

# FIBERS AND COMPOSITES

*Edited by*  
***Pierre Delhaès***



**Taylor & Francis**  
Taylor & Francis Group

LONDON AND NEW YORK

First published 2003  
by Taylor & Francis  
11 New Fetter Lane, London EC4P 4EE

Simultaneously published in the USA and Canada  
by Taylor & Francis Inc,  
29 West 35th Street, New York, NY 10001

*Taylor & Francis is an imprint of the Taylor & Francis Group*

© 2003 Taylor & Francis

Typeset in Times New Roman by  
Newgen Imaging Systems (P) Ltd, Chennai, India  
Printed and bound in Great Britain by  
TJ International Ltd, Padstow, Cornwall

All rights reserved. No part of this book may be reprinted or reproduced or utilised in any form or by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying and recording, or in any information storage or retrieval system, without permission in writing from the publishers.

Every effort has been made to ensure that the advice and information in this book is true and accurate at the time of going to press. However, neither the publisher nor the authors can accept any legal responsibility or liability for any errors or omissions that may be made. In the case of drug administration, any medical procedure or the use of technical equipment mentioned within this book, you are strongly advised to consult the manufacturer's guidelines.

*British Library Cataloguing in Publication Data*  
A catalogue record for this book is available from the British Library

*Library of Congress Cataloging in Publication Data*  
A catalog record for this book has been requested

ISBN 0-415-30826-7

# CONTENTS

*Introduction to the series*  
*List of contributors*

## **PART I**

### **Carbon fibers**

#### **1 Formation of microstructure in mesophase carbon fibers**

J. L. WHITE, B. FATHOLLAHI, AND X. BOURRAT

*Introduction*  
*Microstructural approach*  
*Manipulation of mesophase flow in a spinneret*  
*Discussion*

#### **2 The effect of processing on the structure and properties**

D. D. EDIE

*Introduction*  
*PAN-based carbon fibers*  
*Pitch-based carbon fibers*  
*New developments*  
*Summary*

#### **3 Electronic and thermal properties of carbon fibers**

J.-P. ISSI

*Introduction*  
*Experimental challenges*  
*Electrical resistivity*  
*Thermal conductivity*  
*Thermoelectric power*  
*Fibrous intercalation compounds*  
*Sample characterization*  
*Carbon fiber composites*  
*Conclusions*

## **PART II**

### **CVD/CVI processes**

#### **4 Fundamentals of chemical vapor deposition in hot wall reactors**

K. J. HÜTTINGER

*Introduction*

*Elementary processes*

*Hydrogen inhibition*

*Surface area/volume ratio*

*Saturation adsorption*

*The role of a complex deposition chemistry for CVI*

*Considerations about the formation of different  
carbon microstructures*

*Summary*

#### **5 Chemical vapor infiltration processes of carbon materials**

P. DELHAÈS

*Introduction*

*General background on CVD and CVI processes*

*CVI processes and efficiency*

*Pyrocarbon microstructures*

*Physical models*

*Carbon–carbon composites*

*Conclusion and outlook*

#### **6 Industrial carbon chemical vapor infiltration (CVI) processes**

I. GOLECKI

*Introduction*

*Overview of carbon CVI*

*Chemical vapor infiltration processes*

*Summary*

#### **7 Liquid impregnation techniques for carbon–carbon composites**

R. MENÉNDEZ, E. CASAL, AND M. GRANDA

*Introduction*

*Impregnation technology*

*Densification efficiency*

*Matrix precursors*

*New developments in C–C composites*

*Summary and conclusions*

## **PART III**

### **Properties of matrices and composites**

#### **8 Structure of pyrocarbons**

X. BOURRAT

*Introduction*

*The various pyrocarbons*

*Cones and regenerative features*

*Carbon layer diameter and growth mechanisms*

*Density and anisotropy of pyrocarbons*

*Conclusions*

#### **9 Role of chemistry in advanced carbon-based composites**

C. VIX-GUTERL AND P. EHRBURGER

*Introduction: principle of composite materials*

*Surface properties of carbon fibers*

*Surface treatment of carbon fibers*

*Carbon fiber reinforced polymers*

*Carbon-carbon composites*

*Carbon-based composites with other matrices*

*Conclusion*

#### **10 Carbon-cement composites**

D. D. L. CHUNG

*Introduction*

*Structural behavior*

*Thermal behavior*

*Electrical behavior*

*Radio wave reflectivity*

*Cathodic protection of steel reinforcement in concrete*

*Strain sensing*

*Damage sensing*

*Temperature sensing through the thermistor effect*

*Thermoelectric behavior*

*Corrosion resistance*

*Conclusion*

## INTRODUCTION TO THE SERIES

The *World of Carbon* book series aims to propose different approaches to carbon materials which summarize the essential information regarding advances and results accumulated in basic and applied research during the last century. Indeed, carbon associated with other atoms is a key element in nature and life. The focus of these books is, however, elemental carbon in a condensed phase, that is, mainly related to materials science.

Besides the natural forms of carbon found in earth and in extraterrestrial media, the artificial ones have led to manifold technical applications. They cover areas such as industrial chemistry and metallurgy, terrestrial transports as well as aircraft and aeronautics or environmental protection. These examples are related to the numerous old and new forms of carbon that we have partly presented in the first book of the series.

The field of research of carbon materials is a beautiful example of the strong interactions between science and technology, where back and forth activity has worked together for a long time. As with other scientific events, a historical approach shows that advances are step-by-step rather than linear with strong breakthroughs; different strata of knowledge are accumulated but sometimes with a loss of memory of the previous one. It is crucial for scientific knowledge, as a part of human activity, that a basic synthesis is realized, which summarized the numerous annual publications. The aim of this series is thus to provide short tutorial articles containing a comprehensive summary of the different topics related to the science of carbon materials. They will be addressed to engineers, scientists and students who are seeking fundamental points without “reinventing the wheel”.

*World of Carbon* series will be devoted to specific subjects, which cover all forms of carbons: the old ones like graphites or diamonds, but also the applied ones as fibers and composites. Each volume will cover fundamental research in chemistry and physics, as well as current applications and future developments. Such is the case of the second volume, which is devoted to the different forms of fibers, their precursors and their uses. This is one part of the most important industrial applications of graphitic carbons as also carbon blacks, foams and aerogels, insertion and reactivity products. Other polymorphic forms will not be neglected in the future, as carbynes or the new molecular curved forms, fullerenes and nanotubes, which are opening new avenues in nanotechnology.

Finally, we expect to present a collection of articles at a level and a style accessible to a large audience that will cover almost all aspects of carbon materials.

Pierre Delhaès  
January 2003

## CONTRIBUTORS

### **X. Bourrat**

Université de Bordeaux1  
Laboratoire des Composites  
Thermo-Structuraux  
LCTS, 3 Allée La Boëëie  
F-33 600 Pessac, France  
e-mail: bourrat@lets.u-bordeaux.fr

### **E. Casal**

Instituto Nacional del Carbón, CSIC  
Apartado 73, 33080 Oviedo, Spain  
e-mail: ecasal@incarc.csic.cs

### **D. D. L. Chung**

Composite Materials Research Laboratory  
University at Buffalo  
The State University of New York  
Buffalo, NY 14260-4400, USA  
e-mail: ddlchung@aesu.buffals.edu

### **P. Delhaès**

Centre de recherche Paul Pascal  
(CNRS and Université de Bordeaux1)  
33600 Pessac, France  
e-mail: delhaes@crpp.u-bordeaux.fr

### **D. D. Edie**

Department of Chemical Engineering and  
Center for Advanced Engineering Fibers  
and Films  
Clemson University, Clemson  
South Carolina 29634-0909, USA  
e-mail: dan.edie@ccs.clemson.edu

### **P. Ehrburger**

Université de Haute-Alsace, Laboratoire  
Gestion des Risques et Environnement  
25 rue de Chemnitz – 68200 Mulhouse  
France  
e-mail: P.Ehrburger@uha.fr

### **B. Fathollahi**

Chemical Engineering Program  
Jacobs School of Engineering  
University of California, San Diego  
La Jolla, CA 92093-0411, USA  
e-mail: bfatholl@ucsd.edu

### **I. Golecki**

Corporate R&D Materials Laboratory  
Honeywell International, Inc.  
Mail Stop CTC-1, 101 Columbia Road  
Morristown, NJ 07962, USA  
e-mail: ilan.golecki@honeywell.com

### **M. Granda**

Instituto Nacional del Carbón, CSIC  
Apartado 73, 33080 Oviedo, Spain  
e-mail: mgranda@incarc.csic.cs

### **K. J. Hüttinger**

Institut für Chemische Technik  
Kaiserstrasse 12.76128 karlsruhe  
Universität Karlsruhe, Germany  
e-mail: Huettinger@ict.uni-karlsruhe.de

### **J.-P. Issi**

Unité de Physico-Chimie et de Physique  
des Matériaux  
Université Catholique de Louvain  
1, Place Croix du Sud, B-1348  
Louvain-la-Neuve  
Belgique  
e-mail: issi@pcpm.ucl.ac.bc

### **R. Menéndez**

Instituto Nacional del Carbón, CSIC  
Apartado 73, 33080 Oviedo, Spain  
e-mail: rosminen@incarc.csic.cs

**C. Vix-Guterl**

Institut de Chimie des Surfaces et  
Interfaces  
15 rue Jean Starcky  
68057 Mulhouse Cedex, France  
e-mail: C.Vix@uha.fr

**J. L. White<sup>†</sup>**

Chemical Engineering Program  
Jacobs School of Engineering  
University of California, San Diego  
La Jolla, CA 92093-0411  
USA