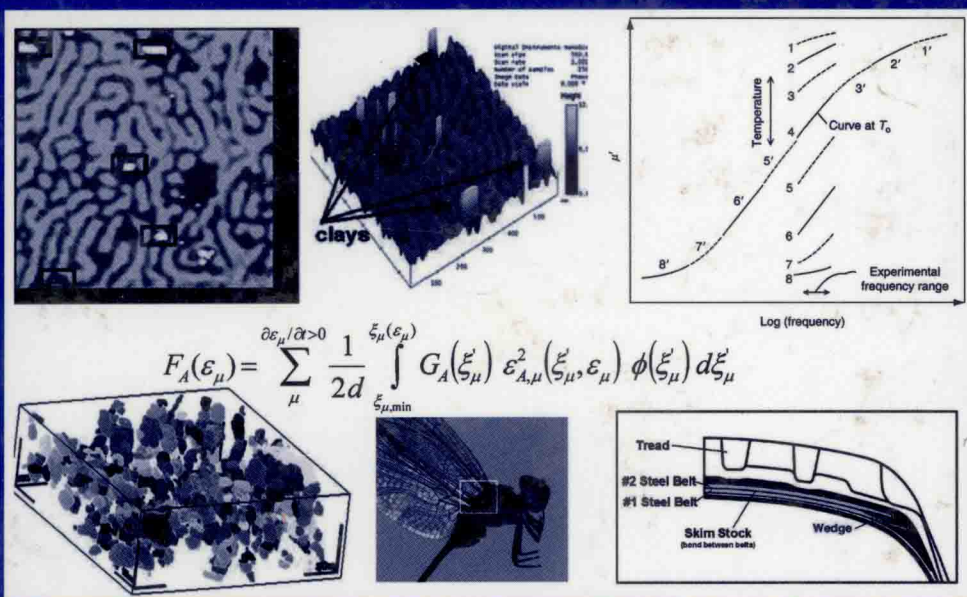


# Current Topics in ELASTOMERS RESEARCH



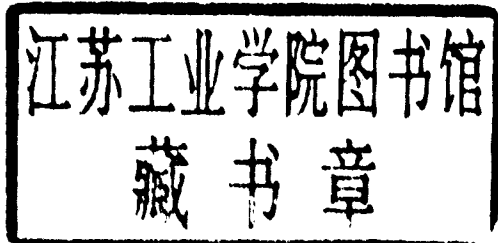
*Edited by*  
**Anil K. Bhowmick**

***Current Topics in***

---

**ELASTOMERS  
RESEARCH**

*Edited by*  
**Anil K. Bhowmick**



**CRC Press**

Taylor & Francis Group  
Boca Raton London New York

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2008 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works  
Printed in the United States of America on acid-free paper  
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-0-8493-7317-6 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The Authors and Publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

**Library of Congress Cataloging-in-Publication Data**

---

Bhowmick, Anil K., 1954-  
Current topics in elastomers research / Anil K. Bhowmick.  
p. cm.  
Includes bibliographical references and index.  
ISBN-13: 978-0-8493-7317-6 (alk. paper)  
ISBN-10: 0-8493-7317-4 (alk. paper)  
1. Elastomers. I. Title.

TS1925.B46 2008  
678--dc22

2007040724

---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>  
and the CRC Press Web site at  
<http://www.crcpress.com>

## *Dedication*

---

*Dedicated to my only son BUNA*

---

# Preface

Rubber is an important engineering material and is used in many critical applications. An example of its importance is the space shuttle *Challenger* disaster because of a failed rubber O-ring. Rubber has implications ranging from birth control to the growth of modern civilization. Can we imagine fast transportation without rubber tires? Artificial hearts can be made of rubber. Hence, research activities are always intense in the biomedical field in spite of new and continuous challenges. Research has also burgeoned because of the development of innovative materials and stringent application requirements. However, many of these activities are concentrated in the industry and are not published in the open literature. Any researcher or beginner in rubber science and technology will always have a question, “What are the topics of rubber research in the world?” It is with this perspective that the book has been compiled to give its readership a broad view of rubber research activities in the world.

The book is divided into 7 sections with 38 chapters. An introductory chapter, the first section, sets the tone of the book. The second section, “New Elastomers and Composites,” deals with a variety of newly developed rubbery materials and composites, and also their chemistry and structure–property relationship. The third section, “Rubber Ingredients,” covers the important ingredients, current thought in this field, and the mechanisms of action of these ingredients. The fourth section, “New Characterization Techniques,” predominantly describes two techniques, 3D-TEM and AFM, currently used by leading researchers. The fifth section, “Physics and Engineering,” discusses reinforcement mechanisms; effects of time, temperature, and fluids; viscoelastic properties; fatigue life; abrasion; adhesion; rheology; mixing and processing; and the state of the art in these areas. The sixth section discusses, “Tires,” one of the major applications of rubber, whose critical requirements have guided research for more than 50 years, and which are also described. Only tires are discussed as an example of a typical rubber product as it was not possible to include recent developments of other products. The last section, “Eco-Friendly Technology and Recycling,” discusses important topics in any engineering field in the globalization era.

Although this book covers a large number of topics by experts from various countries, critics might say that a few more topics need to be included. This was not possible because information in certain areas is still classified. Also, some ideas have been repeated in the book to stress the importance of the subject and also to emphasize the views of the contributors engaged in growing or nascent fields of research.

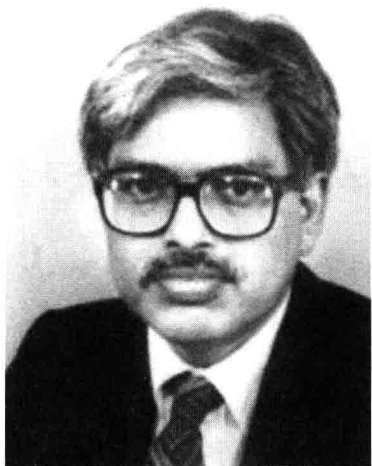
All topics have been contributed by leading experts and stalwarts in their fields. I am grateful to the contributors for their time and efforts to make the venture successful. The book took shape because of continued support from my former as well as present students: Anirban Ganguly, Dr. Susmita Sadhu, Madhuchhanda Maiti, Dr. Abhijit Bandyopadhyay, Jinu J. George, Dr. Sritama Kar, Dr. Francis R. Costa, Dr. Naba K. Dutta, Dr. Namita R. Roychowdhury, Dr. Sudip Ray, Dr. Rajatendu Sengupta, Dr. Indranil Banik, Dr. Papiya Sen Majumdar, Dr. V. Vijayabaskar, Dr. Arup K. Chandra, Saikat Dasgupta, Dr. Anand Srinivasan, Dr. A.M. Shanmugharaj, Mithun Bhattacharya, Dinesh Kumar Kotneer, Suman Mitra, Pradip K. Maji, Ganesh Basak, Anusuya Choudhury, Anjan Biswas, Haimanti Datta, and Samik Gupta. I also thank my colleagues at IIT Kharagpur for their support, and the outstanding cooperation of my research collaborators and funding agencies in India and abroad. I would like to thank various companies, authors, editors, and journals for giving me permission to reproduce material and also for providing other necessary assistance.

Finally, I would like to thank my late parents Jatindra M. Bhowmick and Hemprova Bhowmick, and also Dr. S.K. Biswas (late) and K. Biswas for inspiring me during the early stages of preparation of the book. I also express my gratitude to my son Asmit (BUNA) and my wife Dr. Kundakali, for sparing me to work in the office, when actually I should have been at home in their company.

**Anil K. Bhowmick**  
*Indian Institute of Technology*  
*Kharagpur*

---

# Editor



**Anil K. Bhowmick** is a professor and former head of the Rubber Technology Center, and was former dean of postgraduate studies and dean of sponsored research and industrial consultancy at IIT Kharagpur. He was previously associated with the University of Akron, Ohio, the London School of Polymer Technology, and the Tokyo Institute of Technology. His main research interests are in the fields of nanocomposites, thermoplastic elastomers and polymer blends, polymer modification, rubber technology, failure and degradation of polymers, and adhesion and adhesives. He has more than 400 publications in these fields, written 35 book chapters, and has coedited 5 books. He was also coeditor of the *Journal of Macromolecular Science* special issue on polymer and composite characterization. He is the 2002 winner of the Chemistry of Thermoplastic Elastomers Award, the 1997 winner of the George Stafford Whitby Award of the rubber division,

American Chemical Society, for distinguished teaching and innovative research, and the 2001 K.M. Philip Award of the All India Rubber Industries Association for outstanding contributions to the growth and development of rubber industries in India. He has also received the 1991 NOCIL Award, the 1990 JSPS Award, the 1990 Commonwealth Award, the 1989 MRF Award, and the 1989 Stanton-Redcroft ITAS Award. He is on the editorial boards of the *Journal of Adhesion Science and Technology*, the *Journal of Applied Polymer Science*, the *Journal of Materials Science*, *Polymers and Polymer Composites*, the *Journal of Materials Science*, and *Rubber Chemistry and Technology*.

---

# Contributors

**John M. Baldwin**

Exponent Failure Analysis Associates  
Farmington Hills, Michigan  
and  
Department of Chemistry  
Oakland University  
Rochester Hills, Michigan

**Abhijit Bandyopadhyay**

Rubber Technology Center  
Indian Institute of Technology  
Kharagpur, India

**Indranil Banik**

Centre for Biocomposites and  
Biomaterials Processing  
University of Toronto  
Toronto, Ontario, Canada

**David R. Bauer**

Exponent Failure Analysis Associates  
Farmington Hills, Michigan

**Satinath Bhattacharya**

Rheology and Materials Processing  
Centre  
RMIT University  
Melbourne, Australia

**Anil K. Bhowmick**

Rubber Technology Centre  
Indian Institute of Technology  
Kharagpur, India

**Robert P. Campion**

Materials Engineering Research  
Laboratory Ltd.  
Hitchin, Hertfordshire, United Kingdom

**Arup K. Chandra**

Apollo Tyres Ltd., R&D Centre  
Limda, Gujarat, India

**Namita Roy Choudhury**

Ian Wark Research Institute  
University of South Australia  
Mawson Lakes, Australia

**Francis R. Costa**

Leibniz-Institut für Polymerforschung  
Dresden, Germany

**Rabin N. Datta**

Department of Rubber Technology  
University of Twente  
Enschede, the Netherlands

**Sudhin Datta**

R&D Polymers  
Exxon Mobil Chemical Co  
Baytown, Texas

**Des (C.J.) Derham**

Materials Engineering Research  
Laboratory Ltd.  
Hitchin, Hertfordshire, United Kingdom

**Wilma Dierkes**

Department of Elastomer Technology  
and Engineering  
University of Twente  
Enschede, the Netherlands

**Herman Dikland**

DSM Elastomers  
Geleen, the Netherlands



**Martin van Duin**

DSM Elastomers  
Geleen, the Netherlands

**Naba K. Dutta**

Ian Wark Research Institute  
University of South Australia  
Mawson Lakes, Australia

**Christopher M. Elvin**

CSIRO Livestock Industries  
Queensland Bioscience Precinct  
St Lucia, Australia

**Ali Fatemi**

Mechanical, Industrial and Manufacturing  
Engineering Department  
The University of Toledo  
Toledo, Ohio

**Ephraim Feinblum**

Dimona Silica Industries Ltd.  
Be'er-Sheva, Israel

**Yoshihide Fukahori**

Materials Department  
Queen Mary, University of London  
London, United Kingdom

**Anirban Ganguly**

Rubber Technology Centre  
Indian Institute of Technology  
Kharagpur, India

**Alan N. Gent**

Department of Polymer Science  
The University of Akron  
Akron, Ohio

**Jinu Jacob George**

Rubber Technology Centre  
Indian Institute of Technology  
Kharagpur, India

**Karl A. Grosch**

VMI Holland BV  
Geiraweg, the Netherlands

**Saikat Das Gupta**

Hari Shankar Singhania Elastomer  
and Tyre Research Institute  
Kankroli, Rajsamand  
Rajasthan, India

**Ryan J. Harbour**

Mechanical, Industrial and Manufacturing  
Engineering Department  
The University of Toledo  
Toledo, Ohio

**Gert Heinrich**

Leibniz-Institut für Polymerforschung  
Dresden, Germany

**Nico M. Huntink**

Teijin Aramid BV  
Arnhem, the Netherlands

**Mickey G. Huson**

CSIRO Textile and Fibre Technology  
Geelong, Australia

**Frederick Ignatz-Hoover**

Flexsys America L.P.  
Akron, Ohio

**Yuko Ikeda**

Graduate School of Science  
and Technology  
Kyoto Institute of Technology  
Matsugasaki, Kyoto, Japan

**Sritama Kar**

Rubber Technology Centre  
Indian Institute of Technology  
Kharagpur, India

**Atsushi Kato**

NISSAN ARC, Ltd.  
Yokosuka, Kanagawa, Japan

**Manfred Klüppel**

Deutsches Institut für  
Kautschuktechnologie  
Hannover, Germany

**Shinzo Kohjiya**

Mapua Institute of Technology  
Intramuros, Manila, Philippines

**Doug J. Kohls**

University of Cincinnati  
Cincinnati, Ohio

**Raissa Kosso**

Dimona Silica Industries Ltd.  
Be'er-Sheva, Israel

**Jean L. Leblanc**

Polymer Rheology and Processing  
Universite Pierre et Mariè Curie  
Vitry-sur-Seine, France

**Michael V. Lewan**

Materials Engineering Research  
Laboratory Ltd.  
Hitchin, Hertfordshire, United Kingdom

**Sergei N. Magonov**

Nanotechnology Measurements Division  
Agilent Technologies  
Chandler, Arizona

**Madhuchhanda Maiti**

Reliance Industries Limited  
Vadodara Manufacturing Division  
Vadodara, Gujarat, India

**Papiya Sen Majumder**

Leibniz-Institut für Polymerforschung  
Dresden, Germany

**Duryodhan Mangaraj**

Innovative Polymer Solutions  
Delaware, Ohio

**Will V. Mars**

Cooper Tire and Rubber Company  
Findlay, Ohio

**José Miguel Martín-Martínez**

Adhesion and Adhesives Laboratory  
University of Alicante  
Alicante, Spain

**Hans-Georg Meyer**

Berstorff Rubber Processing Machinery  
Hannover, Germany

**Glyn J. Morgan**

Materials Engineering Research  
Laboratory Ltd.  
Hitchin, Hertfordshire, United Kingdom

**Michael D. Morris**

Business and Technology Center  
Cabot Corporation  
Billerica, Massachusetts

**Rabindra Mukhopadhyay**

Hari Shankar Singhania Elastomer  
and Tyre Research Institute  
Kankroli, Rajsamand  
Rajasthan, India

**Ken Nakajima**

Department of Organic and Polymeric Materials  
Graduate School of Science and Engineering  
Tokyo Institute of Technology  
Meguro, Tokyo, Japan

**Gerard Nijman**

Department of R&D  
Vredestein Banden BV  
Enschede, the Netherlands

**Toshio Nishi**

Department of Organic and Polymeric Materials  
Graduate School of Science and Engineering  
Tokyo Institute of Technology  
Meguro, Tokyo, Japan

**Jacques Noordermeer**

Department of Elastomer Technology  
and Engineering  
University of Twente  
Enschede, the Netherlands

**Muthukumaraswamy Pannirselvam**

Rheology and Materials Processing  
Centre  
RMIT University  
Melbourne, Australia

**Alice Bope Parsons**

Battelle Memorial Institute  
Columbus, Ohio

**Judit E. Puskas**

Department of Polymer Science  
The University of Akron  
Akron, Ohio

**R.S. Rajeev**

School of Mechanical and Aerospace  
Engineering  
Queen's University  
Belfast, Northern Ireland, United Kingdom

**C.M. Roland**

Chemistry Division  
Naval Research Laboratory  
Washington, DC

**Susmita Dey Sadhu**

Department of Polymer Science  
Bhaskaracharya College of Applied Sciences  
University of Delhi  
Delhi, India

**Dale W. Schaefer**

University of Cincinnati  
Cincinnati, Ohio

**Rajatendu Sengupta**

Hari Shankar Singhanian Elastomer  
and Tyre Research Institute  
Kankroli, Rajsamand  
Rajasthan, India  
and  
Rubber Technology Center  
Indian Institute of Technology  
Kharagpur, India

**Dipak K. Setua**

Defence Research & Development  
Organization  
Ministry of Defence  
Kanpur, India

**A.M. Shanmugharaj**

Institute for Materials Chemistry  
and Engineering  
Kyushu University  
Fukuoka, Japan

**Rui Shi**

Department of Polymer Engineering  
School of Material Science and Engineering  
Beijing University of Chemical Technology  
Beijing, China

**Anandhan Srinivasan**

Asian Institute of Medicine  
Science and Technology  
Sungal Petani, Kedah, Malaysia

**Byron To**

Flexsys America L.P.  
Akron, Ohio

**V. Vijayabaskar**

Product Development Centre  
Balmer Lawrie & Co. Ltd.  
Manali, Chennai, India

**Thomas A. Vilgis**

Max-Planck-Institut für Polymerforschung  
Mainz, Germany

**Meng-Jiao Wang**

Business and Technology Center  
Cabot Corporation  
Billerica, Massachusetts

**Natalya A. Yerina**

Veeco Instruments  
Santa Barbara, California

**Li-Qun Zhang**

Department of Polymer Engineering  
School of Material Science and Engineering  
Beijing University of Chemical Technology  
Beijing, China

---

# Contents

Preface.....	xi
Editor.....	xiii
Contributors .....	xv

## **SECTION I    *Introductory Chapter***

<b>Chapter 1</b>	Some Outstanding Problems in the Mechanics of Rubbery Solids .....	3
	<i>Alan N. Gent</i>	

## **SECTION II    *New Elastomers and Composites***

<b>Chapter 2</b>	Elastomer–Clay Nanocomposites .....	23
	<i>Susmita Dey Sadhu, Madhuchhanda Maiti, and Anil K. Bhowmick</i>	
<b>Chapter 3</b>	Rubber–Silica Hybrid Nanocomposites .....	57
	<i>Abhijit Bandyopadhyay and Anil K. Bhowmick</i>	
<b>Chapter 4</b>	Rubber Nanocomposites Based on Miscellaneous Nanofillers .....	89
	<i>Anirban Ganguly, Jinu Jacob George, Sritama Kar, Abhijit Bandyopadhyay, and Anil K. Bhowmick</i>	
<b>Chapter 5</b>	Thermoplastic Elastomers.....	101
	<i>Francis R. Costa, Naba K. Dutta, Namita Roy Choudhury, and Anil K. Bhowmick</i>	
<b>Chapter 6</b>	Plastomers.....	165
	<i>Sudhin Datta</i>	
<b>Chapter 7</b>	New Elastomers: Biomacromolecular Engineering via Carbocationic Polymerization .....	193
	<i>Judit E. Puskas</i>	
<b>Chapter 8</b>	Novel Elastomers for Biomedical Applications .....	221
	<i>Li-Qun Zhang and Rui Shi</i>	

<b>Chapter 9</b>	Recombinant Resilin—A Protein-Based Elastomer .....	255
	<i>Mickey G. Huson and Christopher M. Elvin</i>	
<b>Chapter 10</b>	Smart Elastomers .....	277
	<i>Dipak K. Setua</i>	
<b>Chapter 11</b>	Recent Developments in Rubber–Rubber and Rubber–Plastics Blends .....	297
	<i>Duryodhan Mangaraj and Alice Bope Parsons</i>	
<b>Chapter 12</b>	Fiber-Reinforced Elastomers .....	351
	<i>R.S. Rajeev</i>	
<b>Chapter 13</b>	A Chemical Modification Approach for Improving the Oil Resistance of Ethylene–Propylene Copolymers .....	395
	<i>Herman Dikland and Martin van Duin</i>	

### **SECTION III Rubber Ingredients**

<b>Chapter 14</b>	Rubber-Curing Systems .....	415
	<i>Rabin N. Datta</i>	
<b>Chapter 15</b>	Degradation and Protection .....	463
	<i>Rabin N. Datta and Nico M. Huntink</i>	
<b>Chapter 16</b>	Q-Flex QDI Quinone Diimine Antidegradant—Improved Mixing Chemistry Resulting in a Better Balance of Productivity and Performance .....	489
	<i>Frederick Ignatz-Hoover and Byron To</i>	
<b>Chapter 17</b>	Silica Fillers for Elastomer Reinforcement .....	503
	<i>Doug J. Kohls, Dale W. Schaefer, Raissa Kosso, and Ephraim Feinblum</i>	
<b>Chapter 18</b>	Mechanism of the Carbon Black Reinforcement of Rubbers .....	517
	<i>Yoshihide Fukahori</i>	

### **SECTION IV New Characterization Techniques**

<b>Chapter 19</b>	Visualization of Nano-Filler Dispersion and Morphology in Rubbery Matrix by 3D-TEM .....	543
	<i>Shinzo Kohjiya, Yuko Ikeda, and Atsushi Kato</i>	

- Chapter 20** Scanning Probe Microscopy of Elastomers and Rubbery Materials..... 553  
*Sergei N. Magonov and Natalya A. Yerina*
- Chapter 21** Recent Developments in Rubber Research Using Atomic Force Microscopy ..... 579  
*Ken Nakajima and Toshio Nishi*

## **SECTION V   *Physics and Engineering***

- Chapter 22** Reinforced Elastomers: From Molecular Physics to Industrial Applications ..... 607  
*Gert Heinrich, Manfred Klüppel, and Thomas A. Vilgis*
- Chapter 23** Effects of Time, Temperature, and Fluids on the Long-Term Service Durability of Elastomers and Elastomeric Components ..... 625  
*Robert P. Campion, Des (C.J.) Derham, Glyn J. Morgan, and Michael V. Lewan*
- Chapter 24** Extrapolating the Viscoelastic Response of Rubber ..... 657  
*C.M. Roland*
- Chapter 25** Recent Advances in Fatigue Life Prediction Methods for Rubber Components ..... 673  
*Ryan J. Harbour, Ali Fatemi, and Will V. Mars*
- Chapter 26** Rubber Friction and Abrasion in Relation to Tire Traction and Wear ..... 685  
*Karl A. Grosch*
- Chapter 27** Improving Adhesion of Rubber..... 761  
*José Miguel Martín-Martínez*
- Chapter 28** Rheology of Rubber and Rubber Nanocomposites..... 775  
*Muthukumaraswamy Pannirselvam and Satinath Bhattacharya*
- Chapter 29** Rubber–Silica Mixing..... 801  
*Wilma Dierkes and Jacques Noordermeer*
- Chapter 30** Stream Effects and Nonlinear Viscoelasticity in Rubber Processing Operations ..... 817  
*Jean L. Leblanc*

<b>Chapter 31</b>	Electron Beam Processing of Rubber.....	851
	<i>Rajatendu Sengupta, Indranil Banik, Papiya Sen Majumder, V. Vijayabaskar, and Anil K. Bhowmick</i>	

## **SECTION VI    *Tires***

<b>Chapter 32</b>	Tire Technology—Recent Advances and Future Trends.....	919
	<i>Arup K. Chandra</i>	
<b>Chapter 33</b>	Recent Developments in Fillers for Tire Applications.....	935
	<i>Meng-Jiao Wang and Michael D. Morris</i>	
<b>Chapter 34</b>	Rubber Oxidation in Tires.....	955
	<i>John M. Baldwin and David R. Bauer</i>	
<b>Chapter 35</b>	Recent Developments in Rubber Mixing and Cord Calendering in Tire Production .....	975
	<i>Gerard Nijman</i>	
<b>Chapter 36</b>	High-Tech Quadroplex Extrusion Technology for the Tire Industry .....	1013
	<i>Hans-Georg Meyer</i>	

## **SECTION VII    *Eco-Friendly Technology and Recycling***

<b>Chapter 37</b>	Recent Advances in Eco-Friendly Elastomer Technology.....	1021
	<i>Rabindra Mukhopadhyay, Rajatendu Sengupta, and Saikat Das Gupta</i>	
<b>Chapter 38</b>	Waste Rubber Recycling .....	1043
	<i>Anandhan Srinivasan, A.M. Shanmugharaj, and Anil K. Bhowmick</i>	
<b>Index</b> .....		1067

# *Section I*

---

## *Introductory Chapter*



