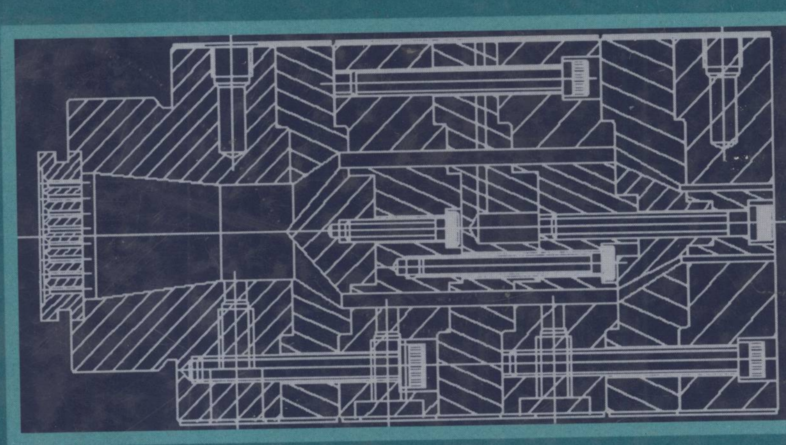
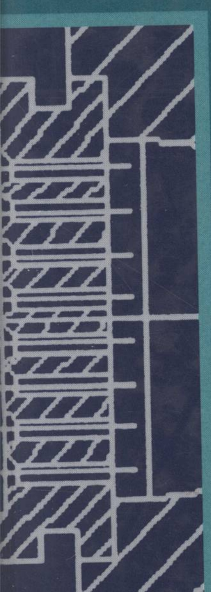
Extruder Principles and Operation

Second edition





M.J. Stevens
and J.A. Covas

CHAPMAN & HALL

Extruder Principles and Operation

Second edition

M. J. Stevens

Formerly, Institute of Polymer Technology
Loughborough University of Technology, UK

and

J. A. Covas

Department of Polymer Engineering
University of Minho, Braga, Portugal

CHAPMAN & HALL

London · Glasgow · Weinheim · New York · Tokyo · Melbourne · Madras

Published by Chapman & Hall, 2–6 Boundary Row, London SE1 8HN, UK

Chapman & Hall, 2–6 Boundary Row, London SE1 8HN, UK

Blackie Academic & Professional, Wester Cleddens Road, Bishopbriggs, Glasgow G64 2NZ, UK

Chapman & Hall GmbH, Pappelallee 3, 69469 Weinheim, Germany

Chapman & Hall USA, 115 Fifth Avenue, New York, NY 10003, USA

Chapman & Hall Japan, ITP-Japan, Kyowa Building, 3F, 2-2-1 Hirakawacho, Chiyoda-ku, Tokyo 102, Japan

Chapman & Hall Australia, 102 Dodds Street, South Melbourne, Victoria 3205, Australia

Chapman & Hall India, R. Seshadri, 32 Second Main Road, CIT East, Madras 600 035, India

First editon 1985

Second edition 1995

Typeset in 10/12 pt Times by Thomson Press (I) Ltd., New Delhi, India

Printed in Great Britain at the University Press, Cambridge

ISBN 0 412 63590 9

A catalogue record for this book is available from the British Library

Library of Congress Catalog Card Number: 95-68494

Printed on acid-free text paper, manufactured in accordance with ANSI/NISO Z39.48-1992 (Permanence of Paper).

Extruder Principles and Operation

Preface

This book is intended to fill a gap between the theoretical studies and the practical experience of the processor in the extrusion of thermoplastic polymers. The former have provided a basis for numerical design of extruders and their components, but generally give scant attention to the practical performance, especially to the conflict between production rate and product quality. In practice extruders are frequently purchased to perform a range of duties; even so, the operator may have to use a machine designed for another purpose and not necessarily suitable for the polymer, process or product in hand. The operator's experience enables him to make good product in unpromising circumstances, but a large number of variables and interactions often give apparently contradictory results. The hope is that this book will provide a logical background, based on both theory and experience, which will help the industrial processor to obtain the best performance from his equipment, to recognize its limitations, and to face new problems with confidence. Mathematics is used only to the extent that it clarifies effects which cannot easily be expressed in words; if it is passed over, at least a qualitative understanding should remain. The approximate theory will not satisfy the purist, but this seems to the authors less important than a clear representation of the physical mechanisms on which so much of the polymer processing industry depends.

M. J. STEVENS
J. A. COVAS

Acknowledgements

The authors are responsible for statements and opinions expressed in this book, which are their own, but would like gratefully to acknowledge the assistance over many years from the staff of the Institute of Polymer Technology, Loughborough University of Technology and, respectively, from Imperial Chemical Industries PLC, Petrochemicals and Plastics Division and the staff of the Department of Polymer Engineering, University of Minho, Braga, Portugal.

The contributions of O. S. Carneiro and A. G. Cunha who, during their research projects, obtained some of the information presented in Chapters 5 and 7, are also gratefully acknowledged.

Contents

Introduction 1

1.1 SCOPE AND LIMITATIONS

The objective of this book is to summarize the principles of screw extrusion processes for plastics and rubbers, the practical performance and its theoretical explanation, and operating procedures to exploit this performance. Unlike design, the latter are not well covered in existing literature. This book aims to make an original contribution to effective practical operation and so does not attempt comprehensively to review the literature, but only to refer to those works which contribute to an understanding of operation.

The scope of the work includes the principles and operation of the screw extruder as a machine, as a combination with a die, and as part of a total fabrication process, including subsidiary functions such as compounding and venting. It includes the special requirements for the extruder of individual processes such as wire covering, tubular film blowing and blow moulding, but does not attempt to cover other aspects of these processes. In order that the objective may be adequately covered in a book of reasonable size, certain matters are excluded, and the reader's attention is directed to the references at the back of the book for further information. In particular, the mechanical construction and adaptation for special purposes of screw extruders is governed partly by the process requirements described in Chapter 2, but also by standardization, manufacturing methods and mechanical reliability. Mechanical construction is dealt with in Chapter 6 of Fisher (1976) and Chapter 6 of Schenkel (1966). Commercial models and unconventional types of extruder are also covered by Fisher and Schenkel, as well as by periodic reviews such as *Plastics and Rubber Weekly**. As this book is primarily concerned with operation, it does not purport to be a manual for the precise dimensional design of machine, screw or die for a specific performance. This is covered by several authors, including Fenner (1970).

* *Plastics and Rubber Weekly*, Maclaren and Sons Ltd, London.

1.2 METHOD

First a number of practical extrusion processes are described in outline, together with the requirements they impose on the extruder and die. The relevant general equations of mass and heat flow are then presented and their application to extrusion problems developed. The significance is explained of the properties of plastics and rubber materials suitable for extrusion, especially the flow and thermal properties of polymer melts. Then the flow equations are developed for the design and operation of dies. A simplified extrusion theory is developed for both mass flow and energy consumption in single-screw machines and presented in both algebraic and graphical form to demonstrate the effects of dimensional and operational variables on output, energy balance, melt temperature and product uniformity. These effects are used to propose strategies for operation to optimize the performance of the extruder. The general principles and operation of twin-screw extruders are then briefly described. A discussion follows on the operation of the extruder and control to eliminate faults in the total system. In particular, the problem of scaling up an extrusion process from the development laboratory to large-scale production is studied. Although the simplified theory is approximate, its predictions are largely borne out in practice. It is used in preference to more exact methods since the algebraic form of the solutions permits a ready identification and understanding of the effects of separate variables on extruder and die performance; this tends to be obscured in the more exact methods, which usually involve digital computation.

As a complement to the analysis of steady-state operation, recommendations for start-up, shut-down, dismantling and cleaning are given, based on practical experience.

The total commercial process of extrusion of plastics and rubbers covers the conversion of a raw polymer, usually in the form of powder or pellets, into a saleable finished or semi-finished product. This will include matters of management and plant organization common to many other materials and processes. It will also include polymer handling and storage, product specification and quality control, plant layout, installation and maintenance, product finishing, assembly, packing and distribution, all of which are general to many plastics processes and only indirectly concerned with the actual operation of extrusion. The intention of this volume is to provide the specific requirements of extrusion, and their explanations, which form the technical background to the total process and its peripheral aspects.

In its simplest terms, extrusion consists of forcing a polymer in liquid form (usually molten) under pressure through a die to produce a continuous section or profile. This may then be sized, drawn down, corrugated, etc., to modify and control the shape and dimensions of the section and in some cases the properties (mechanical, optical, etc.). In the case of thermoplastics, the product or **extrudate** must be cooled to retain its shape, while rubbers are chemically cross-linked (**cured**) to achieve properties such as elasticity and resistance to chemicals and heat. In some processes, e.g. blow moulding, injection moulding and in-line vacuum forming, the extrudate may be shaped into a discontinuous or intermittent form before cooling or curing. Other subsidiary processes, such as printing, slitting and on-line testing, may precede coiling or cutting into handleable lengths. The detail of these operations after the die (collectively **post-forming**) is highly specific to the material and product, much of it confidential to each company, so space precludes exhaustive study here. However, it is just as important as the extruder to the 'quality', dimensions and surface finish of the product; an understanding of the effects of, say, the ratio of haul-off rate to extruder output is essential to economic production. The effects of changes after the die are usually visible, if not self-evident, but one cannot see what is going on inside the extruder, and this book aims to provide the basic mechanisms which help to explain the performance of the screw(s) and die, and hence their interactions with post-forming operations. The book also introduces strategies for operation (Chapters 9 and 10) and control (Chapter 11), as well as some practical experience on selection of screws, start-up, cleaning and fault-finding (Chapters 11 and 12).

An important subject for development engineers is the prediction of the performance of full-scale production plant from that of a small laboratory process, since by its nature heavy moving machinery is expensive to modify or replace and, owing to special materials and manufacture, changes cause lengthy and costly production delays; this is given special attention. Literature references are given at the end of the book in alphabetical order. Mathematical equations are numbered in order of appearance, separately for each chapter and appendix. SI units are used throughout, with c.g.s. or f.p.s. units in brackets where appropriate. Unless otherwise stated, numerical constants are dimensionless, and therefore the same in any consistent system of units.

2 Practical extrusion processes and their requirements

This chapter makes a brief survey of the common applications of screw extruders. It also attempts an explanation of why the requirements of these applications differ, at least in degree, so that when the implications of the general theory in Chapters 5–10 are applied to practice in Chapter 11, it is clear why different materials, processes and products may require different operational and control strategies. These requirements must necessarily be stated in qualitative terms, and users will no doubt be able to give examples where practice appears to contradict statements made here; the author's hope is that the deductions in later chapters will be helpful in the majority of cases and in the remainder will provide a guide to the correct methods and criteria, based on sound analysis.

The single-screw extruder is primarily a drag pump, suitable for working with highly viscous fluids and capable of operation at the high pressures and temperatures consequently required for processing high molecular weight polymers in their thermoplastic state. As explained in section 6.2, the drag mechanism leads to an output which is more or less influenced by back pressure, and section 8.5 shows that this also leads to changes in energy balance, so the interdependence of variables is a vital aspect of performance. The single-screw machine is also mechanically simple and robust, permitting high-energy inputs at relatively low speeds.The usual screw configuration, having 20 or more turns with a pitch similar to screw diameter, gives a long slender machine in which substantial longitudinal temperature gradients can be maintained and controlled, and an appreciable residence time permitting a degree of end-to-end mixing. In addition to this distributive mixing, high shear stresses, especially over the flight tip, give a degree of dispersive mixing for breaking up solid agglomerates, e.g. pigments. As explained in section 6.2, the complex flow within a relatively narrow channel leads to side-to-side mixing and a fair uniformity of composition and temperature. Coincidentally, the single screw is also an effective conveyor of particulate solids, at approximately the rate required by the melt section, so that gravity feeding is usually sufficient.

The drag mechanism also causes internal shearing of the viscous material being pumped, leading to additional power consumption and temperature rise in the polymer. This inefficiency as a pump may be utilized beneficially by assisting external heating in melting the polymer and in heating it internally rather than by conduction, with consequent reduction of internal temperature gradients. The single-screw extruder may be used as a continuous stirred reactor for highly viscous materials, e.g. polymerization and intentional degradation, though differing viscosities of components and products may lead to slip and pumping problems. The end-to-end mixing mentioned previously may also lead to a wide distribution of residence times, undesirable in chemical reaction.

In contrast, the twin-screw extruder (Chapter 10) has a much narrower distribution of residence times and is less sensitive to slip, making this type more suitable for reaction processes and dissimilar viscosities. It approaches more nearly a positive-displacement action, largely independent of back pressure for both output and energy balance. Unlike the single-screw machine,

Table 2.1 Thermoplastics used in extrusion

Abbreviation	*Base polymer*
	AMORPHOUS
ABS	acrylonitrile-butadiene-styrene
PMMA	polymethylmethacrylate
CAB	cellulose acetate butyrate
PC	polycarbonate
PS	polystyrene
PVAC	polyvinyl acetate
PVAL	polyvinyl alcohol
SAN	styrene-acrylonitrile
UPVC	unplasticized (rigid) polyvinyl chloride
PPVC	plasticized (flexible) polyvinyl chloride
HIPS	high impact polystyrene (rubber-toughened)
	SEMI-CRYSTALLINE
POM	polyoxymethylene; polyformaldehyde (polyacetal)
EVAC	ethylene vinyl acetate copolymer
PA	polyamide (nylon)
PETP	polyethylene terephthalate (saturated polyester)
PBTP	polybutylene terephthalate
LDPE	low density polyethylene
LLDPE	linear low density polyethylene
HDPE	high density polyethylene
PP	polypropylene (homo- and copolymers)
PEEK	polyether ether ketone
PTFE	polytetrafluoroethylene (ram extrusion only)

Based on BS 3502: Pt 1 (1978), with additions.

in the twin-screw extruder mixing, both distributive and dispersive, takes place largely in the various clearance gaps. Internal shearing in the screw channels is also less, leading to lower mechanical power inputs, and the polymer is melted more by heat conduction through the barrel wall.

The extruder performs a number of other functions, and these are used either principally or incidentally in a wide range of specialized applications. The extruder is essentially suitable for continuous operation; however, it is widely used in many blow moulding machines and most injection moulding machines on an intermittent basis. It performs surprisingly well in this mode, though factors addtional to those presented in this book must be taken into account; the former are not readily represented in analytical terms.

The screw extruder is thus highly suitable for continuously processing a wide range of synthetic thermoplastic polymers into an equally wide range of finished or semi-finished products. Table 2.1 lists the principal thermoplastics used in extrusion, together with the standard abbreviations. A large number of 'specialty' polymers are extruded for specific applications; these include some fluoropolymers, but PTFE is usually ram extruded because of volume changes and decomposition at high temperatures and extremely high viscosity at lower temperatures. In addition, many raw and unvulcanized rubbers are processed on screw extruders and in special cases, e.g. injection and dough moulding, linear prepolymers of phenolic and polyester thermosetting polymers are successfully handled. The true thermoplastics are often processed, either precompounded with stabilizers, fillers, plasticizers, pigments, processing lubricants, fire-retardants, etc., or these additives are incorporated within the extruder as part of the shaping process. When required in a final cross-linked form (e.g. HDPE by radiation), this is usually by a process following the extrusion operation. Rubbers and thermosets are usually precompounded with cross-linking (vulcanizing) agents as well as fillers, pigments, etc., so that heating in the extruder commences the cross-linking reaction; it is then a matter of controlling temperature, residence time, etc., so that the material remains sufficiently thermoplastic in the extruder and die, while cross-linking is completed in subsequent operations.

2.1 SHAPING PROCESSES AND THEIR REQUIREMENTS

2.1.1 Solid sections

The first of the shaping processes is for solid sections, e.g. rod, strip, profiles and sections. These are used as stock for subsequent machining, gaskets, structural sections (angles, channels, etc.), rainwater guttering, curtain rail, lighting diffusers and many other purposes. Shaping is principally by the melt die, in which uniform flow rate and uniform die swell (elastic recovery) are pre-eminent. This involves uniform melt and metal temperatures, and control of land length and shear history. Drawdown, if any, is usually no more than to the extent of negativing die swell, and cooling is usually in air or waterbath while supported on a band conveyor or rollers. Sizing is usually only for fine control of shape or dimensions and is frequently omitted. Elastic memory in the polymer and flow patterns in the die may give rise to twisting or lengthwise curling, and attempts to remove these by guides or tension, rather than by correcting the cause, will usually distort the shape and/or dimensions, or give residual stress which may cause distortion in service. Except for small and simple sections, which if flexible may be coiled, these products are usually stored and transported in cut straight lengths.

2.1.2 Hollow sections

These include circular tube and pipe, square tube for racking and light furniture, and complex hollow sections such as window framing, in some cases incorporating metal sections which are sheathed during extrusion (Fig. 2.1). Applications for tube and pipe include medical, food, chemical, hydraulic, gas and water distribution, effluent and drainage, and conduit and sleeving, e.g. for electrical and telephone cables. Sizes range from medical tubing less than 1 mm in diameter to water and drainage pipe 600 mm in diameter. The die cores or mandrels forming the internal shape may be supported on a 'spider' which divides the flow, or at the rear of a crosshead or side-entry die. Note that this also carries the thrust due to the drag of the polymer on the core. Complex sections involve difficulties in achieving uniform flow and avoiding distortion due to non-uniform elastic strain and thermal contraction. In this case, as with open sections, drawdown will be a minimum to control die swell. However, with symmetrical sections, especially circular tube, drawdown does not distort the section, but reduces both diameter and thickness. It is often used for small diameters, permitting a larger die with lower resistance and higher throughput. Sizing during cooling is almost universal, fixing *either* the internal or external diameter. The dimensions of the (melt) die and the relation between output and haul-off rate then determine the final thickness and consequently the other (external or internal) diameter. Precise internal diameter is required for metering and sliding seals, e.g. in disposable hypodermics and beer pumps, and precise external diameter is required for use with injection moulded fittings in compression and solvent jointing. In larger pressure pipes, e.g. for gas and water distribution, internal surface finish may also be important in minimizing crack initiation and, in chemical applications, to reduce environmental stress cracking. In both cases residual stress in the pipe should be minimized. With large pipes, say over 300 mm in diameter, the linear speed during extrusion tends to be low unless a very large extruder is used, and consequently the time for thermal degradation in the die is large. If this is minimized, e.g. with UPVC, by reducing die length, then rapid changes of cross-section occur leading to

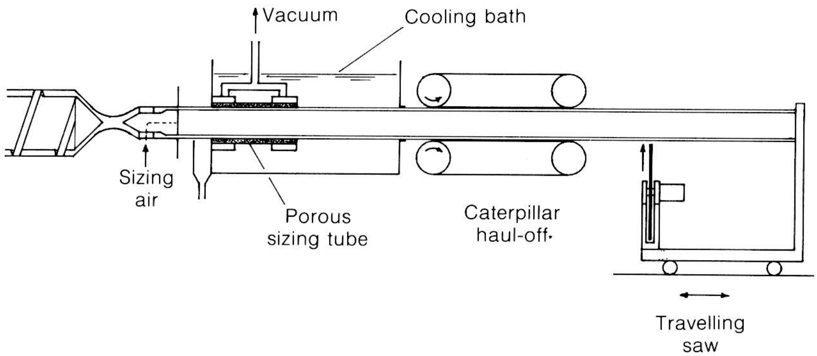


Figure 2.1 Tube extrusion.

residual stress, excessive die swell and transverse orientation of the polymer, instead of the normal longitudinal orientation which tends to occur, especially at low extrusion temperatures. Sizing may be by one or more sizing plates, by internal pressure (through the die spider) against a lubricated sizing tube or by external vacuum on a porous or perforated sizing tube. Since sizing must be accompanied by cooling, the former usually occurs while the product is submerged in a waterbath. Wherever possible, tubes are coiled in lengths of 30 m or more to reduce subsequent jointing. Large rigid pipes are cut in straight lengths up to 20 m long, depending on transport facilities.

Die adjustment, to achieve concentricity and uniform wall thickness in tube, is discussed in Chapter 5. Such adjustment should only be used for fine control, since substantial circumferential variations, e.g. in die gap or land length, are likely to lead to non-axial flow and non-uniform swelling, and possibly to lateral pressure differences on the die mandrel, which distorts, tending to negative the adjustment. In such cases, the cause of non-uniform flow or viscosity from the extruder should be corrected. As with the choker bars used for flat sheet dies (p. 83), a restrictor ring with a narrow annular gap may also be used well before the die lips to remove uneven flow inherent in the design of the die or adaptor. Low velocities in the die may be used to give good surface finish and low residual strain (and swelling). The consequent low resistance permits use of long die lips, which also promotes good surface and low swelling; even so, pressure may be too low for adequate melting and mixing in the extruder, and screen packs may be added to increase the back pressure.

Corrugated tube may be produced in line by a shaping operation following or in place of sizing and during cooling. Reinforced tube may be extruded by passing the reinforcement through the die and extruding around it, as in wire covering, or by plaiting or winding the reinforcement on to the cooled lining tube. Further polymer (possibly of different composition) may then be wrapped or extruded over the assembly. The former, integrated process uses die pressure to force the polymer into intimate contact with the reinforcement