Polymer Engineering Principles

Properties, Processes, Tests for Design

Richard C. Progelhof
James L. Throne

HANSER

Richard C. Progelhof / James L. Throne

Polymer Engineering Principles

Properties, Processes, and
Tests for Design

With 478 Illustrations and 122 Tables

Hanser Publishers, Munich Vienna New York Barcelona

Hanser/Gardner Publications, Inc., Cincinnati

The Authors:
Richard C. Progelhof, Division of Engineering and Engineering Technology, Penn State Erie, The Behrend College, Erie, PA 16563-0101, USA
James L. Throne, Sherwood Technologies, Inc., Hinckley, OH 44233-9676, USA

Distributed in the USA and in Canada by
Hanser/Gardner Publications, Inc.
6600 Clough Pike, Cincinnati, Ohio 45244-4090, USA
Fax: + 1 (513) 527-8950

Distributed in all other countries by
Carl Hanser Verlag
Postfach 86 04 20, 81631 München, Germany
Fax: + 49 (89) 98 48 09

Die Deutsche Bibliothek - CIP-Einheitsaufnahme
Progelhof, Richard C.:
Polymer engineering principles : properties, processes,
and tests for design ; with 122 tables / Richard C. Progelhof ;
James L. Throne. - Munich ; Vienna ; New York ; Barcelona :
Hanser, 1993
ISBN 3-446-17337-4 brosch.
ISBN 3-446-15686-0 Pb.
NE: Throne, James L.:

ISBN 1-56990-150-3 (hardcover) Hanser/Gardner Publications, Inc., Cincinnati
ISBN 1-56990-151-1 (paperback) Hanser/Gardner Publications, Inc., Cincinnati

Typesetting in the USA by Compset, Inc., Beverly, Massachusetts
Printed and bound in Germany by Passavia Druckerei GmbH, Passau

Progelhof/Throne

Polymer Engineering Principles

SPE Books from Hanser Publishers

Bernhardt, Computer Aided Engineering for Injection Molding
Brostow/Cornéliussen, Failure of Plastics
Charrier, Polymeric Materials and Processing—Plastics, Elastomers and Composites
Ehrig, Plastics Recycling
Gordon, Total Quality Process Control for Injection Molding
Gruenwald, Plastics: How Structure Determines Properties
Macosko, Fundamentals of Reaction Injection Molding
Manzione, Applications of Computer Aided Engineering in Injection Molding
Matsuoka, Relaxation Phenomena in Polymers
Menges/Mohren, How to Make Injection Molds
Michaeli, Extrusion Dies for Plastics and Rubber
O'Brien, Applications of Computer Modeling for Extrusion and Other Continuous Polymer Processes
Progelhof/Throne, Polymer Engineering Principles
Rauwendaal, Polymer Extrusion
Saechtling, International Plastics Handbook for the Technologist, Engineer and User
Stoeckhert, Mold-Making Handbook for the Plastics Engineer
Throne, Thermoforming
Tucker, Fundamentals of Computer Modeling for Polymer Processing
Ulrich, Introduction to Industrial Polymers
Wright, Molded Thermosets: A Handbook for Plastics Engineers, Molders and Designers

FOREWORD

The Society of Plastics Engineers is pleased to endorse and sponsor this volume entitled *Polymer Engineering Principles: Properties, Processes, and Tests for Design.* SPE's Technical Volumes Committee believes that this book has the potential to be an SPE best seller because of its far-reaching utility as both a textbook and reference title. The volume includes an attractively concise introduction to polymers, followed by detailed chapters on physical, chemical, and load-bearing properties. The hundreds of figures and tables integrated throughout the text, including later chapters on polymer processing, testing, and design, make this a valuable tool for people in the academic arena as well as practicing engineers.

SPE, through its Technical Volumes Committee, has long sponsored books on various aspects of plastics. Its involvement has ranged from identification of needed volumes and recruitment of authors to peer review and approval and publication of new books.

Technical competence pervades all SPE activities, not only in the publication of books, but also in other areas, such as sponsorship of technical conferences and educational programs. In addition, the Society publishes periodicals, including *Plastics Engineering, Polymer Engineering and Science, Polymer Processing and Rheology, Journal of Vinyl Technology* and *Polymer Composites,* as well as conference proceedings and other publications, all of which are subject to rigorous technical review procedures.

The resource of some 37,000 practicing plastics engineers has made SPE the largest organization of its type worldwide. Further information is available from the Society at 14 Fairfield Drive, Brookfield, Connecticut 06804, U.S.A.

Eugene De Michele
Executive Director
Society of Plastics Engineers

Technical Volumes Committee
Claire Bluestein, Chairperson
Captan Associates, Inc.

PREFACE

Polymers are organic macromolecules. They do not have the inherent strength of traditional materials such as wood, steel or even concrete. They are expensive man-made materials whose physical states can be easily altered by combining more than one polymer, by adding agents to improve processing, by adding fillers or reinforcing fibers, and so on. The resulting polymeric materials can be easily shaped, have excellent chemical resistance, good ductility and volumetric color. On the outside, deliberate attempts to produce useful organic macromolecules can be traced back no more than 150 years. Commercial purely synthetic polymers are truly twentieth century materials.

The engineer or designer needs the properties of a selected material in order to determine its suitability in the required environment. The environment may be entirely mechanical as with the design of a shelf. It may be entirely chemical as in the design of a bleach bottle. Or it may be a combination of environmental effects, such as hydromechanical, chemical and thermal in the case of a brake-fluid hose. The engineer or designer needs to know how plastics differ in performance from one polymer to another, and from that of traditional materials. The designer or engineer usually relies on properties that are obtained from testing routines originally established for traditional materials such as metals. He/she must realize that, unlike traditional material response, polymer behavior changes with changes in intensity and duration of the impressed environmental effect.

The intent of this book is modest. It is designed to lead the reader from an understanding of the basic elements that make up a polymer, through the inherent characteristics of a polymer such as glass transition temperature, melt temperature, molecular weight distribution and degree of crystallinity, through solid and fluid characteristics and basic processing principles, to an understanding of polymer response to testing conditions. The book has six chapters:

1. *Introduction to Polymers.* After a brief history, the nature of a polymer is discussed, beginning with atomic structure, continuing through the concept of a monomer to the building of a large molecule. Combinations of polymers are then discussed, and the nature of the bonding forces that allow polymer toughness and chemical resistance are considered. The comparative polymeric natures of thermoplastic and thermosetting resins are then put into perspective.

2. *The Polymer Solid State.* Several definitions of molecular weight and molecular weight distribution are presented as well as methods for determining them. The crystalline nature of polymers is then discussed. This leads to the molecular nature of

polymer transitions, including glass transition temperature, and then to the transport properties of polymers. And finally, the effect of additives, fillers and reinforcements on the molecular state of polymers is discussed.

3. *Mechanical Properties of Polymers.* Polymers, as a class of materials, exhibit solid-like properties at times and at other times exhibit fluid-like properties. After a brief review of classical material response to applied load, the viscoelastic nature of polymers is considered, under constant load and under dynamic load. The response of polymeric materials to impact or short-term loading and creep or long-term loading is then discussed in the light of viscoelasticity.

4. *Polymer Fluid and Chemical Properties.* Polymers in a liquid state are highly viscoelastic and usually have very high viscosities when compared with simple molecule fluids. As a result, they can behave as elastic liquids and can generate substantial heat while being processed. Polymers are compressible at high processing pressures. The thermodynamics of polymers are discussed in detail. The chapter ends with a discussion of polymer resistance to solvents and chemicals.

5. *Processing.* A brief overview of the major commercial ways of processing polymers into final product shapes is given here. Emphasis is placed on understanding the interaction of the processing environment and the polymer. Extrusion and injection molding are the major commercial thermoplastic processes that are considered in detail. Compression molding is the primary commercial thermosetting resin process that is emphasized. The interrelationship between polymer properties and computer-aided design databases is considered in some detail.

6. *Testing for Design.* This extensive chapter is the major focus of the book, with the preceding chapters needed for full understanding. The chapter focuses on standard test procedures for fluid and solid polymers and how these tests can be used to obtain an understanding of polymer response to real environmental effects. In addition to the standard tensile and flexural testing, friction and wear testing, environmental stress crack testing, weathering, fire retardancy testing and electrical resistance testing are also considered.

These contents are not meant to be new, novel or even evolutionary. The book is not a handbook or a compendium of polymer material properties. For this, we recommend the reader to the following:

D.W. Van Krevelen, *Properties of Polymers,* Elsevier, New York NY (1976).

H. Domininghaus, *Die Kunststoffe und ihre Eigenschaften,* VDI Verlag, Düsseldorf, FRG (1986).

H. Saechtling, *International Plastics Handbook,* Hanser Verlag, Munich (1987).

Modern Plastics Encyclopedia, Published every October by Modern Plastics, 1221 Ave. of the Americas, New York NY 10020.

Encyclopedia of Polymer Science and Engineering, 2nd. Ed., John Wiley & Sons, Inc., 605 Third Ave., New York NY 10158 (1985-1990).

The book is also not meant to be all-inclusive. The rapid growth of the industry has spurred publication of many books that specialize in narrow segments of this material. We do not pretend to summarize other treatises. Instead, wherever appropriate, we refer the reader to them for more information. As an example, in Chapter 5, we present a brief overview of the economically important polymer processes, so that the reader may appreciate how processing constraints influence polymer performance in the final part. There are a dozen or more excellent textbooks that focus specifically on polymer processing and these are cited in the references of that chapter.

We believe that this material will allow the reader to gain a better understanding of the limitations inherent in standard handbook data. With this understanding, the engineer or designer should be better able to select polymer materials that have optimum response to environmental effects. As with any survey text, the key to presenting this material is in knowing what to include. We have focused on polymers that form the major constituent of the final product. The polymer may be "neat" or pure, but it may also be combined with other polymers, adducts such as processing aids, fillers or reinforcing elements. We have chosen not to include the rapidly growing area of composites. It is not at all clear that the mechanical properties of the polymer matrix can be isolated from that of the composite. And despite the intense world-wide research and development efforts in this area, applications are currently restricted to products such as aircraft and aerospace components, where performance dominates material and manufacturing economics.

Many sections in this book owe allegiance to a few classic treatises:

R.D. Deanin, *Polymer Structure, Properties and Applications*, Cahners Books, Boston (1972). A logical progression from the chemical nature of the polymer to its interaction with adducts.

J.M. Dealy, *Rheometers for Molten Plastics*, Van Nostrand Reinhold Co., New York (1982). The best of several books that relate the fundamentals of polymer fluid flow to the current methods of measuring shear viscosity, normal stress difference, elongational viscosity and so on.

M.L. Miller, *The Structure of Polymers*, Reinhold, New York (1966). An early book that relates polymer mechanical response to polymer structure, including an extensive section on crystallinity.

T. Alfrey, Jr., *Mechanical Behavior of High Polymers*, Interscience Publishers, New York (1948). The classic work relating linear viscoelasticity of polymers to their mechanical response to applied load.

S. Turner, *Mechanical Testing of Polymers*, 2nd Ed., George Godwin/PRI, London (1983). A thoughtful discussion of the purpose of testing of polymers, in which the distinction between a material *property* and a material *parameter* is clearly made and reinforced via examples.

One of us (JLT) wishes to thank two years of first-year Polymer Engineering graduate student classes and one year of senior undergraduate Mechanical Engineering

students for deciphering, reviewing, correcting, editing and otherwise struggling with the manuscript in a very difficult format.

The influence of the late John L. O'Toole pervades this work. His best written effort was the Annual Design Guide in Modern Plastics Encyclopedia. More importantly, John was a teacher's teacher. He taught us to understand, in general but simple terms, how a polymer responds to controlled environmental forces. He convinced us that temperature must always be considered an important physical parameter. And he taught us that we must always stress that polymer material properties *depend* on the duration and intensity of environmental change. Thus, it is incumbent upon us to reinforce his admonition that the engineer or designer must appreciate that he/she is dealing with material parameters rather than material constants that are typical of traditional materials. We dedicate this book to the memory of our mentor, counselor and friend, John L. O'Toole.

R.C. Progelhof
J.L. Throne

HOW TO USE THIS BOOK AS A TEXTBOOK

The book naturally progresses from simple differentiation of polymers from more traditional materials such as metals and ceramics, through solid and fluid mechanics of polymers to an analysis of the standard tests that help to define those polymer properties needed to design today's functional products. The text material is not meant to be encyclopedic in scope.

However, by design, the authors have included more material than can be covered in a single course of 40 contact hours or so. We believe that this allows the instructor to tailor the course material to his or her interests without requiring extensive supplemental materials.

The authors recognize that this penalizes the student who must now purchase a book that is more extensive and hence more expensive than one more carefully designed to meet a given course syllabus. However, we believe that the material selected for inclusion is classic in nature and based on well-founded concepts. As a result, the student should have every confidence that the book will remain a good source for information on polymer material properties for many years to come.

There are several ways of adapting the material to a one-semester senior-level undergraduate or introductory graduate-level course. Three scenarios follow:

Scenario One
Emphasis on Solid Polymer Science

Chapter 1 Introduction
Chapter 2 The Polymer Solid State
Chapter 3 Mechanical Properties of Polymers
Chapter 4 Polymer Fluid and Chemical Properties (Sections 4.1 through 4.5)
Chapter 6 Testing for Design (Sections 6.3 through 6.6)

Scenario Two
Emphasis on Fluid and Chemical Polymer Science

Chapter 1	Introduction
Chapter 2	The Polymer Solid State
Chapter 3	Mechanical Properties of Polymers (Sections 3.1 through 3.7)
Chapter 4	Polymer Fluid and Chemical Properties
Chapter 6	Testing for Design (Sections 6.1 through 6.2, 6.3, 6.7 through 6.10)

Scenario Three
Emphasis on Processing Effects on Properties

Chapter 1	Introduction
Chapter 2	The Polymer Solid State
Chapter 3	Mechanical Properties of Polymers (Sections 3.1 through 3.7)
Chapter 4	Polymer Fluid and Chemical Properties (Sections 4.1 through 4.5)
Chapter 5	Processing
Chapter 6	Testing for Design (Sections 6.1 through 6.2; Sections 6.6 through 6.7)

At the end of the text, there are ***homework problems*** for each chapter and each major emphasis within each chapter. ***Answers*** are given for many problems. In addition, the authors have extensively used open ***literature references*** to illustrate many of the major points.

To aid in skimming the book, general discussion is in large type and ***examples*** are given in smaller type. A ***glossary*** of terms is provided at the end of each chapter and the book contains extensive ***subject and author indices.***

CONTENTS

CONVERSION FACTORS

Length:				
m	× 3.28	ft	× 0.3048	m
μm	× 10^{-6}	m	× 10^{6}	μm
km	× 1.609	mile	× 0.622	km
Å	× 10^{-10}	m	× 10^{10}	Å
mm	× 39.37	mils	× 0.0254	mm
Area:				
m^2	× 10.76	ft^2	× 0.0929	m^2
cm^2	× 0.155	in^2	× 6.452	cm^2
mm^2	× 1.55×10^{-3}	in^2	× 645.2	mm^2
Volume:				
m^3	× 35.31	ft^3	× 0.02832	m^3
m^3	× 6.102×10^{4}	in^3	× 1.639×10^{-5}	in^3
mm^3	× 6.102×10^{-5}	in^3	× 1.639×10^{4}	mm^3
liter	× 1000	cm^3	× 0.001	liter
cm^3	× 29.57	fluid oz	× 0.0338	cm^3
m^3	× 264.2	US gallon	× 3.785×10^{-3}	m^3
Mass:				
g	× 0.0022	lb_m	× 453.6	g
kg	× 2.205	lb_m	× 0.4536	kg
kg	× 0.001	metric tonne	× 1000	kg
kg	× 0.0011	US ton	× 907.2	kg
Density:				
g/cm^3	× 62.42	lb_m/ft^3	× 0.016	g/cm^3
g/cm^3	× 0.03611	lb_m/in^3	× 27.69	g/cm^3
kg/m^3	× 0.06242	lb_m/ft^3	× 16.02	kg/m^3
g/cm^3	× 0.578	oz/in^3	× 1.73	g/cm^3
kg/m^3	× 5.78×10^{-4}	oz/in^3	× 1.73×10^{3}	kg/m^3

Force:

N	× 0.2248	lb_f	× 4.448	N
kg_f	× 0.2292	lb_f	× 4.363	kg_f
kN	× 0.2248	kip (10^3 lb_f)	× 4.448	kN
dyne	× 2.248×10^{-6}	lb_f	× 2.248×10^{-6}	dyne
dyne	× 10^6	N	× 10^5	dyne

Pressure:

Pa	× 1.45×10^{-4}	lb_f/in^2	× 6895	Pa
MPa	× 9.869	atm	× 1.013×10^5	MPa
Pa	× 10	dyn/cm^2	× 0.100	Pa
Pa	× 7.5×10^{-3}	1 mm Hg	× 133.3	Pa
Pa	× 4.012×10^{-3}	1 inch H_2O	× 248.9	Pa
MPa	× 10	bar	× 0.1	MPa
N/mm^2	× 145	lb_f/in^2	× 6.895×10^{-3}	N/mm^2

Energy:

J	× 9.478×10^{-4}	Btu	× 1055	J
ft lb_f	× 1.286×10^{-3}	Btu	× 778	ft lb_f
J	× 0.2388	cal	× 4.187	J
J	× 1×10^7	erg	× 1×10^{-7}	J
J	× 2.778×10^{-7}	kW h	× 3.60×10^6	MJ
J	× 1	W s	× 1	kJ
J	× 0.7375	ft lb_f	× 1.356	J

Energy, Power, Heat, Fluid Flow Rate:

W	× 3.413	Btu/h	× 0.293	W
W	× 10^7	erg/s	× 1×10^{-7}	W
W	× 0.7375	ft lb_f/s	× 1.356	W
kW	× 1.34	hp	× 0.746	kW
liter/min	× 0.2642	gal/min	× 3.785	liter/min
liter/min	× 2.393	ft^3/h	× 0.4719	liter/min

Heat Flux:

W/m^2	× 0.317	Btu/h ft^2	× 3.155	W/m^2
cal/s cm^2	× 3.687	Btu/h ft^2	× 0.2712	cal/s cm^2
W/m^2	× 6.452×10^{-4}	W/in^2	× 1550	W/m^2

Specific Heat:

J/kg K	× 2.388×10^{-4}	Btu/lb_m °F	× 4187	J/kg K
cal/g °C	× 1	Btu/lb_m °F	× 1	cal/g °C

Thermal Conductivity:

W/m K	× 0.5777	Btu/h ft °F	× 1.731	W/m K
W/m K	× 1.926×10^{-3}	Btu in/s ft^2 °F	× 519.2	W/m K
W/m K	× 7.028	Btu in/h ft^2 °F	× 0.1442	W/m K
W/m K	× 2.39×10^{-3}	cal/cm s °C	× 418.4	W/m K

Heat Transfer Coefficient:

W/m^2 K	× 0.1761	Btu/h ft^2 °F	× 5.678	W/m^2 K

Velocity:

km/h	× 0.6205	miles/h	× 1.609	km/h
m/s	× 3.6	km/h	× 0.2778	m/s
m/s	× 39.37	in/s	× 0.0254	m/s
m/s	× 3.281	ft/s	× 0.3048	m/s
m/s	$\times 1.181 \times 10^4$	ft/h	$\times 8.467 \times 10^{-5}$	m/s

Mass Flow Rate:

kg/s	$\times 7.937 \times 10^3$	lb_m/h	$\times 1.26 \times 10^{-4}$	kg/s
kg/s	× 2.205	lb_m/s	× 0.4536	kg/s

Viscosity:

Pa·s	× 10	Poise	× 0.1	Pa·s
Pa·s	× 1000	centipoise	× 0.001	Pa·s
m^2/s	× 10.76	ft^2/s	× 0.0929	m^2/s
Pa·s	× 1.488	lb_m/s ft	× 0.672	Pa·s
centipoise	$\times 1.488 \times 10^3$	lb_m/s ft	$\times 6.72 \times 10^{-4}$	centipoise
m^2/s	$\times 10^6$	centistokes	$\times 1 \times 10^{-6}$	m^2/s
Pa·s	$\times 1.45 \times 10^{-4}$	$lb_f\ s/in^2$	$\times 6.895 \times 10^3$	Pa·s
Pa·s	$\times 2.088 \times 10^{-2}$	$lb_f\ s/ft^2$	× 47.88	Pa·s

Stress:

MPa	× 145	lb_f/in^2	$\times 6.895 \times 10^{-3}$	MPa
MPa	× 0.102	kg_f/mm^2	× 9.807	MPa
MPa	× 0.0725	ton_f/in^2	× 13.79	MPa
MPa	× 1	MN/m^2	× 1	MPa

Bending Moment:

N m	× 8.85	lb_f in	× 0.113	N m
N m	× 0.7375	lb_f ft	× 1.356	N m
N m/m	× 0.2248	lb_f in/in	× 4.448	N m/m
N m/m	$\times 1.873 \times 10^{-2}$	lb_f ft/in	× 53.38	N m/m

Fracture Toughness and Impact Strength:

MPa $m^{1/2}$	× 0.9099	ksi $in^{1/2}$	× 1.099	MPa $m^{1/2}$
J/m	× 0.2248	ft lb_f/ft	× 4.448	J/m
J/m	× 0.01874	ft lb_f/in	× 53.37	J/m
J/m^2	$\times 4.757 \times 10^{-4}$	ft lb_f/in^2	× 2102	J/m^2