

CARBON MATERIALS FOR CATALYSIS

Edited by

Philippe Serp
José Luís Figueiredo



A JOHN WILEY & SONS, INC., PUBLICATION

CARBON MATERIALS FOR CATALYSIS

CARBON MATERIALS FOR CATALYSIS

Edited by

Philippe Serp
José Luís Figueiredo



A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2009 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Serp, Philippe.

Carbon Materials for Catalysis / Philippe Serp, José Luís Figueiredo.

p. cm.

Includes index.

ISBN 978-0-470-17885-0 (cloth)

1. Carbon. 2. Catalysis. I. Figueiredo, José Luís. II. Title.

TP245.C4S47 2009

660'.2995—dc22

2008019014

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Contents

Contributors	xv
Preface	xix
1 Physicochemical Properties of Carbon Materials: A Brief Overview	1
<i>Ljubisa R. Radovic</i>	
1.1. Introduction, 1	
1.2. Formation of Carbons, 2	
1.2.1. Gas Phase, 2	
1.2.2. Liquid Phase, 3	
1.2.3. Solid Phase, 4	
1.3. Structure and Properties of Carbons, 5	
1.3.1. Macrostructure, 5	
1.3.2. Microstructure, 8	
1.3.3. Nanostructure, 8	
1.3.4. Bulk Properties, 16	
1.3.5. Surface Properties, 19	
1.4. Reactions of Carbons, 23	
1.4.1. Gas Phase, 23	
1.4.2. Liquid Phase, 25	
1.4.3. Solid Phase, 27	
1.5. Conclusions, 33	
References, 34	
2 Surface Chemistry of Carbon Materials	45
<i>Teresa J. Bandosz</i>	
2.1. Introduction, 45	
2.2. Surface Functionalities, 47	
2.2.1. Oxygen-Containing Functionalities, 48	
2.2.2. Nitrogen-Containing Functionalities, 50	
2.2.3. Hydrogen–Carbon Species, 51	
2.2.4. Sulfur, Phosphorus, and Halogen Functionalities, 51	

2.3.	Surface Modifications, 54
2.3.1.	Oxidation, 54
2.3.2.	Introduction of Nitrogen-Containing Species, 55
2.3.3.	Introduction of Sulfur Functionality, 55
2.3.4.	Halogenation, 56
2.3.5.	Impregnation and Dry Mixing, 56
2.3.6.	Heat Treatment, 56
2.4.	Characterization of Surface Chemistry, 58
2.4.1.	Elemental Analysis, 58
2.4.2.	Titration, 58
2.4.3.	pH of Carbons, Point of Zero Charge, and Isoelectric Point, 61
2.4.4.	Spectroscopic Methods, 63
2.4.5.	Calorimetric Techniques, 72
2.4.6.	Inverse Gas Chromatography, 75
2.4.7.	Temperature-Programmed Desorption, 75
2.4.8.	Characterization of Surface Functionalities by Electrochemical Techniques, 78
2.5.	Role of Surface Chemistry in the Reactive Adsorption on Activated Carbons, 78
2.6.	Role of Carbon Surface Chemistry in Catalysis, 80
	References, 82

3 Molecular Simulations Applied to Adsorption on and Reaction with Carbon 93

Zhonghua (John) Zhu

3.1.	Introduction, 93
3.2.	Molecular Simulation Methods Applied to Carbon Reactions, 94
3.2.1.	Electronic Structure Methods (or Quantum Mechanics Methods), 94
3.2.2.	Molecular Dynamics Simulations, 97
3.2.3.	Monte Carlo Simulations, 98
3.3.	Hydrogen Adsorption on and Reaction with Carbon, 98
3.3.1.	Atomic Hydrogen Adsorption on the Basal Plane of Graphite, 98
3.3.2.	Reactivities of Graphite Edge Sites and Hydrogen Reactions on These Sites, 101
3.3.3.	Hydrogen Storage in Carbon Nanotubes, 104
3.4.	Carbon Reactions with Oxygen-Containing Gases, 105
3.4.1.	Carbon Reactions with Oxygen-Containing Gases and the Unified Mechanism, 106
3.4.2.	Catalyzed Gas–Carbon Reactions, 110

3.4.3. More Specific Studies on NO_x , H_2 , CO_2 , and O_2 –Carbon Reactions, 118	
3.5. Metal–Carbon Interactions, 122	
3.6. Conclusions, 125	
References, 126	
4 Carbon as Catalyst Support	131
<i>Francisco Rodríguez-Reinoso and Antonio Sepúlveda-Escribano</i>	
4.1. Introduction, 131	
4.2. Properties Affecting Carbon’s Role as Catalyst Support, 132	
4.2.1. Surface Area and Porosity, 132	
4.2.2. Surface Chemical Properties, 134	
4.2.3. Inertness, 136	
4.3. Preparation of Carbon-Supported Catalysts, 137	
4.3.1. Impregnation, 137	
4.3.2. Other Methods, 139	
4.4. Applications, 140	
4.4.1. Ammonia Synthesis, 141	
4.4.2. Hydrotreating Reactions, 143	
4.4.3. Hydrogenation Reactions, 147	
4.5. Summary, 150	
References, 150	
5 Preparation of Carbon-Supported Metal Catalysts	157
<i>Johannes H. Bitter and Krijn P. de Jong</i>	
5.1. Introduction, 157	
5.2. Impregnation and Adsorption, 157	
5.2.1. Interaction Between Support and Precursor, 158	
5.2.2. Role of Pore Structure, 164	
5.3. Deposition Precipitation, 165	
5.3.1. Increase in pH, 166	
5.3.2. Change of Valency, 169	
5.3.3. Ligand Removal, 170	
5.4. Emerging Preparation Methods, 171	
5.5. Conclusions, 172	
References, 173	
6 Carbon as Catalyst	177
<i>José Luís Figueiredo and Manuel Fernando R. Pereira</i>	
6.1. Introduction, 177	
6.2. Factors Affecting the Performance of a Carbon Catalyst, 178	

6.2.1.	Nature of the Active Sites, 178
6.2.2.	Concentration of the Active Sites, 179
6.2.3.	Accessibility of the Active Sites, 179
6.3.	Reactions Catalyzed by Carbons, 180
6.3.1.	Oxidative Dehydrogenation, 181
6.3.2.	Dehydration of Alcohols, 186
6.3.3.	SO _x Oxidation, 188
6.3.4.	NO _x Reduction, 190
6.3.5.	H ₂ S Oxidation, 194
6.3.6.	Hydrogen Peroxide Reactions, 196
6.3.7.	Catalytic Ozonation, 198
6.3.8.	Catalytic Wet Air Oxidation, 203
6.3.9.	Other Reactions, 205
6.4.	Conclusions, 207
	References, 208

7 Catalytic Properties of Nitrogen-Containing Carbons 219

Hanns-Peter Boehm

7.1.	Introduction, 219
7.2.	Nitrogen Doping of Carbons, 220
7.2.1.	Preparation of Nitrogen-Containing Carbons, 220
7.2.2.	Quantitative Analysis, 227
7.2.3.	Electron Emission Spectrometric Analysis, 227
7.2.4.	Properties of Nitrogen-Containing Carbons, 233
7.3.	Catalysis of Oxidation Reactions with Dioxygen, 238
7.3.1.	Oxidation of Aqueous Sulfurous Acid, 238
7.3.2.	Oxidation of Oxalic Acid, 244
7.3.3.	Oxidation of Sulfur Dioxide, 244
7.3.4.	Oxidation of Iron(II) Ions, 246
7.3.5.	Oxidation of Other Compounds, 247
7.4.	Catalysis of Aging of Carbons, 251
7.5.	Catalysis of Dehydrochlorination Reactions, 254
7.6.	Mechanism of Catalysis by Nitrogen-Containing Carbons, 257
	References, 259

8 Carbon-Anchored Metal Complex Catalysts 267

Cristina Freire and Ana Rosa Silva

8.1.	Introduction, 267
8.2.	General Methods for Molecule Immobilization, 268
8.3.	Methods for Immobilization of Transition-Metal Complexes Onto Carbon Materials, 270

8.3.1.	Functionalization of Carbon Materials, 271	
8.3.2.	Direct Immobilization of Metal Complexes, 278	
8.3.3.	Metal Complex Immobilization via Spacers, 285	
8.4.	Application of Coordination Compounds Anchored Onto Carbon Materials in Several Catalytic Reactions, 289	
8.4.1.	[M(<i>salen</i>)]-Based Materials, 290	
8.4.2.	[M(<i>acac</i>) ₂]-Based Materials, 293	
8.4.3.	Metal Phthalocyanine and Porphyrin-Based Materials, 294	
8.5.	Application of Carbon-Supported Organometallic Compounds in Hydrogenation and Hydroformylation Catalytic Reactions, 296	
8.5.1.	Materials Based on Pd and Rh Amino Complexes, 296	
8.5.2.	Materials Based on Rh and Pd Complexes with π -Bonding Ligands (Phosphines and Dienes), 297	
8.6.	Carbon-Supported Organometallic Complexes in the Polymerization Reaction of Olefins, 300	
8.7.	Conclusions, 301	
	References, 302	
9	Carbon Nanotubes and Nanofibers in Catalysis	309
	<i>Philippe Serp</i>	
9.1.	Introduction, 309	
9.2.	Catalytic Growth of Carbon Nanofibers and Nanotubes, 312	
9.2.1.	Catalytic Carbon Deposition, 312	
9.2.2.	Growth Mechanism, 313	
9.3.	Why CNTs or CNFs Can Be Suitable for Use in Catalysis, 324	
9.3.1.	Structural Features and Electronic Properties, 324	
9.3.2.	Adsorption Properties, 328	
9.3.3.	Mechanical and Thermal Properties, 330	
9.3.4.	Macroscopic Shaping of CNTs and CNFs, 331	
9.4.	Preparation of Supported Catalysts on CNTs and CNFs, 333	
9.5.	Catalytic Performance of CNT- and CNF-Based Catalysts, 340	
9.5.1.	Hydrogenation Reactions, 340	
9.5.2.	Reactions Involving CO/H ₂ , 344	
9.5.3.	Polymerization, 345	
9.5.4.	Carbon Nanotubes Synthesis by Catalytic Decomposition of Hydrocarbons, 348	
9.5.5.	Ammonia Synthesis and Decomposition, 349	
9.5.6.	Environmental Catalysis and Oxidation Reactions, 350	
9.5.7.	Other Reactions, 351	
9.5.8.	Fuel Cell Electrocatalysts, 354	
9.5.9.	CNTs for Enzyme Immobilization, 355	

9.5.10. CNTs and CNFs as Catalysts, 356	
9.6. Conclusions, 356	
References, 358	
10 Carbon Gels in Catalysis	373
<i>Carlos Moreno-Castilla</i>	
10.1. Introduction, 373	
10.2. Carbon Gels: Preparation and Surface Properties, 374	
10.3. Metal-Doped Carbon Gels, 376	
10.3.1. Dissolving the Metal Precursor in the Initial Mixture, 378	
10.3.2. Introducing a Functionalized Moiety, 381	
10.3.3. Depositing the Metal Precursor on the Organic or Carbon Gel, 382	
10.4. Catalytic Reactions of Metal-Doped Carbon Gels, 383	
10.4.1. Environmental Applications, 384	
10.4.2. Fuel Cell Applications, 387	
10.4.3. C=C Double-Bond Hydrogenation, 389	
10.4.4. Skeletal Isomerization of 1-Butene, 391	
10.4.5. Hydrodechlorination Reaction, 392	
10.4.6. Other Reactions, 392	
10.5. Conclusions, 393	
References, 395	
11 Carbon Monoliths in Catalysis	401
<i>Karen M. de Lathouder, Edwin Crezee, Freek Kapteijn, and Jacob A. Moulijn</i>	
11.1. Introduction, 401	
11.2. Carbon, 401	
11.3. Monolithic Structures, 402	
11.4. Carbon Monoliths, 402	
11.5. Carbon Monoliths in Catalysis: An Overview, 404	
11.6. Example of Carbon Monoliths as Catalyst Support Material, 405	
11.6.1. Carbon Monoliths as Support Material in Biocatalysis, 405	
11.6.2. Selective Hydrogenation of D-Glucose over Monolithic Ruthenium Catalysts, 405	
11.6.3. Performance of Carbon Monoliths, 406	
11.6.4. Morphology and Porosity of Various Carbon Composites, 407	
11.6.5. Enzyme Adsorption and Catalyst Performance in the MSR, 413	
11.6.6. Performance of Monolithic Ruthenium Catalysts, 416	
11.7. Evaluation and Practical Considerations, 420	

11.7.1. Monolithic Biocatalysts, 420	
11.7.2. Monolithic Ruthenium Catalysts, 421	
11.7.3. Practical Considerations, 421	
11.8. Conclusions, 423	
References, 424	
12 Carbon Materials as Supports for Fuel Cell Electrocatalysts	429
<i>Frédéric Maillard, Pavel A. Simonov, and Elena R. Savinova</i>	
12.1. Introduction, 429	
12.2. Structure and Morphology of Carbon Materials, 433	
12.2.1. Carbon Blacks, 433	
12.2.2. Activated Carbons, 434	
12.2.3. Carbons of the Sibunit Family, 435	
12.2.4. Ordered Mesoporous Carbons, 436	
12.2.5. Carbon Aerogels, 436	
12.2.6. Carbon Nanotubes and Nanofibers, 437	
12.3. Physicochemical Properties of Carbon Materials Relevant to Fuel Cell Operation, 438	
12.3.1. Electron Conduction, 438	
12.3.2. Surface Properties, 440	
12.4. Preparation of Carbon-Supported Electrocatalysts, 443	
12.4.1. Methods Based on Impregnation, 444	
12.4.2. Colloidal Synthesis, 445	
12.4.3. Electrodeposition, 445	
12.4.4. Other Methods, 446	
12.5. Structural Characterization of Carbon-Supported Metal Catalysts, 446	
12.5.1. Adsorption Studies, 447	
12.5.2. Transmission Electron Microscopy, 448	
12.5.3. Xray Diffraction and Xray Absorption Spectroscopy, 449	
12.5.4. Electrochemical Methods, 450	
12.6. Influence of Carbon Supports on the Catalytic Layers in PEMFCs, 452	
12.6.1. Intrinsic Catalytic Activity, 452	
12.6.2. Macrokinetic Parameters, 456	
12.6.3. Novel Carbon Materials as Supports for Fuel Cell Electrocatalysts, 462	
12.7. Corrosion and Stability of Carbon-Supported Catalysts, 464	
12.7.1. Influence of Microstructure on the Corrosion of Carbon Materials, 464	
12.7.2. Mechanism of Carbon Corrosion, 466	

12.7.3. Corrosion and Stability of MEAs,	467
12.8. Conclusions,	469
References,	470
13 Carbon Materials in Photocatalysis	481
<i>Joaquim Luís Faria and Wendong Wang</i>	
13.1. Introduction,	481
13.2. Carbon Materials Employed to Modify TiO ₂ in Photocatalysis,	482
13.2.1. Activated Carbon,	482
13.2.2. Carbon Black and Graphite,	483
13.2.3. Carbon Fiber,	483
13.2.4. Carbon Nanotubes,	483
13.2.5. Other Forms of Carbon,	484
13.3. Synthesis and Characterization of Carbon–TiO ₂ Composites,	484
13.3.1. Mechanical Mixture of TiO ₂ and Carbon Materials,	485
13.3.2. TiO ₂ Coated or Loaded on Carbon Materials,	485
13.3.3. Carbon Materials Coated or Deposited on TiO ₂ ,	485
13.3.4. Other Approaches and Concurrent Synthesis of TiO ₂ –Carbon Composites,	486
13.3.5. Methods of Characterization,	486
13.4. Photodegradation on Carbon-Containing Surfaces,	487
13.4.1. Heterogeneous Photocatalysis in the Liquid Phase with Carbon–TiO ₂ Composites,	487
13.4.2. Heterogeneous Photocatalysis in the Gas Phase with Carbon–TiO ₂ Composites,	491
13.5. Role of the Carbon Phase in Heterogeneous Photocatalysis,	492
13.6. Conclusions,	498
References,	499
14 Carbon-Based Sensors	507
<i>Jun Li</i>	
14.1. Introduction,	507
14.1.1. Structure of Various Carbon Allotropes,	507
14.1.2. sp ² Carbon Materials: Graphite, Fullerenes, and Carbon Nanotubes,	509
14.2. Physicochemical Properties of sp ² Carbon Materials Relevant to Carbon Sensors,	510
14.2.1. Electrical and Electronic Properties,	510
14.2.2. Chemical Properties,	515
14.2.3. Electrochemical Properties,	516

14.3.	Carbon-Based Sensors, 517	
14.3.1.	Carbon Materials as Loading Media, 518	
14.3.2.	Carbon Electronic Sensors, 518	
14.3.3.	Carbon Electrochemical Sensors, 523	
14.3.4.	Carbon Composite Sensors, 530	
14.4.	Summary, 530	
	References, 530	
15	Carbon-Supported Catalysts for the Chemical Industry	535
	<i>Venu Arunajatesan, Baoshu Chen, Konrad Möbus, Daniel J. Ostgard, Thomas Tacke, and Dorit Wolf</i>	
15.1.	Introduction, 535	
15.2.	Requirements for Carbon Materials as Catalyst Supports in Industrial Applications, 536	
15.2.1.	Activated Carbon, 536	
15.2.2.	Carbon Black, 540	
15.3.	Industrial Manufacture of Carbon Supports, 544	
15.3.1.	Activated Carbon, 544	
15.3.2.	Carbon Black, 544	
15.4.	Manufacture of Carbon-Supported Catalysts, 545	
15.4.1.	Powder Catalysts, 545	
15.4.2.	Preparation Technology, 547	
15.5.	Reaction Technology, 547	
15.5.1.	Batch Stirred-Tank and Loop Reactors, 548	
15.5.2.	Fixed-Bed Reactors, 550	
15.6.	Industrial Applications, 551	
15.6.1.	Fatty Acid Hydrogenation, 551	
15.6.2.	Selective Nitrobenzene Hydrogenations, 554	
15.6.3.	Reductive Alkylation, 555	
15.6.4.	Toluenediamine, 556	
15.6.5.	Butanediol, 558	
15.6.6.	Purified Terephthalic Acid, 560	
15.7.	Testing and Evaluation of Carbon Catalysts, 561	
15.7.1.	Current Methods for Catalyst Evaluation, 561	
15.7.2.	High-Throughput Testing of Carbon Powder Catalysts, 563	
15.7.3.	Catalyst Profiling, 565	
15.8.	Conclusions, 567	
	References, 568	
Index		573

Contributors

VENU ARUNAJATESAN, Evonik Degussa Corporation, 5150 Gilbertsville Highway, Calvert City, KY, 42029

e-mail: venu.arunajatesan@evonik.com

TERESA J. BANDOSZ, Department of Chemistry, Marshak Science Building J-1024, The City College of New York, The City University of New York, 160 Convent Avenue, New York, NY 10031

e-mail: tbandoz@ccny.cuny.edu

JOHANNES H. BITTER, Department of Inorganic Chemistry, Debye Institute, Utrecht University, Sorbonnelaan 16, 3584 CA Utrecht, The Netherlands

e-mail: j.h.bitter@uu.nl

HANNS-PETER BOEHM, Department of Chemistry and Biochemistry, University of Munich, Butenandtstrasse 5-13, 81377 Munich, Germany

e-mail: hpb@cup.uni-muenchen.de

BAOSHU CHEN, Degussa GmbH, Business Line Catalysts, Rodenbacher Chaussee 4, 63457 Hanau-Wolfgang, Germany

e-mail: baoshu.chen@evonik.com

EDWIN CREZEE, Albemarle Catalysts, Nieuwendammerkade 1-3, P.O. Box 37650, 1030 BE Amsterdam, The Netherlands

e-mail: edwincrezee@yahoo.co.uk

KRIJN P. DE JONG, Department of Inorganic Chemistry, Debye Institute, Utrecht University, Sorbonnelaan 16, 3584 CA Utrecht, The Netherlands

e-mail: k.p.dejong@uu.nl

KAREN M. DE LATHOUDER, Shell Nederland Raffinaderij B.V., Vondelingenweg 601, Postbus 3000, 3190 GA Hoogvliet, Rotterdam, The Netherlands

e-mail: karen.delathouder@shell.com

JOAQUIM LUÍS FARIA, Laboratório de Catálise e Materiais, Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

e-mail: jlfaria@fe.up.pt

JOSÉ LUÍS FIGUEIREDO, Laboratório de Catálise e Materiais, Departamento de Engenharia Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

e-mail: jlfig@fe.up.pt

CRISTINA FREIRE, REQUIMTE/Departamento de Química, Faculdade de Ciências, Universidade do Porto, 4169-007 Porto, Portugal
e-mail: acfreire@fc.up.pt

FREEK KAPTEIJN, Catalysis Engineering, DelftChemTech, Delft University of Technology, Julianalaan 136, 2628 BL, Delft, The Netherlands
e-mail: f.kapteijn@tudelft.nl

JUN LI, Department of Chemistry, Kansas State University, 111 Willard Hall, Manhattan, KS 66506-3701
e-mail: junli@ksu.edu

FRÉDÉRIC MAILLARD, Laboratoire d'Electrochimie et de Physico-chimie des Matériaux et des Interfaces, UMR 5631 CNRS/INPG/UJF, 1130, rue de la Piscine, BP75, 38402 Saint Martin d'Hères, France
e-mail: frederic.maillard@lepmi.inpg.fr

KONRAD MÖBUS, Evonik Degussa GmbH, Business Line Catalysts, Rodenbacher Chaussee 4, 63457 Hanau-Wolfgang, Germany
e-mail: konrad.moebus@evonik.com

CARLOS MORENO-CASTILLA, Inorganic Chemistry Department, Granada University, 18071 Granada, Spain
e-mail: cmoreno@ugr.es

JACOB A. MOULIJN, Catalysis Engineering, DelftChemTech, Delft University of Technology, Julianalaan 136, 2628 BL, Delft, The Netherlands
e-mail: J.A.Moulijn@tudelft.nl

DANIEL J. OSTGARD, Degussa GmbH, Business Line Catalysts, Rodenbacher Chaussee 4, 63457 Hanau-Wolfgang, Germany
e-mail: dan.ostgard@evonik.com

MANUEL FERNANDO R. PEREIRA, Laboratório de Catálise e Materiais, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
e-mail: fpereira@fe.up.pt

LJUBISA R. RADOVIC, Energy and Minerals Engineering, 205 Hosler Building, The Pennsylvania State University, University Park, PA 16802
e-mail: lrr3@psu.edu

FRANCISCO RODRÍGUEZ-REINOSO, Universidad de Alicante, Departamento de Química Inorgánica, E-03080 Alicante, Spain
e-mail: reinoso@ua.es

ELENA R. SAVINOVA, Laboratoire des Matériaux, Surfaces et Procédés pour la Catalyse, UMR-7515, ECPM, Université Louis Pasteur, 67087 Strasbourg, France
e-mail: elena.savinova@ecpm.u-strasbg.fr

ANTONIO SEPÚLVEDA-ESCRIBANO, Universidad de Alicante, Departamento de Química Inorgánica, E-03080 Alicante, Spain
e-mail: asepul@ua.es

PHILIPPE SERP, Laboratoire de Chimie de Coordination, composante ENSIACET, UPR 8241 CNRS 118 Route de Narbonne, Toulouse University, 31077 Toulouse Cedex 4, France
e-mail: Philippe.Serp@ensiacet.fr

ANA ROSA SILVA, REQUIMTE/Departamento de Química, Faculdade de Ciências, Universidade do Porto, 4169-007 Porto, Portugal *Present address:* Unilever R&D, Port Sunlight, UK
e-mail: anarosa.silva@unilever.com

PAVEL A. SIMONOV, Boreskov Institute of Catalysis, Russian Academy of Sciences, Pr. Akademika Lavrentieva 5, 630090 Novosibirsk, Russia
e-mail: spa@catalysis.nsk.su

THOMAS TACKE, Evonik Degussa GmbH, Science to Business Center Bio, Paul-Baumann-Strasse 1, 45764 Marl, Germany
e-mail: thomas.tacke@evonik.com

WENDONG WANG, Department of Chemical Physics, University of Science and Technology of China, Hefei 230026, Anhui, China
e-mail: wangwd@ustc.edu.cn

DORIT WOLF, Evonik Degussa GmbH, Business Line Catalysts, Rodenbacher Chaussee 4, 63457 Hanau-Wolfgang, Germany
e-mail: dorit.wolf@evonik.com

ZHONGHUA (JOHN) ZHU, Division of Chemical Engineering, School of Engineering, University of Queensland, Brisbane 4072, Australia
e-mail: z.zhu@uq.edu.au

Preface

Carbon is a versatile and fascinating material that can be used in a number of technological processes, including high-tech processes. This is due largely to the ability of carbon atoms to bond with each other in various ways to form linear, planar, and tetrahedral bonding arrangements, thus producing materials with a large range of properties. Physicochemical characteristics such as electrical conductivity, surface area and porosity, and surface chemistry may be tuned for specific applications.

Carbon materials such as activated carbons, carbon blacks, graphite, and graphitic materials have been used for decades in heterogeneous catalysis, as either catalysts or catalyst supports. Activated carbon catalysts are used in the synthesis of phosgene from carbon monoxide and chlorine, in the synthesis of thionyl chloride from sulfur dioxide and chlorine, and in the oxidation of *N*-phosphonomethyliminodiacetic acid to produce a biodegradable herbicide, Glyphosate. Activated carbons impregnated with ZnO, CuO, or Fe₂O₃ are designed specifically for the desulfurization of natural gas. The Merox process developed by Universal Oil Products to remove mercaptan sulfur from petroleum fractions involves a catalyst consisting of cobalt phthalocyaninedisulfonate impregnated onto a suitable high-surface-area activated carbon. Furthermore, because of their high thermal stability in reducing atmospheres and their ability to facilitate the preparation of well-dispersed metal particles on surfaces that do not exhibit acid–base properties, carbon materials are used to support precious metals for hydrogenation reactions in the fine-chemicals industry. The recovery and recycling of metals, particularly of noble metals, is simplified with carbons, as these supports can be burned off. These materials offer unparalleled flexibility in tailoring catalyst properties to specific needs.

Compared to the predominant applications of these carbon materials as adsorbents for drinking water, wastewater, and gas purification, as fillers in rubber production, or as refractory materials, however, their use in the catalyst market represents only a moderate share. The potential growth of the market for carbons in catalysis depends on (1) better understanding of the chemistry of carbon surfaces and fine tuning of the microstructure of these materials, which could then be exploited in the design of truly unique catalysts; and (2) improvements in quality control and production methods, to supply constant-quality materials (synthetic carbons). There are additional opportunities to increase the market value of carbon materials in the near future, due to the rapidly advancing development of fuel cells, the use of novel carbon materials, the increasing need for catalytic

materials in very selective reactions, and the identification of some high-volume applications.

Patents appear continuously to meet industrial needs, and the growth of scientific publications dealing with the use of carbon materials in catalysis is exponential. However, the last major review of this field was published over a decade ago (L.R. Radovic and F. Rodríguez-Reinoso, in P.A. Thrower, Ed., *Chemistry and Physics of Carbon*, Vol. 25, Marcel Dekker, New York, 1997, p. 243). In the meantime, new materials, such as carbon nanotubes, nanofibers, aerogels, and xerogels, have become widely available, and our knowledge of the surface chemistry of carbon materials has improved substantially. We are now able to modify in a controlled manner the nature and concentration of functional groups on the surface of carbon materials, which can serve as active sites in catalysis or as anchoring centers for active phases or their precursors. High-performance nanostructured catalysts can thus be prepared. Moreover, analytical tools have been developed for the identification and quantification of surface groups, paving the way for the proper interpretation of kinetic data and providing for useful correlations of catalytic activity. There is clearly a need to establish the state of the art in order to identify the required areas of research, to stimulate more systematic approaches, and to promote further technological developments in the field—and that is the purpose of this book.

The material is organized into 15 chapters written by recognized experts in their fields. It has been decided to cover in depth new and hot topics as well as those that have not yet been the subject of extensive reviews. In the first three chapters the properties of carbon materials relevant to catalysis are discussed, with a special emphasis given to the description of carbon surface features, in particular to surface functional groups and their characterization methods, and to the theoretical investigation of molecular interactions on carbon surfaces. This provides a fundamental background for an understanding of the material covered in subsequent chapters.

The next two chapters provide a comprehensive review of carbon-supported metal catalysts and their preparation methods. The most important applications are discussed, special attention being given to the most innovative.

Chapter 6 provides an extensive review of the uses of carbon as a catalyst, with particular emphasis being placed on cases in which active sites have been properly identified and activity correlations established. The special case of nitrogen-doped carbons and their catalytic activity in oxidation reactions is discussed in Chapter 7, and Chapter 8 covers the heterogenization of homogeneous catalysts by anchoring transition-metal complexes onto the surface of suitable carbon materials.

Two important classes of new carbon materials, carbon nanotubes/nanofibers and carbon aerogels/xerogels/cryogels are reviewed and discussed in the next two chapters. These materials exhibit interesting properties that can be exploited in many applications, particularly in catalysis.

Chapter 11 provides a short review of carbon-based monoliths, their preparation, and applications in various liquid-phase processes, including bioconversions.

Chapters 12 and 13 cover two of the most important novel catalytic applications of carbon materials, electrocatalysis and photocatalysis. In the first case, carbons are used mostly as supports for metal catalysts in fuel cells, while the synergistic effects of carbon-based composite semiconductor materials, such as C-TiO₂, make them particularly effective in photocatalytic degradation reactions.

Chapter 14 addresses the special topic of sensors, in which advantage is taken of the unique properties of nanostructured carbon materials such as nanotubes and fullerenes. Finally, applications of carbon-supported precious metal catalysts are reviewed from an industrial perspective in Chapter 15.

Since this is a multiauthored book, significant differences in style from chapter to chapter are inevitable, but we have tried to avoid overlaps as much as possible. We thank all the authors for their efforts to meet the deadlines and to follow the format defined for the book. We would also like to acknowledge the assistance of Anita Lekhwani at Wiley, whose advice has been most helpful at the various stages of preparation of the manuscript. Finally, we hope that the book will be useful to fellow scientists and practitioners and will stimulate further research and discussion on the development of carbon materials for catalysis.

Toulouse

PHILIPPE SERP

Porto

JOSÉ LUÍS FIGUEIREDO

February 2008

1 Physicochemical Properties of Carbon Materials: A Brief Overview

LJUBISA R. RADOVIC

1.1 INTRODUCTION

To justify the title and the contents of this brief introductory review, it is appropriate to recall the words of Nernst, written more than a century ago (1893) in the Preface to the first edition of his *Theoretical Chemistry from the Standpoint of Avogadro's Rule and Thermodynamics* (<http://books.google.com>): “[T]he development of physical chemistry as a special branch of natural science means—and I would lay particular emphasis on this—not so much the shaping of a new science, but rather the co-operation of two sciences which hitherto have been, on the whole, quite independent of each other.”

Catalytic applications of carbon materials are as old as the discipline of physical chemistry, and probably even older. Over the past century or so, the level of fundamental understanding of these technological applications and this discipline has increased tremendously, of course. Yet, despite (or because?) of this progress, there is a pervasive problem in carbon science and technology: It is an eminently interdisciplinary field, and the danger that “the left hand doesn’t know what the right hand is doing” is considerable. In principle and increasingly in practice, as Nernst himself had anticipated, this problem has also plagued physical chemistry but it has been overcome; it took almost a century for Dirac’s prophecy to be realized, but it has been done. With the discovery of quantum mechanics, chemistry has been essentially reduced to physics. Dirac proclaimed that “the underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known” [1]. So in the second century of existence of physical chemistry as a discipline, the key question is whether carbon chemists really understand what the carbon physicists are arguing, and vice versa. Here I explore some answers to this question, those that are considered

to be of greatest relevance to catalytic applications of carbon materials. Knowing that, despite the wonderful opportunities offered by electronic storage and retrieval of information, researchers today continue to struggle to keep up with the literature in their own (increasingly narrow?) field, it is anticipated that the path outlined by Dirac continues to be a difficult one. Yet the obvious rewards to those who succeed in integrating carbon physics and carbon chemistry should be a powerful enough incentive. Much of the evidence of progress in this endeavor, or lack thereof, has accumulated in the 30 volumes [2] of the book series *Chemistry and Physics of Carbon* inaugurated by Philip Walker almost half a century ago, when carbon science was in its infancy. It is true that “the study of carbon has grown to become a specialism” [3] but, as argued below, it is inappropriate to obscure it unduly [3] as not only “a combination of physics and chemistry” but also of “fluid dynamics and chemical engineering, with dashes of astrophysics and geology” [3]. From a historical perspective, the development of carbon science and technology provides several ironic and exemplary twists of fate for chemists and physicists. The most fascinating one is related to the discovery of C₆₀, buckminsterfullerene. Its chemical identification [4] was brought about by the pursuit of an astrophysical issue (the nature of interstellar dust), whereas researchers in a physics department [5] were the first to achieve its chemical separation.

Catalytic behavior of carbon materials depends on their surface properties, but surface properties are to a large extent a consequence of bulk properties. Therefore, after a brief overview of the ways that carbon materials are formed, I discuss their bulk properties briefly before focusing on their physical and chemical surface properties and their chemical (re)activity.

1.2 FORMATION OF CARBONS

All carbon materials, including those used for catalytic applications, are formed in either the gas, liquid, or solid phase; and these conditions to a large extent dictate the variabilities possible in their physicochemical properties. The range of hydrocarbon feedstocks used as carbon precursors is also dictated by these conditions; and seemingly subtle changes often produce profound structural effects. These are discussed briefly below.

1.2.1 Gas Phase

Figure 1.1 summarizes the very wide range of carbon products that can be produced in gas-phase reactions under perhaps surprisingly similar conditions from a very wide variety of carbon-containing gases (e.g., CO, CH₄, C₂H₂, C₃H₆, C₆H₆, natural gas, volatile products of coal or biomass pyrolysis). The relatively disordered (but not amorphous), nongraphitic and nongraphitizable carbon black or soot particles result because nucleation of the carbon precursors occurs during pyrolysis in the gas phase. The much more ordered (quasicrystalline)

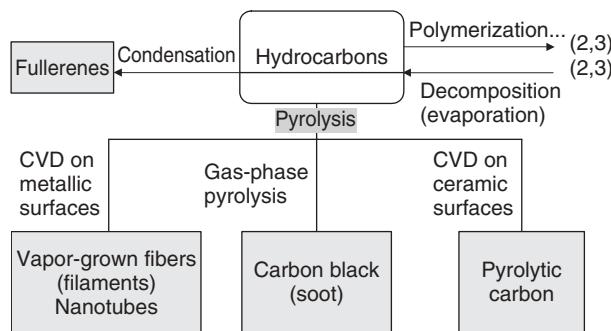


Figure 1.1 Summary of the processes of carbon formation in the gas phase and the resulting carbon macrostructures. (Hydrocarbon polymerization or decomposition can lead to interconversion of gaseous, liquid, or solid carbon precursors; see also Figures 1.2 and 1.3.)

nongraphitic but graphitizable pyrolytic carbon is obtained by virtue of chemical vapor deposition (CVD) of carbon precursors on a relatively inert (e.g., ceramic) substrate; the structure of crystalline graphite (in pyrolytic graphite) is achieved upon simple heat treatment above about 2773 K. On a more reactive metallic surface (most notably, Fe, Co, or Ni), the deposition of carbon precursors typically results in carbon dissolution, intra- and/or suprametal diffusion, and precipitation in the form of nanotubes or filaments (fibers). The novel aspect of this process is the emergence of curvature of sp^2 bonds in the growing graphene layers; its origin remains a debatable and arguably unresolved issue. Whether it is analogous to the curvature induced by formation and entrapment of pentagons and/or heptagons, phenomena responsible for the formation of fullerenes upon condensation of gas(eous fragments), or to some other effect, including the role of the crystallography or morphology of the metal substrate, remains to be verified.

1.2.2 Liquid Phase

Figure 1.2 summarizes the variety of carbon products obtained in liquid-phase reactions using thermoplastic polymers, either the natural (such as bituminous coals) or synthetic ones [such as poly(vinyl chloride), $-\text{CH}_2\text{Cl}_2-n$]. At the most commonly utilized carbonization conditions, typically above 2273 K in a largely nonreactive medium, the degree of alignment and the mobility of emerging, growing, and coalescing carbon crystallites is considerable, but the consequent relative orientations of the resulting graphene layers are insufficient to achieve the perfect crystalline structure of graphite, and these materials are the nongraphitic but graphitizable cokes. However, their further exposure to higher temperature, typically in excess of 2773 K, results readily in the formation of (synthetic) graphite. If during the carbonization process the intermediate molten phase is

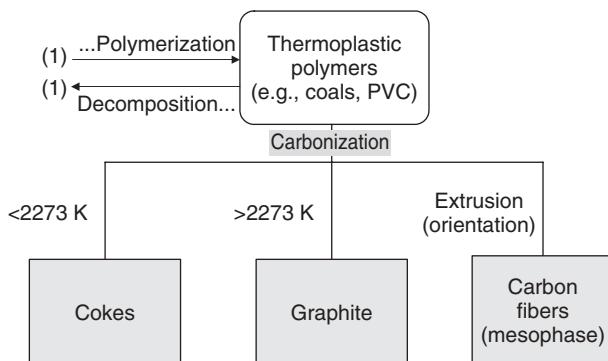


Figure 1.2 Summary of the processes of carbon formation in the liquid phase and the resulting carbon macrostructures.

subjected to extrusion and orientation, highly graphitizable carbon fibers (e.g., from mesophase pitch) can be obtained.

1.2.3 Solid Phase

Figure 1.3 summarizes the carbon formation processes taking place in the solid phase, with thermosetting carbon precursors such as low-rank coals, preoxidized bituminous coals, and wood, or thermosetting polymers such as poly(vinylidene chloride) (PVDC), $-\text{CHCl}_3-n$. (Note how very sensitive the carbonization process is to structural details of the carbon precursor: The absence of one hydrogen atom in the monomer precludes the formation of a molten phase during thermal decomposition of PVDC.) Because there is no plastic phase during the devolatilization process, there is extensive development of porosity in chars,

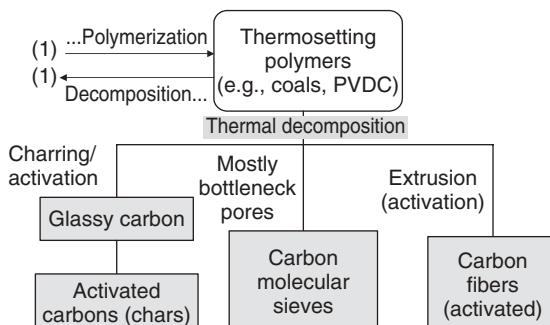


Figure 1.3 Summary of the processes of carbon formation in the solid phase and the resulting carbon macrostructures.

and this can be tailored further by selective gasification to produce activated carbons or molecular sieves, from either carbonized granules or powders or fibers. If the heat-treatment temperature is high, the product remains nongraphitic and nongraphitizable, but it acquires a shiny appearance and its pores become very narrow and essentially impervious to most gases and liquids: It is glassy or glasslike (vitreous) [6] and possesses a low surface area, although its low density (e.g., 1.5 g/cm³) reveals the presence of considerable closed porosity (even to helium at ambient temperature), which can be exposed and developed upon activation (selective gasification) at higher temperatures.

1.3 STRUCTURE AND PROPERTIES OF CARBONS

Both the bulk and the surface properties of carbon materials are dependent on their structure (i.e., on the spatial arrangement of carbon atoms). The structure is in turn dependent on the precursor used and the conditions of formation, as outlined in Section 1.2. Because of the prodigious variety of possible carbon atom arrangements within the seemingly restrictive constraint of sp² hybridization characteristic of graphitelike carbons, it is useful to distinguish between the various levels of structure, and these are discussed in the following sections. The increasingly popular and often abused term *nanostructure* should be the easiest to define unambiguously, at a scale below 10 nm, although of course it is the most difficult one to verify experimentally. Conversely, the boundary between *macrostructure* and *microstructure* is much easier to ascertain experimentally, but it is less straightforward to define it precisely. The latter term is well recognized, especially for polycrystalline materials, although perhaps surprisingly it does not have an International Union of Pure and Applied Chemistry (IUPAC) definition (see www.iupac.org/publications/compendium/index.html): for example, “the structure of a crystal on the scale on which deviations from perfect order become evident” [7] or “the structural features . . . (e.g., grain and phase structure) that are subject to observation under a microscope” [8,9]. In practice, this sets the macro/micro boundary in a broad range of about 1 to 100 μm .

In Table 1.1 we summarize the prodigious variety of bulk and surface properties of carbon materials, especially those of greatest relevance for catalytic behavior. Typical values or typical ranges are most often quoted rather than definite values, because these depend on too many factors to discuss here. Specific literature references are also not provided for this reason; not only handbooks [10,11] and the *Chemistry and Physics of Carbon* series [2] were consulted, but representative research or review papers as well as some commercial product brochures were examined.

1.3.1 Macrostructure

The macrostructure level of carbon atom arrangement confers the most readily recognizable features on carbon materials, and it should not allow room for

Table 1.1 Typical Property Values of Principal Carbon Materials^a

Property	Graphite	PC	CF	GLF	AC	CB	Cokes	Chars
True (He) density (g/cm ³)	2.268	>2.0	<2.2	<2.0	<2.0	<2.0	<2.0	<2.0
Particle (Hg) density (g/cm ³)	>2.0	>2.0	—	1.5	1.2–1.6	1.5–2.0	1.5–2.0	1.4–1.8
Packing (bulk) density (g/cm ³)	>1.0	—	1.4–2.2	0.75	0.6–0.8	0.2–0.5	0.7–1.0	0.7–0.9
Spacing between two adjacent basal planes (nm) ^b	0.3354	0.34–0.36	0.34–0.36	>0.344	>0.344	0.35–0.36	0.34–0.36	>0.344
Crystallite height (nm)	>100	>10	>5	<10	<5	1.0–2.5	2.0–100	<5
Crystallite width (nm)	>100	>5	5.0–50	<10	<5	1.0–3.0	2.0–50	<5
Specific heat (kJ/kg/K)	0.8	—	—	5	—	0.02	—	10
Thermal conductivity (W/m/K)	—	—	—	8–1100	—	—	—	—
Parallel to basal plane (<i>ab</i> -direction)	400	190–390	—	—	—	—	—	—
Perpendicular to basal plane (<i>c</i> -direction)	<80	1.0–3.0	—	—	—	—	—	—
Electrical resistivity ($\Omega \cdot \text{m} \times 10^6$)	—	—	—	10–10 ²	10 ³ –10 ⁶	ca. 10 ²	10–10 ³	10 ² –10 ³
Parallel to basal plane (<i>ab</i> -direction)	0.4	4.0–5.0	2.0–20	—	—	—	—	—
Perpendicular to basal plane (<i>c</i> -direction)	>40	1000–3000	—	—	—	—	—	—
BET surface area (m ² /g)	<10	<10	<10	<1	500–3000	20–2500	<500	<500

^aPC, pyrolytic carbon; CF, carbon fibers; GLF, glasslike fibers; AC, activated carbon (including fibers or cloth); CB, carbon blacks.

^bCarbons with spacing greater than 0.344 nm are turbostratic.

Note: If no values are provided, the variability is considered too wide for a meaningful summary.