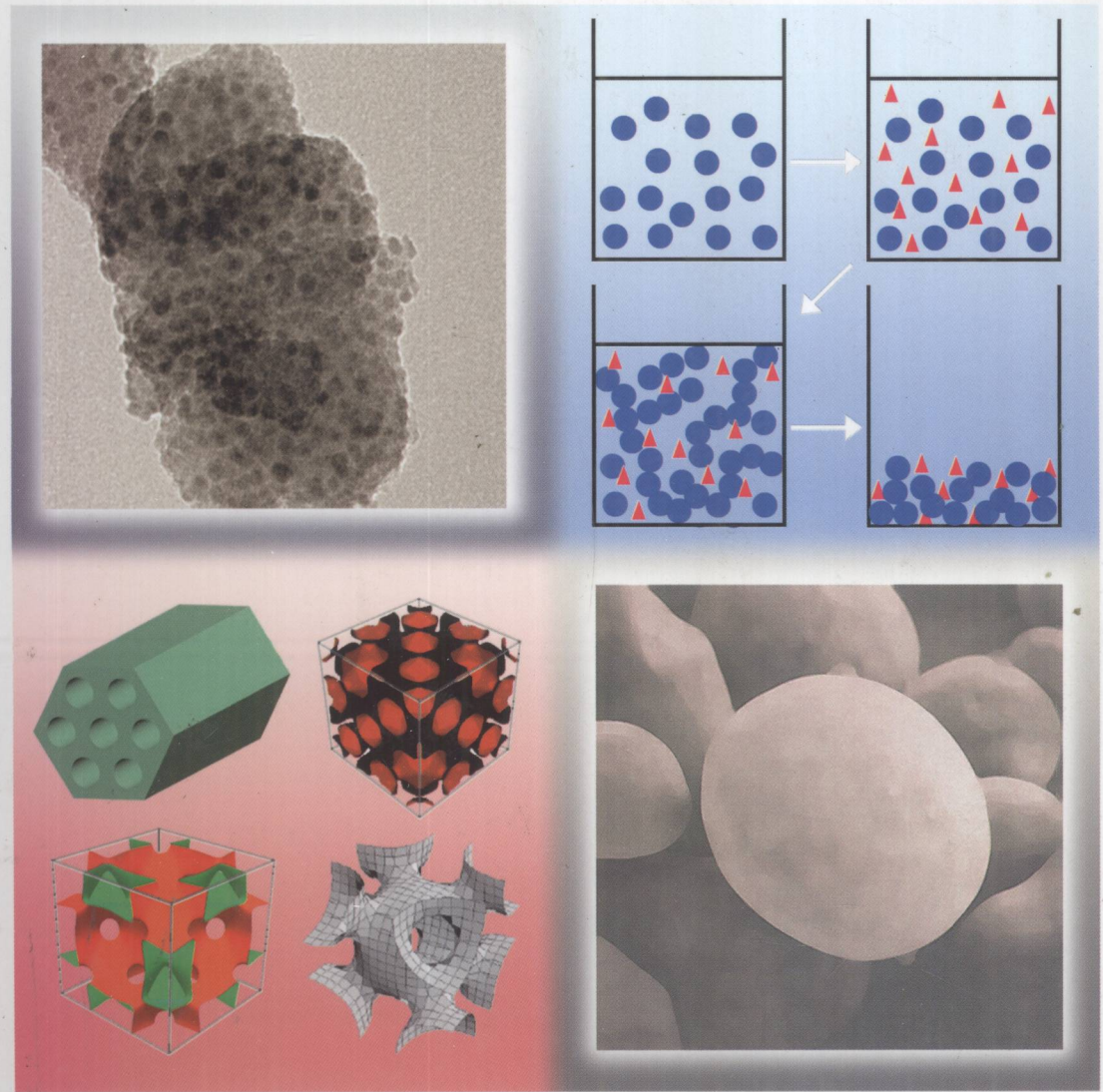
Edited by
Krijn P. de Jong

WILEY-VCH

Synthesis of Solid Catalysts



Synthesis of Solid Catalysts

Edited by
Krijn P. de Jong

WILEY-VCH Verlag GmbH & Co. KGaA

The Editor

Prof. Dr. Krijn P. de Jong
Inorganic Chemistry and Catalysis
Utrecht University
Sorbonnelaan 16
3548 CA Utrecht
The Netherlands

Library of Congress Card No.: applied for

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

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Cover Design Adam Design, Weinheim
Typesetting Laserwords, Chennai, India
Printing betz-druck GmbH, Darmstadt
Binding Litges & Dopf GmbH, Heppenheim

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN: 978-3-527-32040-0

Synthesis of Solid Catalysts

Edited by
Krijn P. de Jong

Related Titles

Jackson, S. D., Hargreaves, J. S. J. (ed.)

Metal Oxide Catalysis

2009
ISBN: 978-3-527-31815-5

Mizuno, N. (ed.)

Modern Heterogeneous Oxidation Catalysis

Designs, Reactions and Characterization

2009
ISBN: 978-3-527-31859-9

van Santen, R. A., Sautet, P. (eds.)

Computational Methods in Catalysis and Materials Science

An Introduction for Scientists and Engineers

2009
ISBN: 978-3-527-32032-5

Ozkan, U. (ed.)

Design of Heterogeneous Catalysts

New Approaches based on Synthesis, Characterization and Modeling

2009
ISBN: 978-3-527-32079-0

Ding, K., Uozumi, Y. (eds.)

Handbook of Asymmetric Heterogeneous Catalysis

2008
ISBN: 978-3-527-31913-8

Ertl, G., Knözinger, H., Schüth, F., Weitkamp, J. (eds.)

Handbook of Heterogeneous Catalysis

8 Volumes

2008
ISBN: 978-3-527-31241-2

Astruc, D. (ed.)

Nanoparticles and Catalysis

2008
ISBN: 978-3-527-31572-7

Chorkendorff, I., Niemantsverdriet, J. W.

Concepts of Modern Catalysis and Kinetics

2007
ISBN: 978-3-527-31672-4

Centi, G., van Santen, R. A. (eds.)

Catalysis for Renewables

From Feedstock to Energy Production

2007
ISBN: 978-3-527-31788-2

Sheldon, R. A., Arends, I., Hanefeld, U.

Green Chemistry and Catalysis

2007
ISBN: 978-3-527-30715-9

Preface

Solid catalysts are used in modern energy, chemical and environmental processes. Catalyst performance – activity, selectivity and stability – is largely determined by their preparation. In this respect, catalyst synthesis may be considered as one of the most influential 'unit operations' in industry. This book provides an introduction to basic concepts and research tools relevant to catalyst synthesis followed by a number of case studies. In this way it is an introduction to the field of catalyst synthesis for students and newcomers as well as a reference book for experienced scientists and practitioners. I hope that this book will stimulate the research field of catalyst synthesis and that it will support research and applications of solid catalysts by facilitating reliable and reproducible synthesis of materials.

For me it has been a privilege to work with so many colleagues in developing this book. I thank all of the lead authors as well as their co-authors for working with me on this project. It has been rewarding and I hope that we can continue to work together to foster and develop the field of catalyst synthesis.

I would like to thank Jos van Dillen and John Geus. They taught me as a graduate student at Utrecht University that catalyst synthesis is a research topic in its own right. For many years colleagues at the Shell Research Laboratories in Amsterdam provided a stimulating environment to synthesize and use solid catalysts. More recently at Utrecht University, staff, students and postdoctoral fellows have worked with me in the field of catalyst synthesis. Working with them has been a pleasure and is acknowledged.

Utrecht, December 2008

Krijn P. de Jong

Synthesis of Solid Catalysts. Edited by K.P. de Jong

ISBN: 978-3-527-32040-0

List of Contributors

Metin Bulut
KU Leuven
COK, Dept. M2S
23 Kasteelpark Arenberg
3001 Leuven (Heverlee)
Belgium

Xavier Carrier
Laboratoire de Réactivité
de Surface
(UMR 7197 CNRS)
UPMC (Université Pierre et
Marie Curie)
Tour 54-55
4 Place Jussieu
75252 Paris Cedex 05
France

Michel Che
Laboratoire de Réactivité
de Surface
(UMR 7197 CNRS)
UPMC (Université Pierre et
Marie Curie)
Tour 54-55
4 Place Jussieu
75252 Paris Cedex 05
France

Krijn P. de Jong
Utrecht University
Inorganic Chemistry
and Catalysis
Sorbonnelaan 16
3584 CA Utrecht
The Netherlands

Sonja Eijsbouts
Albemarle Catalysts Company BV
Research Centre Catalysts
1022 AB Amsterdam
The Netherlands

Sophie Hermans
Catholic University of Louvain
Departement de Chemie
Place Louis Pasteur, 1 bte. 3
1348 Louvain-la-Neuve
Belgium

Pierre A. Jacobs
KU Leuven
COK, Dept. M2S
23 Kasteelpark Arenberg
3001 Leuven (Heverlee)
Belgium

Synthesis of Solid Catalysts. Edited by K.P. de Jong

ISBN: 978-3-527-32040-0

Bettina Kraushaar-Czarnetzki
University of Karlsruhe
Institute of Chemical Process
Engineering CVT
Kaiserstr. 12
76128 Karlsruhe
Germany

Miron V. Landau
Ben-Gurion Univ. of the Negev
Dept. of Chem. Engineering
Ben-Gurion av. 1
Beer-Sheva 84105
Israel

Dr. David Linke
Leibniz-Institut für Katalyse
Albert-Einstein-Str. 29a
18059 Rostock
Germany

Martin Lok
Johnson Matthey Catalysts
Belasis Avenue, Billingham
Cleveland, TS23 1LB
UK

Catherine Louis
Laboratoire de Réactivité
de Surface
(UMR 7197 CNRS)
UPMC (Université Pierre et
Marie Curie)
Tour 54-55
Lab. de Reactions de Surfactants
4 Place Jussieu
75252 Paris Cedex 05
France

Alexis Lycourghiotis
University of Patras
Department of chemistry
26500 Patras
Greece

Eric Marceau
Laboratoire de Réactivité
de Surface
(UMR 7197 CNRS)
UPMC (Université Pierre et
Marie Curie)
Tour 54-55
4 Place Jussieu
75252 Paris Cedex 05
France

Martin Muhler
Ruhr-Universität Bochum
LS für Technische Chemie
Universitätsstr. 150
44780 Bochum
Germany

Steffen Peter Müller
University of Karlsruhe (TH)
Institute of Chemical Process
Engineering CVT
Kaiserstr. 12
76128 Karlsruhe
Germany

John R. Regalbuto
University of Illinois
Chemical Engineering
810 Souch Clinton Street
Chicago, IL 60607
USA

Uwe Rodemerck
Leibniz-Institut für Katalyse
Albert-Einstein-Str. 29a
18059 Rostock
Germany

Sabine Schimpf
Ruhr-Universität Bochum
LS für Technische Chemie
Universitätsstr. 150
44780 Bochum
Germany

Stuart Soled
ExxonMobil Research and
Engineering Company
Corporate Strategic Research
1545 Rt. 22 East
Annandale, NJ 08801
USA

Ying Wan
Shanghai Normal University
Department of Chemistry
Guilin Road 100
Shanghai 200234
P. R. China

Bert M. Weckhuysen
Utrecht University
Inorganic Chemistry and Catalysis
Sorbonnelaan 16
3584 CA Utrecht
The Netherlands

Dongyuan Zhao
Fudan University
Laboratory of Advanced Materials
Department of Chemistry
Handan Road 220
Shanghai 200233
P.R. China

Abbreviations

AHM	ammonium-hexa-molybdate
BM	base metal
ccp	cubic close packing
CNF	carbon nanofiber
CNT	carbon nanotube
CT	charge transfer
CVD	chemical vapor deposition
D4R	double four-ring
D6R	double six-ring
DFG	Deutsche Forschungsgemeinschaft
DI	dry impregnation
DoE	design of experiment
DP	deposition precipitation
DTG	differential thermal gravimetry
EDF	equilibrium deposition filtration
EDTA	ethylene diamine tetraacetic acid
EDX	energy-dispersive X-ray spectroscopy
EPR	electron paramagnetic resonance
EXAFS	extended X-ray absorption fine structure spectroscopy
FCC	fluid catalytic cracking
FTIR	Fourier transform infrared
hcp	hexagonal close packing
HDMe	hydrodemetallation
HDN	hydrodenitrogenation
HDO	hydrodeoxygenation
HDS	hydrodesulfurization
HPA	heteropolyacid
IA	ion adsorption
ICI	Imperial Chemical Industries
iep	isoelectric point
IE	ion exchange
IL	ionic liquid
IR	infrared

Synthesis of Solid Catalysts. Edited by K.P. de Jong

ISBN: 978-3-527-32040-0

IWI	incipient wetness impregnation
IZA	International Zeolite Association
MAS-NMR	magic-angle sample spinning nuclear magnetic resonance
MMA	methyl methacrylate
MOF	metal organic framework
MRI	magnetic resonance imaging
MTBE	methyl tert-butylether
(M)HC	(mild) hydrocracking
NMR	nuclear magnetic resonance
NM	noble metal
NTA	nitrilo triacetic acid
OHP	outer Helmholtz plane
Pc	phthalocyanine
PMO	periodic mesoporous organosilica
PTA	platinum tetraammine
PZC	point of zero charge
QMS	quadrupole mass spectroscopy
RDP	reduction deposition precipitation
RFC	reactive frontal chromatography
RPA	revised physical adsorption
RT	room temperature
SAPO	$SiAlPO_4$
SCR	selective catalytic reduction
SDA	structure-directing agent
SEA	strong electrostatic adsorption
SRGO	straight run gas oil
STY	space time yield
3D	three-dimensional
TEA	triethanolamine
TEDDI	tomographic energy-dispersive diffraction imaging
TEM	transmission electron microscope
TEOS	tetraethylorthosilicate
TMA	tetramethylammonium
TMB	trimethyl benzene
TPA	tetrapropylammonium
TPD	temperature-programmed desorption
TPR	temperature-programmed reduction
2D	two-dimensional
USY	ultrastable Y
UV-VIS	ultraviolet-visible spectroscopy
VOC	volatile organic compound
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

Contents

Synthesis of Solid Catalysts. Edited by K.P. de Jong

ISBN: 978-3-527-32040-0