In this section expressions are included that allow prediction of the incidence and frequency of specks or gels based on their frequency in the incoming raw material. Included is a discussion on new instruments that are now available to detect defects in pellets produced at the resin supplier with the ability to remove pellets with defects from the pellet stream.

Over the past five to ten years very high speed single screw extruders have been developed. These extruders are now commercially available and they are used by dozens of companies around the world. These machines run at speeds up to 1500 rpm; they achieve outputs that are about an order of magnitude above those of conventional extruders. This high speed single screw extruder technology is one of the most significant developments. Therefore, this topic has been added to the new edition in Chapter 2.

The author would like to thank Professor Jürgen Miethlinger and Michael Aigner from Johannes Kepler University in Linz, Austria for checking equations in Chapter 7 and finding a few mistakes; these have been corrected.

The author would also like to thank Cheryl Hamilton and Nadine Warkotsch at Carl Hanser Verlag for their encouragement and help in making the fifth edition a reality. The author is grateful for a long and fruitful relationship with Carl Hanser Verlag. Finally, I would like to extend a special thank you to my wife Sietske. She has supported and helped me in many ways for the past forty years. I am grateful for her love and support—I feel very fortunate to have a friend and spouse who makes life worth living.

*Chris Rauwendaal*  
*Auburn, California*  
*October 2013*

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# 1

## Introduction

### ■ 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®.

The book “Troubleshooting the Extrusion Process—A Systematic Approach to Solving Plastic Extrusion Problems” [59] by del Pilar Noriega and Rauwendaal was the first book devoted exclusively to troubleshooting extrusion problems. A second edition of this book was published in 2010.

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-

sion technology, reciprocating extruders, single screw extruder analysis and design, and multiscrew extrusion.

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 4<sup>th</sup> 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 122<sup>nd</sup> ACS meeting in 1953. At this symposium, members of the Polychemicals 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 somewhat 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 pureness 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 compounding. 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 rate about an order of magnitude above the rate of conventional extruders.

## References

1. E. C. Bernhardt (Ed.), "Processing of Thermoplastic Materials," Reinhold, NY (1959)
2. G. Schenkel, "Plastics Extrusion Technology and Theory," Illiffe Books Ltd., London (1966), published in the USA by American Elsevier, NY (1966)
3. G. Schenkel, "Kunststoff Extruder-Technik," Carl Hanser Verlag, Munich (1963)
4. G. Schenkel, "Schneckenpressen fuer Kunststoffe," Carl Hanser Verlag, Munich (1959)
5. Z. Tadmor and I. Klein, "Engineering Principles of Plasticating Extrusion," Van Nostrand Reinhold, NY (1970)
6. H.R. Simonds, A.J. Weith, and W. Schack, "Extrusion of Rubber, Plastics and Metals," Reinhold, NY (1952)
7. E.G. Fisher, "Extrusion of Plastics," Illiffe Books Ltd., London (1954)

8. R. Jacobi, "Grundlagen der Extrudertechnik," Carl Hanser Verlag, Munich (1960)
9. W. Mink, "Grundzuege der Extrudertechnik," Rudolf Zechner Verlag, Speyer am Rhein (1963)
10. A.L. Griff, "Plastics Extrusion Technology," Reinhold, NY (1968)
11. R.T. Fenner, "Extruder Screw Design," Illiffe Books, Ltd., London (1970)
12. N.M. Bikales (Ed.), "Extrusion and Other Plastics Operations," Wiley, NY (1971)
13. P.N. Richardson, "Introduction to Extrusion," Society of Plastics Engineers, Inc. (1974)
14. L.P.B.M. Janssen, "Twin Screw Extrusion," Elsevier, Amsterdam (1978)
15. J.A. Brydson and D.G. Peacock, "Principles of Plastics Extrusion," Applied Science Publishers Ltd., London (1973)
16. F.G. Martelli, "Twin Screw Extrusion, A Basic Understanding," Van Nostrand Reinhold, NY (1983)
17. "Kunststoff-Verarbeitung im Gespraech, 2 Extrusion," BASF, Ludwigshafen (1971)
18. "Der Extruder als Plastifiziereinheit," VDI-Verlag, Duesseldorf (1977)
19. Levy, "Plastics Extrusion Technology Handbook," Industrial Press Inc., NY (1981)
20. H. Potente, "Auslegen von Schneckenmaschinen-Baureihen, Modellgesetze und ihre Anwendung," Carl Hanser Verlag, Munich (1981)
21. H. Herrmann, "Schneckenmaschinen in der Verfahrenstechnik," Springer-Verlag, Berlin (1972)
22. W. Dalhoff, "Systematische Extruder-Konstruktion," Krausskopf-Verlag, Mainz (1974)
23. E. Harms, "Kautschuk-Extruder, Aufbau und Einsatz aus verfahrenstechnischer Sicht," Krausskopf-Verlag Mainz, Bd. 2, Buchreihe Kunststofftechnik (1974)
24. J.M. McKelvey, "Polymer Processing," Wiley, NY (1962)
25. R.M. Ogorkiewicz, "Thermoplastics: Effects of Processing," Illiffe Books Ltd., London (1969)
26. J.R.A. Pearson, "Mechanical Principles of Polymer Melt Processing," Pergamon, Oxford (1966)
27. S. Middleman, "The Flow of High Polymers," Interscience (1968)
28. R.V. Torner, "Grundprozesse der Verarbeitung von Polymeren," VEB Deutscher Verlag fuer Grundstoffindustrie, Leipzig (1973)
29. S. Middleman, "Fundamentals of Polymer Processing," McGraw-Hill, NY (1977)
30. H.L. Williams, "Polymer Engineering," Elsevier, Amsterdam (1975)
31. J.L. Throne, "Plastics Process Engineering," Marcel Dekker, Inc., NY (1979)
32. Z. Tadmor and C. Gogos, "Principles of Polymer Processing," Wiley, NY (1979)
33. R.T. Fenner, "Principles of Polymer Processing," MacMillan Press Ltd., London (1979)
34. N.S. Rao, "Designing Machines and Dies for Polymer Processing with Computer Programs," Carl Hanser Verlag, Munich (1981)
35. J. Frados (Ed.), "Plastics Engineering Handbook," Van Nostrand Reinhold, NY (1976)
36. S.S. Schwartz and S.H. Goodman, "Plastics Materials and Processes," Van Nostrand Reinhold, NY (1982)

37. M. Kaufman, *Plastics & Polymers*, 37, 243 (1969)
38. N.N., *Engineering*, 114, 606 (1922)
39. H.S. Rowell and D. Finlayson, *Engineering*, 126, 249–250, 385–387, 678 (1928)
40. W.H. Darnell and A.J. Mol, *SPE Journal*, 12, 20 (1956)
41. J.F. Carley, R.A. Strub, R.S. Mallouk, J.M. McKelvey, and C.H. Jepson, 122<sup>nd</sup> Meeting of the American Chemical Society, Atlantic City, NJ (1953). The seven papers were published in *Ind. Eng. Chem.*, 45, 970–992 (1953)
42. Z. Tadmor, *Polym. Eng. Sci.*, 6, 3, 1 (1966)
43. B.H. Maddock, *SPE Journal*, 15, 383 (1959)
44. F. Hensen, W. Knappe, and H. Potente (Eds.), “*Plastics Extrusion Technology*,” Carl Hanser Verlag, Munich (1988)
45. F. Hensen, W. Knappe, and H. Potente (Eds.), “*Handbuch der Kunststoff-Extrusionstechnik, Band I Grundlagen*,” Carl Hanser Verlag, Munich (1989)
46. F. Hensen, W. Knappe, and H. Potente (Eds.), “*Handbuch der Kunststoff-Extrusionstechnik, Band II Extrusionsanlagen*,” Carl Hanser Verlag, Munich (1989)
47. J.L. White, “*Twin Screw Extrusion*,” Carl Hanser Verlag, Munich (1991)
48. M. Xanthos (Ed.) “*Reactive Extrusion*,” Carl Hanser Verlag, Munich (1992)
49. C. Rauwendaal, “*Statistical Process Control in Extrusion*,” Carl Hanser Verlag, Munich (1993)
50. C. Rauwendaal (Ed.) “*Mixing in Polymer Processing*,” Marcel Dekker, NY (1991)
51. I. Manas-Zloczower and Z. Tadmor (Eds.), “*Mixing and Compounding—Theory and Practice*,” Carl Hanser Verlag, Munich (1994)
52. M.J. Stevens, “*Extruder Principles and Operation*,” Elsevier Applied Science Publishers, Essex, England (1985)
53. T.I. Butler and E.W. Veasey, “*Film Extrusion Manual, Process, Materials, Properties*,” Tappi Press, Atlanta, GA (1992)
54. C. Rauwendaal, “*Polymer Mixing, A Self-Study Guide*,” Carl Hanser Verlag, Munich (1998)
55. C. Rauwendaal, “*Understanding Extrusion*,” Carl Hanser Verlag, Munich (1998)
56. C. Rauwendaal, “*Statistical Process Control in Injection Molding and Extrusion*,” Carl Hanser Verlag, Munich (2000)
57. C.I. Chung, “*Extrusion of Polymers, Theory and Practice*,” Carl Hanser Verlag, Munich (2000)
58. J.L. White and H. Potente (Eds.), “*Screw Extrusion: Technology and Science*,” Carl Hanser Verlag, Munich (2001)
59. M. Noriega and C. Rauwendaal, “*Troubleshooting the Extrusion Process*,” 1<sup>st</sup> edition, Hanser Verlag, Munich (2001)
60. G.A. Campbell and M.A. Spalding, “*Analyzing and Troubleshooting Single-Screw Extruders*,” Hanser Verlag, Munich (2013)

# **PART I**

**Extrusion Machinery**



# 2

## Different Types of Extruders

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.