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## Food and Non-Food Biomaterials

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# Contents

# Foreword

Extrusion as a means of forming products has been a mainstay in the food and non-food industries for nearly 100 years and has been used to produce a wide variety of products with a wide range of compositions, densities, structures, and textures. Much work and many publications have, over the years, been devoted to the extrusion of food and non-food biomaterials but few works have successfully brought together the engineering aspects of the extrusion process with the physical and chemical changes made to the product at both the fundamental and practical levels.

The authors of this book, who are truly experts and leading scientists in extrusion technology, have produced a very impressive text that surely will be the standard for many years to come. This work will no doubt be extremely useful not only for academicians but also for practicing engineers. To facilitate a thorough understanding of the process, the authors introduce the concept of the Generic Extrusion Process (GEP) to present in a very comprehensive way the fundamentals of extrusion derived from experience in other industries. The basic functions include melt formation, micromixing and reaction, cooking and texturization, and solid-liquid separation. This concept allows for an understanding of the complexity of the extrusion process, linking science with long-term practical experience.

The book is divided into three parts.

- Part 1: Extrusion equipment design and engineering analysis with emphasis on fundamental engineering principles.
- Part 2: Application of extrusion to food and non-food biomaterials that is demonstrated with numerous case studies.
- Part 3: Emerging extrusion technologies with emphasis on developing sustainable extrusion processes.

Each part is well written and very comprehensive.

It is my belief that this work will stand the test of time and be one of best books on extrusion technology.

Martin R. Okos
Professor, Agricultural and Biological Engineering Department
Purdue University, West Lafayette, Indiana, USA

# Acknowledgements

While this book grows out of several years of experience in extrusion processing technology both in academia and in industry, its final format and content reflect the valuable input of several people. My greatest debt is to my friend Professor Maurice Gélus, now retired, who encouraged me to develop research studies in extrusion processing at the Compiègne University of Technology, France. I would like to thank the professors and the graduate students who worked with me and inspired me in my research work in extrusion at the Compiègne University of Technology. They have contributed importantly to the enrichment of the content of this book. I would also like to extend my gratitude to the management of Clextral Company, France, who gave me the opportunity to use my scientific background to the benefit of product and process innovation and development in extrusion, and be confronted with industrial reality. Undoubtedly, my responsibility in Clextral has significantly enriched my experience in the area and has inspired the format and content of this book. My gratitude goes to my colleagues of Clextral who have contributed their valuable experiences in many aspects related to this book. Many thanks also to my friend Professor Osvaldo Campanella, co-author of this book, for the numerous resourcing exchanges we had before and during the completion of this book.

My final debt is to my close family, my wife Colette, and my children, Jérôme, Bérengère and Guillaume, whose love sustained me confidently through the achievement of this long-term project.

Jean-Marie Bouvier

Several teachers have been influential in stimulating my interest in research and encouraging me to continue graduate studies. I would like to thank Professor Ramon Cerro, now at the University of Alabama, who was my first advisor and mentor in my early research career at the University of Litoral, Santa Fe, Argentina. Professor Micha Peleg, my advisor at the University of Massachusetts, who has not only been a scientific mentor, but also a great friend and colleague all these years. In addition to these mentors and colleagues, I would also like to extend my gratitude to students who helped me to advance in the extrusion area. My thanks also go to colleagues who have shared with me knowledge and experience in extrusion and related areas, and Guibing Chen, Zhengjun Xue, Stanley Harlow, and Brenda Bowen who have contributed to create some figures in the book. Professor Jean-Marie Bouvier, co-author of this book, Clextral and his personnel gave me the opportunity to spend a sabbatical leave with them, initiate the book project and gain an enriching professional and personal experience. My gratitude also goes to Purdue University for their support over all these years and especially during the time I was working on this book.

Last but not least, I would like to thank my wife Estela, daughters Carolina and Cecilia and mother Leda. Without their never-ending support and encouragement this book would not have been completed. I would like to dedicate this book to them for always bringing joy to my life, and also to the memory of my father Osvaldo and sister Marta who have brought joy to my life during the times I shared with them.

Osvaldo H. Campanella

# 1 Generic Extrusion Processes

Extrusion, one of the most important innovations of the 20th century, is often presented as a model of scientific and technology transfer between different processing industries, such as the polymer and plastics, food and feed, and paper-milling industries in particular. Although the first technical designs of screw extruders were introduced in the latter years of the 19th century, extrusion processing really established itself approximately 60 years later, with the development in the plastics industry of polymer-based materials. It was later successfully exploited by the industries that processed plant biopolymers and has developed into a widespread extrusion processing culture over the past 80 years.

The purpose of this introductory chapter is to give a brief historical overview of the emergence of screw extruders and of the extrusion processing culture that owes its existence to the remarkable transfers of technology from polymer processing to food and feed processing and to paper milling.

## 1.1 A history of extrusion processing technology

Extrusion is commonly defined as the operation of forming and shaping a molten or dough-like material by forcing it through a restriction, or die. This operation is extensively applied in many processes as a batch or continuous operation. While adhering strictly to this definition, the understanding and analysis of extrusion are quite simple and straightforward.

Extrusion processing technology relies on a continuous process operation which uses extruders to handle process functions such as the transport and compression of particulate components, melting of polymers, mixing of viscous media, cooking of polymeric or biopolymeric materials, product texturization and shaping, defibering and chemical impregnation of fibrous materials, reactive extrusion, fractionation of solid–liquid media, etc. Extrusion processing technology is highly complex and in-depth descriptions and discussions are required in order to provide complete understanding and analysis of this subject.

Extrusion processing technology uses two different equipment designs: the single screw extruder and the twin screw extruder. Within each design, there are various engineering options, which depend upon the equipment manufacturers and/or the processing requirements. Readers who are interested in a complete historical review of the development of extruders should refer to the excellent and well-documented book by White (1990). This introductory chapter focuses mainly on single screw extruders and intermeshing co-rotating twin screw extruders.

### 1.1.1 The introduction of screw extruders

Single screw and intermeshing co-rotating twin screw extruders appeared over the last 30 years of the 19th century. An 1871 US patent to Sturges (1871) presents a single screw machine for pumping and forming soap. Gray (1879) developed a single screw extruder for processing and extruding gutta percha with specific application to wire coating. In fact, the rubber industry was an early user of screw extrusion machinery for the continuous compounding of rubber. Throughout the period from 1880 to 1930, though no notable industrial application emerged, there was significant mechanical engineering activity that brought remarkable improvements to the designs of the single screw extruder (segmented screws, threaded and grooved liners, pin barrel designs, steam-heated barrels, etc.).

In 1869, the first patent for a fully intermeshing co-rotating twin screw extruder was granted to Coignet (1869). This patent described a machine called a malaxator, which pumped and processed artificial stone paste. There was real development of the intermeshing co-rotating

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twin screw extruder design in the late 1930s, when Colombo (1939) proposed an advanced design which was manufactured by the Italian company Lavorazione Materie Plastiche (LMP). LMP machines were deployed extensively to the polymer industry over the period between 1940 and 1956, through manufacturing licenses (to Clextral, formerly CAFL and then Creusot-Loire in France, to R.H. Windsor in England and to Ikegai Iron Works in Japan), and through exportation sales, to IG Farbenindustrie in Germany, for example.

The introduction of thermoplastics in the 1930s gave a boost to the development of extrusion processing technology. In Germany in 1939, Paul Troester Maschinenfabrick (PTM) built an electrically heated, air-cooled single screw extruder, with automatic temperature control and variable screw speed. This was the precursor to modern automated extrusion technology for the emerging plastics industry. In following years, various ancillary equipments were introduced to meet the process requirements of the polymer-processing industry (venting, breaker plates, screen packs, co-extrusion dies, film blowing, etc.).

As the polymer industry burgeoned, along with the complexity of polymer formulations, single screw extruders showed real processing limitations in their ability to efficiently mix, compound and pump polymer melts of specific characteristics. Then, following World War II and at the request of plastics manufacturers, twin screw extrusion technology was introduced, adding significant value to the process. For example, in July 1956 CAFL delivered its first intermeshing co-rotating twin screw extruder (72.5 mm interaxis) to the French Pechiney company (Pennaroya factory of Noyelles-Godault in France), for manufacturing plastic pipes. At the same time, at the request of Bayer, the German company Werner and Pfleiderer made the first prototype of the ZSK 83 intermeshing co-rotating twin screw extruder. Figure 1.1 shows a vertical intermeshing co-rotating twin screw machine supplied by CAFL in 1963, for nylon and tergal spinning.

It must be noted that screw extruders played a determinant role in the spectacular growth of the polymer-processing industry (plastics and rubber) between 1940 and 1960, when world production of plastics exploded from 300,000 to 12 million metric tonnes per year (Utracki, 1995). And extrusion technology really established its processing potential with the development of the polymer-processing industry, where, together with the availability of reliable machinery, flexible and productive processing could be carried out at a competitive cost-to-performance ratio.

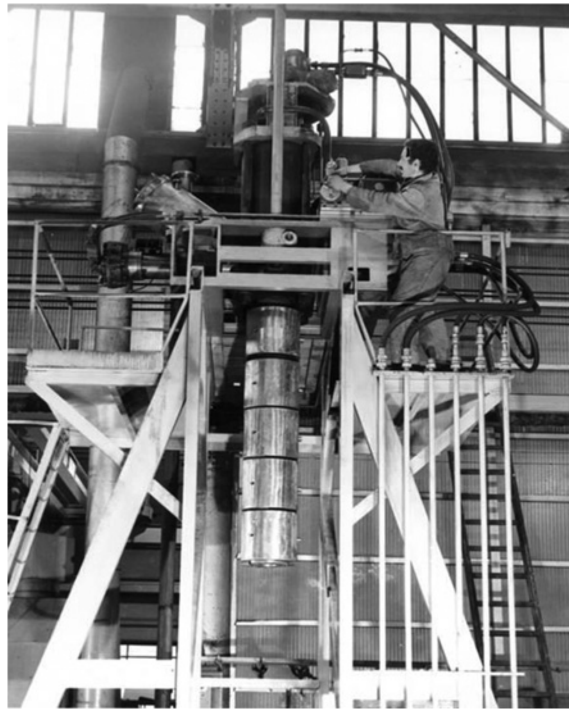

**Figure 1.1** Intermeshing co-rotating twin screw extruder designed in 1963 for nylon and tergal spinning.
Source: Reproduced with permission of Clextral, France.

### 1.1.2 The generic extrusion process concept

The success of extrusion processing technology in the polymer industry resulted in a close relationship between extrusion equipment designers and plastics manufacturers. Both industries pragmatically combined their efforts and skills to make the use of screw extruders technically and economically viable at an industrial level, in order to produce marketable plastic materials.

The term "use of screw extruders" means extrusion processing. This term combines all the relevant technical expertise, know-how and knowledge that allow the process developers to properly operate screw extruders in order to produce the targeted materials with the expected functional and end-use properties. In other words, extrusion processing completes the synthesis, revealing the technical harmony between equipment engineering and product design. This technical harmony, which has revealed itself in the numerous extrusion applications, has led to a few generic processes whose characteristics are worth presenting and analyzing. At this point, the authors wish to introduce the generic extrusion process (GEP) concept as one way of manifesting the synthesis and revealing the fundamentals of extrusion processing technology.

Currently, the GEP concept is fundamental to the presentation and analysis of the extrusion processing culture in a comprehensive way, and is important in achieving the following aims:

- understanding the complexity of extrusion processing technology
- allowing extrusion practitioners to be less dependent on long-term experience when carrying out experimental developments
- linking extrusion science and the long-term experience, the lack of which often dramatically places a limit on the optimal use of screw extruders
- creating the potential for generating new ideas for extrusion applications.

The GEP includes the basic process functions which govern the performances of screw extruders and resulting products in certain groups of extrusion applications. They are presented in the following sections and take into account the industrial application of extrusion processing technology in different fields.

### 1.1.3 Extrusion technology in the polymer-processing industry

The technical synergy which occurred between extrusion equipment manufacturers and the polymer-processing industry led to the first main generic extrusion process, GEP I, "Thermomechanical Plasticating of Polymers and Polymer Melt Forming." Its process functions are applied in a vast number of industrial applications, to process polymeric materials into marketable products. In the extrusion world, this initial generic extrusion process can essentially be considered as the "big bang" of extrusion processing technology, since it has inspired numerous scientists, process engineers, and product manufacturers, and has led to outstanding process and product innovations.

GEP I involves continuous melting, mixing, and forming of polymeric mixtures (polymer resins with various additives) in screw extruders, in order to adjust the processability as well as the physical and chemical characteristics of the resulting compounds, or blends, for future uses. The energy required for this process is provided by heat which can be either transferred by conduction and/or convection between the barrel wall and the material, and/or created by viscous dissipation of mechanical energy into thermal energy. Hence the notion of thermomechanical plasticization of polymers, which has proved to be very efficient, in terms of processing time-temperature history, compared to all other types of alternative processes. The operation can be performed within a short residence time, making it possible to minimize damage to polymers and to preserve their physical and functional properties.

GEP I has many different applications, from the manufacture of simple compounds (polymers compatible with plasticizers and neutral fillers), to speciality compounds and alloys (polymer compounds with active fillers and functional additives). Single screw extrusion is the ideal solution for the production of basic and simple compounds while intermeshing co-rotating twin screw extrusion is better suited to speciality compounds which require a relatively high level of mixing in the extruder and flexibility of the process.

The polymer-processing industry also contributed to the emergence of a second generic extrusion process, GEP II, called "Thermomechanical Micromixing and Reactive Extrusion." This came about in the early 1940s when added-value polymer blends appeared on the market to satisfy specific properties with a broader range of characteristics, depending on the end-uses of the resulting materials. Polymer blend technology aims to combine several components (polymers, highly reactive compatibilizers and impact modifiers; occasionally fillers, fibers, etc.), the end-result being materials characterized by a controlled chemical constitution and morphology. Intermeshing co-rotating twin screw extruders are particularly well suited to continuous reactive processing of polymer blends, as they allow extensive variation in thermal and mechanical energy inputs, control of the residence time and the application of efficient micromixing (intense mixing at the molecular level, due to the intermeshing zone of the screw profile). Thus, the time-temperature-shear history applied in this extruder design shows a satisfactory ability to handle chemical reactions in viscous media. It favorably combines chemical kinetics with the flow and thermal properties of the reactive components and products, in order to control the strong interrelation between processing, material morphology, and product performance.

GEP II is well known and recognized in the polymer-processing industry. It made a significant contribution to the development of the polymer blend industry from the 1960s (polymerization, polymer grafting, cross-linking, etc. applied almost exclusively to synthetic polymers), where extrusion technology offered high added-value processing. As an example, Figure 1.2 shows a two-stage

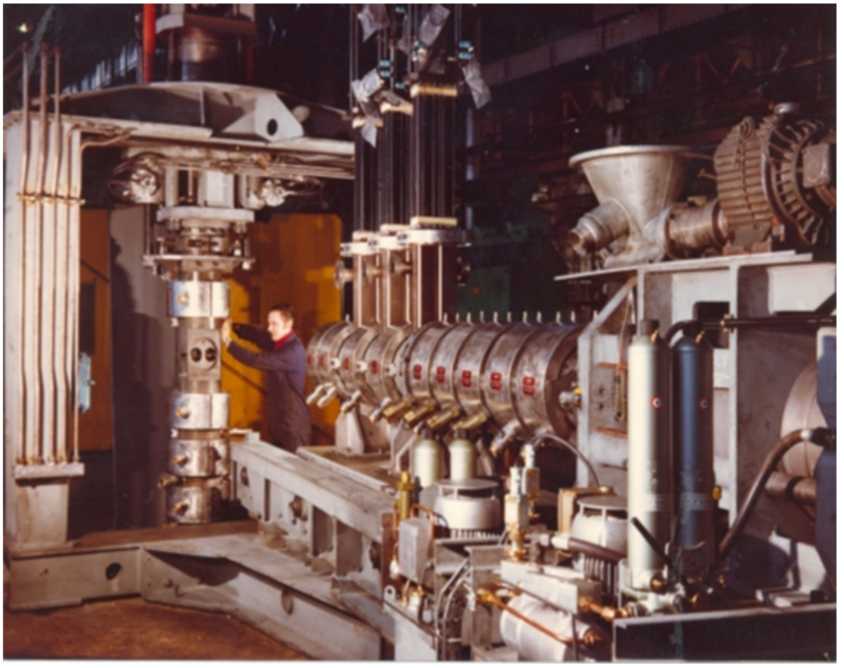

**Figure 1.2** Two-stage reactive extrusion equipment designed in 1966 for polymerization. Source: Reproduced with permission of Clextral, France. For color detail, please see color plate section.

reactive extrusion process applied to continuous rubber polymerization, as well as to nylon and polyester polymerization. It combines two intermeshing co-rotating twin screw extruders in series (one vertical and one horizontal machine). This assembly was designed in 1966, and several units were supplied to the polymer-processing industry.

Today, reactive extrusion is highly active in the technology of blending synthetic polymers, for processing high-performance blends in particular. Besides polymer blending, there are currently very few industrial applications. Among these are the chemical modification of biopolymers such as milk casein converted into caseinates (neutralization of the carboxylic acid functions of casein by use of alkalis) and chemically modified starch for food and non-food uses (hydrolysis, etherification, and esterification). Also, it has been successfully applied to convert diphasic solid–liquid media in the organic chemical industry (e.g. saponification), as well as in the paper-milling industry (e.g. alkaline hydrolysis of lignocellulosics, peroxidic bleaching of cellulose pulps).

Undoubtedly, the role of reactive extrusion can only increase over the coming years with the emergence of biomaterials whose morphology and characteristics can be more precisely tailored to end-use requirements. It can also be used to convert biomass into intermediate components (green chemistry), or to substitute existing batch processes with a significant improvement of processing sustainability.

### 1.1.4 Extrusion technology in the food- and feed-processing industry

The food and feed industry uses screw extrusion technology extensively (both single screw and intermeshing co-rotating twin screw extruders), in particular in two different fields: the cereal-processing industry and the oilseed-processing industry. To date, there has been no real technological synergy between these two industries from the equipment and process engineering standpoints. The cereal-processing industry uses extrusion technology in the second transformation of cereals, which consists of converting cereal flours by kneading, cooking, forming, and texturizing functions to produce both ready-to-eat (RTE) food products and functional ingredients. The cereal-processing industry, due to efficient technology transfer, has benefited considerably from the

(a) (b)

Corn curl snacks
(made on single screw extruder)

Crispy flat bread and co-filled flat bread
(made on intermeshing co-rotating twin screw extruder)

**Figure 1.3** The former extrusion-cooked food products. Source: Reproduced with permission of Clextral, France. For color detail, please see color plate section.

polymer-processing industry in applying extrusion technology to its numerous processes.

The oilseed-processing industry instead uses extrusion technology in the initial transformation of oilseeds which consists of fractionating its main components: the seed hulls, the vegetable oil, and the proteins. This industry has developed specific designs of single screw extruders for solid–liquid separations.

#### 1.1.4.1 Extrusion technology in the cereal-processing industry

Because of the importance of continuous large-scale processing in the pasta industry, it is worth mentioning the development of single screw extruders for continuous pasta pressing in the mid-1930s. The aim is to mix at low shear the ingredients (mainly semolina and water) and pump the resulting dough into a forming die to produce different types of pasta products – long and short pasta. Continuous pasta processing is referred to as cold extrusion (slightly over the ambient temperature), which is now widely used at the start of continuous pasta production lines. Cold extrusion is not covered in this book, as it is extensively described and discussed in many documents and books dealing with pasta processing.

Intermediate/high-shear, hot-extrusion processing appeared almost simultaneously in the cereal-processing industry, due to the remarkable technology transfer of GEP I applied to native cereal-based biopolymers. Harper (1981) presented a well-documented historical review of the deployment of extrusion technology in the cereal-processing industry. A review of the key steps follows.

General Mills Inc. (USA) was the first to introduce a single screw extruder in the processing line of RTE cereals in the late 1930s. The extruder was only used to shape a precooked cereal dough which was subsequently dried and flaked or puffed. In this case, the process functions of the extruder were quite similar to those of pasta pressing. The first expanded, extrusion-cooked product was made in 1936; it was the former corn-based snack product which was commercially exploited by Adams Corporation (USA) from 1946. Figure 1.3a shows the former extrusion-cooked food product (corn curl snack) made using single screw extrusion technology. In the 1950s came the development of dry, expanded extrusion-cooked pet foods. In the 1960s the development of expanded, extrusion-cooked RTE cereals should be mentioned, as well as the introduction of textured vegetable protein (extrusion-cooked soy-based raw materials). All these applications used single screw extruders to continuously process cereal-based raw materials.

Intermeshing co-rotating twin screw extrusion technology was introduced in the late 1960s, spurred on by Clextral and by the industrial and commercial development of crispy flat bread in Europe, which was the result of a collaboration between the CTUC (food technical centre in France), the BSN Group (now the Danone Group), and Clextral. Figure 1.3b shows the former extrusion-cooked food product (crispy flat bread and co-filled flat bread) made using twin screw extrusion technology. From the early 1970s, secure in the potential of twin screw extrusion technology, Clextral successfully promoted intermeshing co-rotating twin screw extrusion technology worldwide to the major segments of the cereal-processing industry (snacks, RTE cereals, textured vegetable proteins, food ingredients such as precooked flours, encapsulated flavors, pet foods, etc.). Then, from the early 1980s, other manufacturers joined Clextral to supply twin screw extruders to the cereal-processing market. It must be noted that the former extrusion-cooked food products (corn curl snack and crispy flat bread) are still on the market today, and they lead their market segment.

Another user of screw extruders is the fish feed industry. In the 1970s, it adopted extrusion technology (single screw and intermeshing co-rotating twin screw extruders) to mix, cook, and texturize aquafeed pellets according to the various needs of fin and shell fish, making it possible to intensify aquaculture with high productivity, while preserving the health of both animals and environment. In this field, large extrusion units are used for producing the main supply of aquafeed pellets. As an example, Figure 1.4 shows a large intermeshing co-rotating twin screw extruder (200 mm screw diameter), able to process approximately 25 metric tonnes of feed mix per hour, which gives approximately 30 metric tonnes of finished aquafeed pellets per hour (after drying and fat coating, in the case of typical salmon feed, for example).

Nowadays, the cereal-processing industry is the second most important user of extrusion technology, owing to an efficient technology transfer of GEP I. Cereals are composed of natural plant polymers or biopolymers, mainly starch polymers (the fractions of amylose and amylopectin), which are neutral semi-crystalline macromolecules, and polymers combining natural amino acids (proteins), which are amphoteric macromolecules. When applying GEP I to native biopolymers with water as the plasticizer, thermomechanical melting of biopolymers occurs, which causes irreversible physicochemical modifications, making them easily digestible by human and animal digestive systems. This has given rise to a new method of continuous cooking of starchy and proteinaceous foodstuffs called high-temperature, short-time (HTST) extrusion cooking which favors mechanical action for the conversion of starches and proteins and consequently offers a unique alternative to traditional hydrothermal cooking. Extrusion cooking of starchy and proteinaceous materials is intended to give the resulting products a specific texture (on the macromolecular and macroscopic level) for a sensory and functional purpose (Guy, 2001; Mercier et al., 1989).

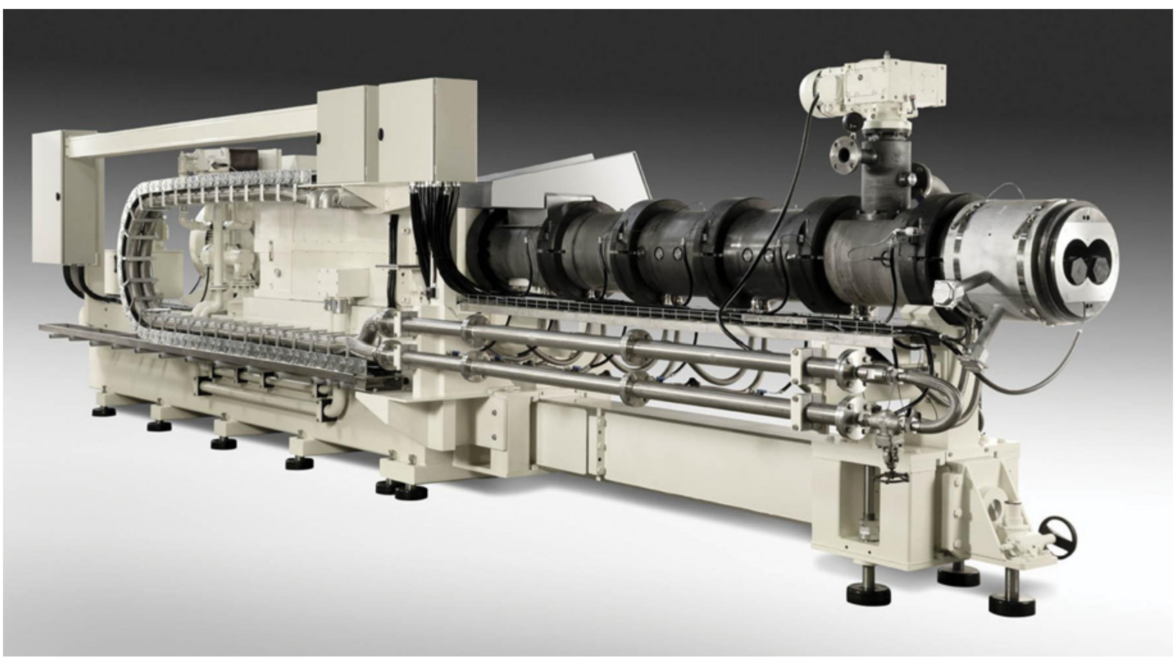

**Figure 1.4** Large intermeshing co-rotating twin screw extruder (200 mm screw diameter) used in the aquafeed processing industry. Source: Reproduced with permission of Clextral, France.

The cereal-processing industry subsequently developed an innovative GEP III called "Thermomechanical Cooking and Food Product Texturization." It was immediately adopted by the food and feed industry for processing starch- and protein-based raw materials, resulting in crispy, textured human-food products (snacks, breakfast cereals, textured vegetable proteins, etc.) and textured animal food products (pet foods and aquafeed pellets in particular).

Both single screw and intermeshing co-rotating twin screw extruders are used. Single screw extrusion is generally used for simple formulations and easy-to-control product characteristics, while intermeshing co-rotating twin screw extrusion is better suited to mixtures with several ingredients and products which require greater flexibility and control of quality. Both single screw and twin screw extrusion technologies are now well established in their respective markets within the cereal-processing industry, on the basis of technical and economic criteria.

#### 1.1.4.2 Extrusion technology in the oilseed-processing industry

The first transformation of oilseeds aims to fractionate their main components by use of a continuous process with the following unit operations in series: dehulling, grinding, thermal cooking, mechanical pressing, and solvent extraction (Laisney, 1984). Mechanical pressing is mainly required for high fat content oilseeds such as sunflower seeds, rapeseeds, cotton seeds, etc.

Mechanical pressing consists of separating part of the oil from the seeds. Originally made by using batch hydraulic presses, the move to continuous mechanical pressing was particularly challenging for the oilseed-processing industry. This became possible when Anderson (USA) created the first continuous single screw press in 1904. Thanks to the efforts of Anderson and a number of other suppliers, this became really popular in the oilseed industry following World War II. Continuous twin screw pressing of oilseeds has been investigated fairly recently, in the 1990s (Bouvier & Guyomard, 1996), but has not yet been industrialized. Though it has been applied in a different industrial field (the paper-milling industry), the first intermeshing co-rotating twin screw press was introduced by Clextral in late 1970s (see section 1.1.5).

The design of single screw presses is similar to that of single screw extruders. The main difference is in the barrel of the single screw press which has openings to collect the oil when it is expressed from the seeds through the pressing effect of the rotating screw. The proteinaceous meal is then extruded at the exit of the screw-barrel assembly.

Continuous single screw pressing has been deployed to other agro-food processing industries to eliminate liquid aqueous juices from various agro-materials such as sugar beet pulp, alfalfa, etc., thus increasing the dryness of those materials at high energy efficiency.

The introduction of continuous screw pressing for solid–liquid separation led to GEP IV, called "Thermomechanical Pretreatment and Solid–Liquid Separation." This process makes the most of the mechanical energy input to generate pressure along the screw and compress plugs of material from which the liquid exudes, while the screw design makes it possible to fine-tune both the pressure distribution and the free volume and to convey the plugs forward. As the barrel has filtering sections where pressurization occurs, continuous fractionation of the liquid is obtained.

GEP IV is most important for the processing industries that deal with biomaterials for food and non-food uses. In fact, it offers a real opportunity to potentially save energy in solid–liquid separation processing, by eliminating water in its liquid state and significantly reducing the amount of water when water-aided extraction is required, leading to environmentally friendly processing. Therefore, GEP IV is a worthwhile and relevant subject for presentation and analysis in this book.

#### 1.1.4.3 An emerging, innovative generic extrusion process

Extrusion technology is still spreading through new processing industries. Engineers and researchers continue to come up with new ideas and invent new processes and products in all fields, both to improve the performances of existing processes and to satisfy new needs expressed by society.

In view of this, there is one innovative GEP that needs to be mentioned. It is presently in the development phase and should reach industrial maturity in the coming years. This new process concerns the field of instant porous powders produced from liquid or from liquid–solid concentrates for food and non-food uses. Instant powder production technology must be able to handle the dehydration of the starting material and the texturization of the resulting powder. The most widespread technologies and processes used are spray drying, drum drying, and freeze drying. One characteristic of these technologies and processes is their generally high investment and operating costs (notably energy), sometimes prohibitively so. Because of its capability to deal with viscous media, to texturize and form mono- and multiphase mixtures, intermeshing co-rotating twin screw extrusion technology is a valuable aid in handling instant powder products and "porosifying" (creating porosity), more cost-effectively than traditional processes and technologies.

The advantages and potential of twin screw extrusion in processing and functionalizing porous powders have led Clextral and its partners to take a hands-on interest in the field in recent years (Bouvier et al., 2006). The current R&D investigations have lead to GEP V, called "Thermophysical Micromixing and Material Porosification." It is also called the "Extrusion-Porosification" process, by its inventors.

This process aims to use the mixing efficiency of intermeshing co-rotating twin screw extrusion technology to mix gases into viscous media, in order to produce aerated foams which lead to porous particles when later dried. This process was invented during consideration of the requirements of the dairy industry for improved performances of the spray-drying process (to reduce operating costs and increase process flexibility) in the production of powders from milk and dairy co-products. However, the dairy industry aside, the process is conceptually generic, as it can be applied to various types of powders (food and non-food) which require easy and quick rehydration for use. For this reason, the authors have dedicated a full chapter in this book to this emerging new extrusion process in the field of porous powder texturization.

### 1.1.5 Extrusion technology in the paper-milling industry

The paper-milling industry is the third most significant user of extrusion technology, owing to two consecutive technology transfers, one from the polymer-processing industry and the other from the food- and feed-processing industry. It adopted extrusion technology quite recently, in the late 1980s, to promote environmentally friendly continuous processing of lignocellulosic materials.

Actually, the adventure began at the end of the 1970s when process engineers and technologists attempted to use intermeshing co-rotating twin screw extrusion

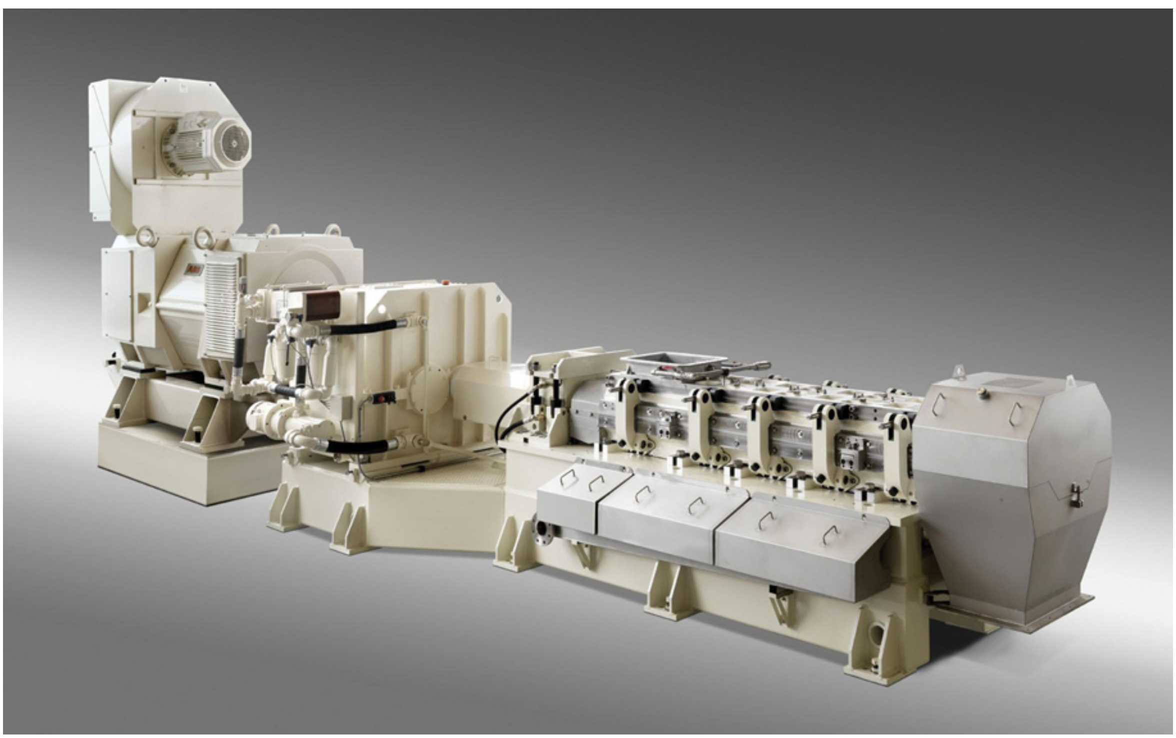

**Figure 1.5** Intermeshing co-rotating twin screw extruder (240 mm screw diameter) used in the paper-milling industry. Source: Reproduced with permission of Clextral, France.

for cellulose fractionating, to take advantage of the continuous nature of the extrusion process and minimize the consumption of utilities (water, energy, and chemicals). This represented a real technological breakthrough for the paper-milling industry, and was the result of the collaboration between Clextral and the Centre Technique du Papier (Grenoble, France), which played a decisive role in the success of this invention. At present, Clextral is the only twin screw extrusion equipment manufacturer in the world that is capable of handling this application. Figure 1.5 shows a Clextral intermeshing co-rotating twin screw extruder for the paper-milling industry.

The extrusion fractionating process includes several unit operations in two intermeshing co-rotating twin screw extruders in series, which use two generic extrusion processes presented earlier, GEP II and GEP IV, as follows.

- In the first extruder, mechanical defibering of lignocellulosics and chemical impregnation of the plant substrate are carried out. This unit exploits the principles of reactive extrusion (GEP II) in a solid–liquid medium to digest the lignin component and bleach the cellulose pulp, making it possible to significantly decrease the consumption of chemicals and reduce the total processing time.
- In the second extruder, washing and fiber refining of the cellulose pulp take place through continuous solid–liquid separation. This unit exploits the principles of mechanical expression (GEP IV), through the ability of the intermeshing co-rotating twin screw extruder to generate pressure build-up sections, thus creating a series of dynamic plugs which cause the separation of the liquid (liquor) from the solid fibrous substrate (cellulose). Mechanical expression allows very effective washing to be achieved with small amounts of water, which leads to an important saving of water, compared with traditional cellulose-washing processes.

Because of the technical and economic environment for cellulose fractionation, twin screw extrusion technology is used for speciality pulps from annual plant by-products such as cotton-based pulp for bank notes and security papers, flax- and hemp-based pulp for cigarette papers and filter papers, and cotton-based pulp for printing and writing paper, etc.

## 1.2 Factors driving the development of extrusion processing technology

Given the major applications that were developed and successfully industrialized in the 20th century, it appears that the adoption of extrusion technology in the processing industries was driven by the following three factors.

- Process productivity (continuous, flexible, versatile processing)
- Product innovation and functionality
- Environmentally friendly processing

### 1.2.1 Process productivity

Extrusion is a continuous process. This is a determinant characteristic in industrial processing, particularly when dealing with viscous media. Actually, early developments and industrialization of screw extruders were driven by continuous processing, such as pasta screw pressing, oilseed screw pressing, and polymer processing. And continuous extrusion processing has been always valuable when promoting extrusion-processed materials at an industrial level.

Extrusion is a flexible and versatile process, due to the modularity of the screw configuration and the wide variations of independent process variables, which make it possible to make extensive adjustments to the processing conditions (energy inputs, residence time, temperature profile, on-line addition of ingredients, etc.), depending upon process requirements and characteristics of the materials. It should be noted that screw extruders can handle a wide variety of media (various viscosities and rheological behaviors and both single- and multiphase mixtures), process functions (intense mixing, chemical reactions, cooking, physical separation, cooling, degassing, etc.) and product characteristics (forming, shaping, texturizing, etc.). Continuous, flexible, versatile processing is globally linked to process productivity. This has been particularly well investigated and exploited in the following fields: polymer processing, oilseed processing, feed processing, and cost-competitive manufacturing.

### 1.2.2 Product innovation and functionality

Extrusion technology has brought determinant value to processing industries in several areas by permitting material and product innovation, in particular through the following:

- physical and chemical fine-tuning of functional properties of the end-products, including polymer blending, modified starches, flavor encapsulation, etc.
- physical fine-tuning of end-use properties of the finished products such as structured polymer-based materials (such as multilayer films, reinforced composites, etc.), textured food and feed cereal-based products (crispy flat

bread, multigrain snacks, crispy-crunchy cereals, chewy pet treats, aquafeeds, etc.).
The growth, in both volume and value, of extrusion-processed materials and products (for food and non-food uses) in the business-to-business and the business-to-consumer markets indicates how defining the impulse of extrusion technology was in the dynamism of product innovation in various processing industries.

### 1.2.3 Environmentally friendly processing

Continuous extrusion is characterized by low processing volumes and relatively low residence times, compared to traditional batch processing. In other words, the extrusion processing volume is restricted in comparison with the processing volume of current agitated vessels. As a matter of fact, the rate of physical and chemical modifications that occur in extrusion processing is usually far higher (heat, mass and momentum transfers, reaction rates, for example) due in particular to significant mechanical energy inputs. This places extrusion processing technology in the process intensification class, leading to economies in energy, raw materials and consumables, a reduced equipment footprint and reduced investment costs compared to non-intensified processing, thus minimizing the impact of the processing industries on the environment.

The positive impact of extrusion processing technology on the environment became particularly noticeable from the 1980s, when promoting this technology in the aquafeed-processing and paper-milling industries. This factor will certainly become increasingly important over the coming years and decades, given the trend driven by sustainable development, which should increasingly encourage process intensification in processing industries.

## 1.3 The industrial and economic importance of extrusion processing technology

From the early designs of screw extruders in the latter years of the 19th century until now, important industrial activity and business have been generated in two main fields:
• *extrusion equipment engineering*; that is, companies which deal with equipment design and manufacturing
• *extrusion process engineering*; that is, processing industries which deal with product design and manufacturing.
Extrusion-related industries really started to develop significant business in the 1930s, when processing industries had to create the appropriate technologies for processing viscous polymer-based materials. Since then, screw extruders have made important contributions to the growth of those industries, which have continuously benefited from the engineering input of equipment manufacturers.

Nowadays, owing to the successful technology transfers that occurred over the 20th century, three main processing industries use extrusion technology in their production units:
• polymer and plastics industry
• food and feed industry
• paper milling industry.
Though there are no established statistics, the industrial impact of extrusion processing technology can be qualitatively assessed. There are several thousand screw extruders presently in operation, with approximate distribution as follows:
• two-thirds of screw extruders in the polymer-processing industry
• approximately 30% of screw extruders in the food- and feed-processing industry (which includes both the cereal-processing and oilseed-processing industry)
• and the balance (less than 5% of screw extruders) in the paper-milling industry and in miscellaneous processing industries such as the chemical (fine chemicals, minerals) and pharmaceutical industries, etc.
The industrial application of extrusion processing technology has generated no less than 100 applications. Some of the major applications used in processing industries include the following.

### 1.3.1 In the polymer and plastics industry

Plastic films for bags, buildings; plastic pipes for water, gas, drains; plastic tubing for automobiles, control cable housing, medical use; plastic insulated wire for the home, automobiles, appliances, electric power distribution; plastic-coated paper for film cartons, meat packaging, moisture barriers; plastic sheeting for formed products, lighting; plastic profiles for sliding and storm windows in the home; polymer alloys, masterbatches, fiber-reinforced composites for compression, injection; energy materials, plastics recycling and reprocessing, modified biopolymers (starches, proteins), and much more.

### 1.3.2 In the food and feed industry

3D snacks, snack pellets, 3D breakfast cereals, pellet-to-flakes cereals, co-filled cereals, crispy flat bread, textured

**Table 1.1** Extrusion processing technology: synthesis.

| Generic extrusion process | Major process functions | Screw extruders used | Relevant applications concerned |
|---|---|---|---|
| I | Thermomechanical polymer melting<br>Mixing<br>Material forming | SSE and TSE | Polymer compounding<br>Plastics shaping/forming<br>Masterbatches<br>Fiber-reinforced composites |
| II | Thermomechanical micromixing<br>Chemical reaction<br>Cooling | TSE | Polymer blends<br>Chemically modified biopolymers<br>Hydrolysis of lignocellulosics and cellulose pulp bleaching |
| III | Thermomechanical plant biopolymer melting<br>Mixing and cooking<br>Product texturization/shaping | SSE and TSE | Snacks and breakfast cereals<br>Crispy flat bread<br>Pet foods and aquafeeds<br>Textured proteins |
| IV | Thermomechanical pretreatment<br>Solid–liquid separation | SSE and TSE | Oil separation from oilseeds<br>Dewatering of agro-products |
| | + Material refining | TSE | Cellulose pulp washing and refining |
| V | Thermophysical micromixing (gas–liquid)<br>Cooling<br>Product porosification | TSE | Instant porous powders<br>(food and non-food products) |

SSE, single screw extruder; TSE, intermeshing co-rotating twin screw extruder.

vegetable proteins, encapsulated flavors, casein-to-caseinates, dry pet foods, pet treats, aquafeeds, oilseed fractionation, sugar beet dewatering, alfalfa dewatering, etc.

### 1.3.3 In the paper milling industry

Cellulose pulping for speciality papers (bank notes, security papers, cigarette papers, filter papers, etc.), wood pulping for horticultural uses, etc.

Table 1.1 gives a synthesis of extrusion processing technology. For each of the generic extrusion processes I–V, the main process functions applied in the extruders are reviewed, together with the screw extruders used and the resulting major applications.

## 1.4 Contents and structure of the book

Industrial applications of extrusion technology have led to the establishment of a rich extrusion processing culture which has emerged progressively from continuous interaction between practitioners and scientists. This is particularly true where extrusion processing media are based on synthetic polymers. As this field has been a former user of extrusion technology, it has had the advantage of extensive scientific investigation and modeling, making it possible to predict process performances. Polymer extrusion processing applied to synthetic polymers has led to many relevant scientific and engineering developments, and the resulting information given in numerous books is particularly rich and well documented.

However, biomaterials extrusion processing (for food and non-food uses) is relatively new for most of the applications, and it suffers from a lack of written information. In addition, this field tends to be more segmented and application oriented. In biomaterials extrusion processing, an accumulation of long-term experience generally precedes the scientific developments, since it usually deals with complex raw materials whose characteristics are not sufficiently known. A multidisciplinary approach to extrusion processing must then be applied, for which the complete prediction of the process performances is not yet available.

The purpose of this book is to provide an engineering analysis of extrusion processing technology dedicated to biomaterials, for food and non-food uses. The content has been inspired both by existing applications of extrusion technology and by emerging applications that are mainly the result of sustainable development. The objective of this work is to broach the distance between long-term experience in extrusion and the science of extrusion, in order to create a link between the world of extrusion practitioners and that of extrusion scientists in the field of biomaterials. For this purpose, the generic extrusion process concept (as described in section 1.1.2) has been applied in order to present and discuss the extrusion processing culture and to organize the framework of the book content.

Apart from this introductory chapter, the book is composed of three main parts and nine chapters.

## Part I: extrusion equipment and extrusion engineering

Chapter 2 reviews the basics of the design and configuration of extrusion equipment. It is dedicated mainly to single screw extruders and intermeshing co-rotating twin screw extruders, as well as to ancillary equipment which is relevant to extrusion processing.

Chapter 3 gives an engineering analysis of extrusion processing (fluid mechanics and transport phenomena) in close relation to the process functions which are presented and discussed in Part II through the generic extrusion processes. Of great interest to extrusion practitioners is the comparison between single screw and twin screw extrusion, which is included at the end of the chapter.

## Part II: generic extrusion processing and industrial applications

Chapter 4 presents and analyzes GEP I, focusing on extrusion processing of bio-based plastics. Resulting applications are included, such as extrusion processing of biodegradable materials and fiber-reinforced composites.

Chapter 5 presents and analyzes GEP II, focusing on reactive extrusion applied to the functional modification of biomaterials for food and non-food uses.

Chapters 6 and 7 are concerned with GEP III, focusing on extrusion cooking of plant biopolymers and methods relating to quality analysis of extrusion-cooked food products. Relevant existing and emerging applications are included.

Chapter 8 deals with the presentation and analysis of GEP IV, focusing on existing applications of screw extrusion pressing. Relevant industrial applications are considered.

## Part III: the prospects for extrusion processing technology

Chapter 9 presents and discusses the emerging GEP V, focusing on bio-based instant porous powders. Although this process has not yet been applied at an industrial level, its potential in terms of industrialization is discussed.

Chapter 10 presents the process intensification concept, and discusses the ability of extrusion technology to intensify specific process functions and, in doing this, to meet the requirements of sustainable development in the processing industries.

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# 2 Extrusion Equipment

It is worth describing the design of extrusion equipment in this chapter, particularly hardware components, which have a direct impact on extrusion processing performance. Single screw and intermeshing co-rotating twin screw extruders are considered exclusively, as they both support the generic extrusion processes which are presented and analyzed in the following chapters.

Screw extruders are composed of four main parts, which are generally supported by a frame (Figure 2.1).

- The kinematics (motor and gearbox, in particular), which delivers the mechanical power required by the extrusion process.
- The screw-barrel assembly, in which the material is converted.
- The die assembly, through which the converted material is shaped, formed, or textured, depending upon the targeted products.
- The central operating cabinet or "brain" of the equipment, which monitors equipment operation (control of independent variables, automation, equipment security, display, etc.).

Equipment parts are presented in this chapter, with emphasis on the hardware of the screw-barrel assembly, the design of which determines the quality of the product obtained in the extrusion process. Screw extruders are associated with ancillary equipment the role of which is to suitably preprocess raw materials upstream, or postprocess products downstream; sometimes they manage on-line the addition or removal of process-related components. Thus, most important ancillary equipments required for traditional extrusion processing are also presented.

The aim of this chapter is not to provide a complete and exhaustive mechanical engineering background on the hardware of extruders and ancillary equipment, but rather to point out those engineering characteristics which are important for successful extrusion processing. Readers who are interested in a detailed description of the hardware of extruders should refer to the excellent and well-documented books published by Martelli (1983) and Rauwendaal (2001).

## 2.1 Extruders

Figure 2.1 shows a schematic view of an extruder and its major parts, all supported by a frame. This can be either a fixed frame or a ready-to-open frame which allows quick, easy access to the screw configuration for cleaning, checks, and maintenance, in particular. The frame opening can be handled either manually or with electrical assistance. Ready-to-open frames are offered by a few suppliers of intermeshing co-rotating twin screw extruders, for the food and feed industry, as well as for the paper-milling industry, as this design does offer recognized operating and economical added value through improved process productivity and flexibility.

The characteristics and functions of extruder parts with respect to their major functions in extrusion processing are now described.

### 2.1.1 The kinematics of extruders

The kinematics of extruders is composed of a motor drive system and a gear reducer, the designs of which determine the torque-speed domain covered by the extrusion equipment. The torque-speed domain is fundamental to defining the extruder's performance in terms of process productivity and product conversion.

#### 2.1.1.1 The gear reducer

The gear reducer transmits the power supplied by the motor to the shank of the screw, the screw shaft for single screw extruders, or the two screw shafts for intermeshing co-rotating twin screw extruders. The gear reducer also

*Extrusion Processing Technology: Food and Non-Food Biomaterials*, First Edition. Jean-Marie Bouvier and Osvaldo H. Campanella.

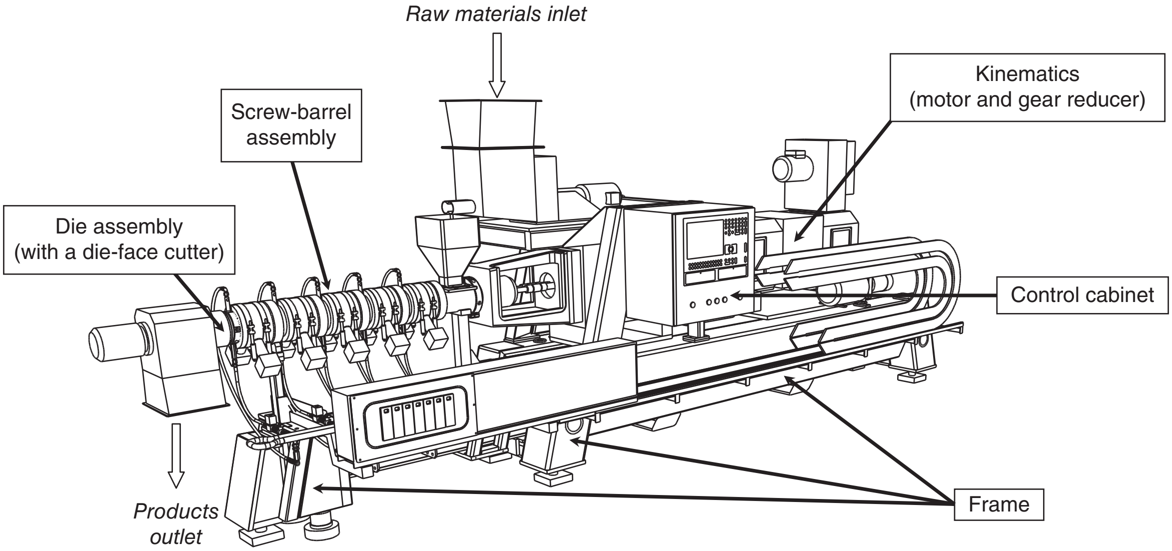



**Figure 2.1** Schematic view of an extruder with the major parts. Source: Reproduced with permission of Clextral, France.

has to match the relatively low speed of the screw(s) to the high speed of the motor drive. The mechanical design of the gear reducers defines the torque-speed domain of the extruder and therefore, the maximum torque and screw speed available for extrusion processing. It should be noted that the efficiency of gear reducers is high, generally greater than 95%.

The design of a twin screw extruder gear reducer is more complex, as it must symmetrically divide the torque between each screw. It is composed of two stages: the first stage reduces the speed of the motor drive (1200 to 2000 rpm) to the final speed of the screws (generally 100 to 1200 rpm for modern intermeshing co-rotating twin screw extruders), while the second stage distributes torque between the two screw shafts. The design and manufacturing of high-performance gear reducers require a high level of expertise due to the tightness of the interaxis of the exit shafts.

Manufacturers have tremendously improved the design and performance of gear reducers over the past 30 years. This is clearly illustrated by the development of the standard maximum torque density-speed characteristics of intermeshing co-rotating twin screw extruders, which progressed from about 2.5 N.m/cm$^3$-250 rpm in the 1970s, to 12 N.m/cm$^3$-1200 rpm in the 1990s. This allowed end-users to significantly improve the competitiveness of extrusion processes through process productivity and product functionalities. Over the same period of time, gear reducers have achieved a high level of reliability which today ensures long lifetimes, over 50,000 hours for most extrusion applications, provided end-users rigorously adhere to the appropriate maintenance and lubrication procedures.

#### 2.1.1.2 The motor drive

The motor drive system allows the torque and screw speed to be fine-tuned according to process requirements, i.e.:

- it maintains a constant screw speed
- it varies the screw speed over a relatively wide range
- it operates at constant torque over the range of screw speed.

Two main motor drive systems are available: DC and AC. Currently, the DC motor drive system is the one most commonly used for both single screw and intermeshing co-rotating twin screw extruders, as it covers a very wide range of screw speed from zero to the nominal speed, and accurately controls the exit torque which is strictly proportional to the intensity of the current delivered to the motor. This system is simple and cost-effective. The main drawback to using DC motors is maintenance of the brushes and commutator.

The AC motor, together with the frequency drive, is increasingly used, as its performance has significantly improved in recent years. It is reliable and, unlike the DC motor, it requires very low maintenance.

Though it is rarely used on regular extruders, it is worth mentioning the hydraulic drive system. It generally consists of a constant-speed AC motor driving a hydraulic pump which drives a hydraulic motor. This system can be controlled quite well, and has a satisfactory level of efficiency and reliability. It is sometimes used in critical environments (explosive environments, for example), or in situations where a very compact extrusion processing unit is required, as the pump assembly can be physically separated from the extruder.

#### 2.1.1.3 Process operation

In practice, most single screw and intermeshing twin screw extruders operate at constant torque over the range of screw speeds. Thus, torque-speed characteristics can be used to determine power-screw speed characteristics by using the well-known relationship $P = CM_dN$, where $P$ is the power (expressed in W), $M_d$ the screw torque (expressed in N.m), $N$ the screw speed (expressed in revolutions per minute, or rpm), and $C$ a constant ($C = 2\pi/60$).

If the torque is consistent with the screw speed, then the power is directly proportional to the screw speed. Thus, the maximum power of the drive is utilized when the motor is running at full speed. Mechanical power consumption is mainly determined by the screw configuration, process throughput, and rheological characteristics of the material in the screw-barrel assembly. Figure 2.2 demonstrates the evolution of the normalized mechanical power, *PN*, consumed by an intermeshing co-rotating twin screw extruder, as a function of the productivity index, *IP*. *IP* is the ratio of the volumetric throughput to the free volume of the screw-barrel assembly, for three different material viscosities assuming a Newtonian

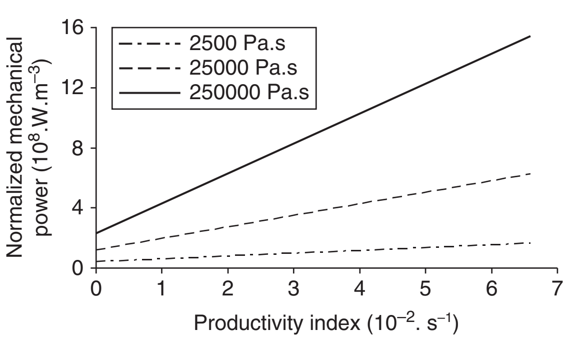



**Figure 2.2** Normalized mechanical power as a function of productivity index (calculations made from LUDOVIC® software).

behavior. Note that *PN* and *IP* are independent of the size of the extruder. Figure 2.2 was based on calculated data obtained from LUDOVIC® computer software at constant screw configuration (Della Valle et al., 1993; Sciences Computers Consultants, 2013). As the calculation assumed Newtonian behavior of the material, the figure shows a linear relationship between *PN* and *IP*, the slope of which increases when material viscosity increases. Values of *PN* at $IP = 0$ correspond to the power consumed with zero throughput where the extruder barrel theoretically contains some material in the filled sections; in this case, *PN* at $IP = 0$ is as high as the material viscosity. Obviously, the capacity of the extruder is governed by screw speed with low-viscosity materials (in the case of feed applications, pet food and aquafeed extrusion processing, for example), while it is governed by torque with high-viscosity materials (in the case of thermoplastic polymer extrusion processing, for example).

It is worth mentioning that a lot of consideration must be given to the kinematics as it has a significant effect on extrusion processing performance. Firstly, the torque-speed characteristics of the kinematics determine the productivity of the extrusion equipment. Secondly, the ability of the kinematics to consistently manage the screw speed, that is, maintain a constant screw speed in a stationary state and vary the screw speed over a relatively wide range, determines both the flexibility and stability of extrusion processing.

### 2.1.2 The screw-barrel assembly

Mechanical power is delivered to the screw-barrel assembly via a thrust bearing box which, in the case of single screw extruders, corresponds to the point where the screw shank, or the screw shaft, connects to the output shaft of the gear reducer; in the case of twin screw extruders, this is where the screw shafts connect to the output shafts of the gear reducer.

The screw-barrel assembly is the central part of an extruder. It receives the main stream of raw materials at the feed port and then it physically and chemically converts them using thermal and mechanical energy, according to product requirements. Its design requires special consideration as it contributes to process performance and the quality of targeted products.

There are two main categories of screw-barrel assembly.

- The "monobloc" screw-barrel assembly, which consists of a single-piece, solid screw surrounded by a cylindrical

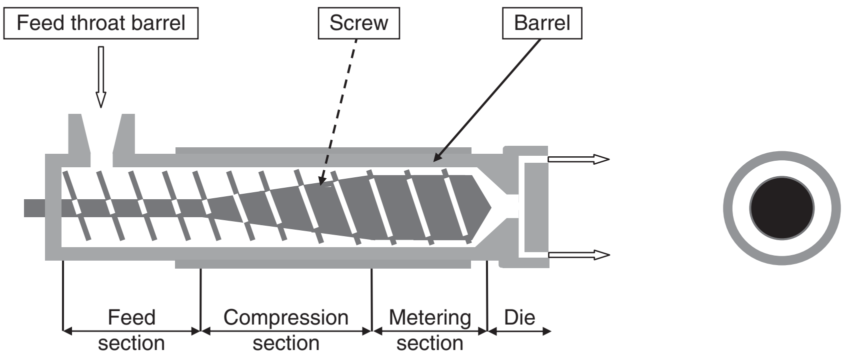



**Figure 2.3** Schematic view of a one-stage 'monobloc' screw-barrel assembly with operating sections.

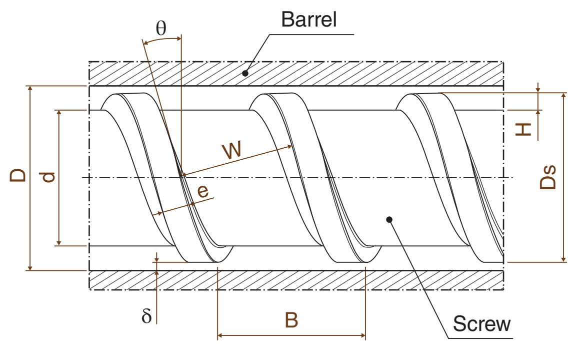
barrel. This is the simplest and most traditional design for the single screw extruder screw-barrel assembly.

- The “modular” screw-barrel assembly, which consists of segmented worm screw elements and a barrel. This design is found on advanced single screw extruders, and is used as standard on intermeshing co-rotating twin screw extruders.

### 2.1.2.1 The “monobloc” design

Figure 2.3 presents a simple version of a single-piece, single-flighted worm screw of a conventional plasticating single screw extruder. It shows three distinct geometrical sections with a channel having variable depth and constant pitch.

- The first section, called the feed section, has deep flights, in order to offer a high transportation capacity for solid and particulate raw material (solid powders and particulates). Its function is to convey the material down the screw.
- The following section, called the compression section, is where the material is compressed under the compressive effect of the screw (in a channel of decreasing depth). At the same time, the material is heated by interparticular friction and conductive heat transfer until melting occurs. In this section, the material changes from a solid particulate state into a melt state (viscous fluid). This is the longest section, and is essential for correct operation of the extruder, as it must be designed in such a way as to completely melt polymeric materials. The melting mechanism of polymeric materials is analyzed in Chapter 4.
- The third section, called the metering section, is where the material is ideally in a molten state. This is a pumping section in which the pressure needed to convey and feed the molten material through the die opening is built up. But it can also be used to fine-tune conversion of the




- Internal diameter of the barrel: D
- Screw root diameter: d
- Screw pitch: B
- Flight width: e
- Screw clearance: δ
- Actual screw diameter: Ds = (D − 2δ)
- Actual height of screw flight: H = (Ds − d)/2
- Channel width: W = B.cosθ − e
- Length of channel in one complete turn of the helix: Z = B/sinθ
- Peripheral speed of the screw: V = π.Ds.N ≈ π.D.N

**Figure 2.4** Geometry of screw-barrel assembly of single screw extruder (monobloc design).

material. In fact, the metering section is characterized by shallow flights which generate high shearing conditions. The mechanical energy dissipated allows the material to be converted into a rheological state which is compatible with satisfactory processing and forming. The melt flow mechanism of molten polymers is analyzed in Chapter 3.

The monobloc screw-barrel assembly is traditionally defined by geometrical parameters, which are presented in Figure 2.4.

The screw pitch determines the helix angle $\theta$, i.e. the angle which the flight makes with a plane normal to the