

Nanoparticle Technology Handbook

edited by
Masuo Hosokawa
Kiyoshi Nogi
Makio Naito
Toyokazu Yokoyama

TB383-62
N186

NANOPARTICLE TECHNOLOGY HANDBOOK

Edited by

Masuo Hosokawa

Hosokawa Micron Corporation
Shoudai Tajika, Hirakata
Osaka, Japan

Kiyoshi Nogi

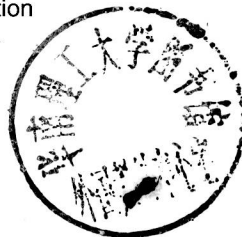
Osaka University, Joining and
Welding Research Institute
Ibraki, Osaka, Japan

Makio Naito

Osaka University, Joining and
Welding Research Institute
Ibraki, Osaka, Japan

Toyokazu Yokoyama

Hosokawa Micron Corporation
Shoudai Tajika, Hirakata
Osaka, Japan



E2008000911



ELSEVIER

Amsterdam • Boston • Heidelberg • London • New York • Oxford • Paris
San Diego • San Francisco • Singapore • Sydney • Tokyo

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

First edition 2007
Reprinted 2008

Copyright © 2007, Elsevier BV. All rights reserved

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 or otherwise without the prior written permission of the publisher

Permissions may be sought directly from Elsevier's Science & Technology Rights
Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333;
email: permissions@elsevier.com. Alternatively you can submit your request online by
visiting the Elsevier web site at <http://elsevier.com/locate/permissions>, and selecting
Obtaining permission to use Elsevier material

Notice

No responsibility is assumed by the publisher for any injury and/or damage to persons
or property as a matter of products liability, negligence or otherwise, or from any use
or operation of any methods, products, instructions or ideas contained in the material
herein. Because of rapid advances in the medical sciences, in particular, independent
verification of diagnoses and drug dosages should be made

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 is available from the Library of Congress

ISBN: 978-0-444-53122-3

For information on all Elsevier publications
visit our website at www.elsevierdirect.com

Printed and bound in *Hungary*

08 09 10 10 9 8 7 6 5 4 3 2

Working together to grow
libraries in developing countries

www.elsevier.com | www.bookaid.org | www.sabre.org

ELSEVIER BOOK AID International Sabre Foundation

NANOPARTICLE TECHNOLOGY HANDBOOK

Preface

During the last few years the term “Nanotechnology” is increasingly employed to describe the process technologies and analytical techniques for material in the ultrafine range of the order of a millionth of a millimeter. Because they are sure to take an important part in shaping the 21st century, great attention is being paid to these technologies, with many countries actively involved in R&D. As the link between these new technologies and the established particle and powder technology, “Nanoparticle technology” includes the concepts and know-how to create, process and apply the ultrafine particles in the nanometer range, and is one of the key technologies for new material developments.

The technologies that are used to treat powders arrived with mankind, and countless inventions and improvements have been made during history. These particles and powders have very different properties from the bulk materials from which they are derived. There are applications to be seen in all industrial areas.

The history of the academic study of particle and powder technology is not so old. The first related society, Chubu Association of Powder Technology, was founded in Japan in 1956. It later became the Society of Powder Technology, Japan, and celebrated its 50th anniversary in 2006. Correspondingly, the Hosokawa Micromeritics Laboratory was established in 1956 and published its 50th anniversary issue of the annual technical journal *Funsai (The Micromeritics)* also in 2006.

Throughout this period a key issue has been to reduce the size of particles to maximise their functional properties and thus find new applications and create new products with superior performance. Great interest has been shown in submicron and even finer particles. Research and development has advanced at a rapid rate due to the cooperation of academia and industry in many areas, starting with particle creation and particle size analysis, and expanding to encompass particle design and processing in the micron- and nanometer-size ranges. Japan has been at the forefront in the conception and development of these technologies.

Due to this interest, the second World Congress in Particle Technology (WCPT) was held in Kyoto in 1990. Eight years later at the 3rd WCPT in Brighton, the author highlighted the importance of these ultrafine particles to an audience of about 700 researchers and engineers during the opening speech. Hosokawa Micron Corp., which celebrated its 90th anniversary in 2006, has been engaged in R&D on particle creation by the build-up (*bottom up*) method in both gaseous and liquid phases for more than 20 years. The result of this research, as combined with that on conventional grinding (*top-down*) processes, has led to the establishment of a mass production system for nanoparticles and to the foundation of a business based on application of these nanoparticles to functional materials.

Founded 15 years ago, the Hosokawa Powder Technology Foundation holds an annual symposium on powder technology for the exchange of information on particle engineering and powder technology. Since 2001, the main topics of the symposium have, in response to the requirements of industry, been related to nanoparticles and nanostructure control. The number of grant proposals received by our Foundation for research into nanoparticles continues to increase, and currently 40% of some 120 proposals relate to nanoparticles.

As a result of this trend, we published 3 years ago, the book *Nanoparticle Technology* to promote nanoparticle-related engineering by documenting the technologies constituting in this field. That book was very well received, and to continue contributing to the common welfare through the promotion of powder technology, we decided to systematically update *Nanoparticle Technology*, adding further developments and many examples of applications. The results of that effort were published in the form of a handbook, first in Japanese in the memorable year 2006, and with the present volume, in English this year. Although R&D in nanoparticle technology advances rapidly, and the contents of the future editions are sure to change, we hope the present

collation of state-of-the-art knowledge and information will be of assistance to the researchers, engineers and others interested in this vitally important field.

In closing, I express my sincere sense of gratitude to the authors, the editing committee and the publishing staff for their great efforts in spite of their busy schedules.

Masuo Hosokawa
President, Hosokawa Micron Corporation
Chairman, Hosokawa Powder Technology Research Institute
President, Hosokawa Powder Technology Foundation

List of Contributors

Hiroya Abe, Dr.

Joining & Welding Research Institute, Osaka University

Tadafumi Adschiri, Dr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Takashi Akatsu, Dr.

Materials and Structures Laboratory,
Tokyo Institute of Technology

Jun Akedo, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Masanori Ando, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Yoshinori Ando, Dr.

Department of Materials Science and Engineering,
Meijo University

Masanobu Awano, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Akira Azushima, Dr.

Graduate School of Engineering, Yokohama National University

Tetsuya Baba, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Kensei Ehara, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Hitoshi Emi, Dr.

Association of Powder Process Industry and Engineering (APPIE)

Hiroshi Fudouzi, Dr.

Optronic Materials Center,
National Institute for Materials Science

Hiroshi Fukui, Dr.

Frontier Science Business Division, Shiseido Co., Ltd.

Takehisa Fukui, Dr.

Hosokawa Powder Technology Research Institute

Yoshinobu Fukumori, Dr.

Faculty of Pharmaceutical Sciences,
Kobe Gakuin University

Masayoshi Fuji, Dr.

Ceramics Research Laboratory, Nagoya Institute of Technology

Hidetoshi Fujii, Dr.

Joining & Welding Research Institute, Osaka University

Hideki Goda Mr.

R&D Department, Photo-electronic Materials Division,
Arakawa Chemical Industries, Ltd.

Kuniaki Gotoh, Dr.

The Graduate School of Natural Science and Technology,
Okayama University

Yukiya Hakuta, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Kaori Hara Ms.

Hosokawa Powder Technology Research Institute

Kazuyuki Hayashi, Dr.

R&D Division, Toda Kogyo Corp.

Ko Higashitani, Dr.

Department of Chemical Engineering,
Kyoto University

Kazuyuki Hirao, Dr.

Department of Material Chemistry, Kyoto University

Masuo Hosokawa Mr.

Hosokawa Micron Corp.

Yuji Hotta, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Hideki Ichikawa, Dr.

Faculty of Pharmaceutical Sciences
Kobe Gakuin University

Takashi Ida, Dr.

Ceramics Research Laboratory, Nagoya Institute of Technology

Manabu Ihara, Dr.

Research Center for Carbon Recycling Energy, Tokyo Institute of Technology

Shinji Inagaki, Dr.

Toyota Central R&D Labs., Inc.

Mitsuteru Inoue, Dr.

Toyohashi University of Technology

Eiji Iritani, Dr.

Department of Chemical Engineering,
Nagoya University

Naoyuki Ishida, Dr.

National Institute of Advanced Industrial Science and
Technology (AIST)

Mikimasa Iwata, Dr.

Central Research Institute of Electric Power Industry

Kotaro Kajikawa, Dr.

Tokyo Institute of Technology

Toshio Kakui, Dr.

Chemicals Division, Lion Corp.

Hidehiro Kamiya, Dr.

Institute of Symbiotic Science and Technology,
Tokyo University of Agriculture & Technology

Kenji Kaneko, Dr.

Department of Material Science and Engineering,
Kyushu University

Kiyoshi Kanie, Dr.

Institute of Multidisciplinary Research for Advanced
Materials, Tohoku University

Hitoshi Kasai, Dr.

Institute of Multidisciplinary Research for Advanced
Materials, Tohoku University

Tomoko Kasuga, Dr.

Electrotechnology Applications R&D Center,
Chubu Electric Power Co. Inc.

Tsutomu Katamoto Mr.

Creative R&D Center, Toda Kogyo Corp.

Shinji Katsura, Dr.

Faculty of Engineering,
Gunma University

Masayoshi Kawahara Mr.

Hosokawa Powder Technology Research Institute

Yoshiaki Kinemuchi, Dr.

National Institute of Advanced Industrial Science
and Technology (AIST)

Soshu Kirihaara, Dr.

Joining & Welding Research Institute,
Osaka University

Akihiko Kondoh, Dr.

Department of Chemical Science and Engineering,
Kobe University

Katsuyoshi Kondou, Dr.

Joining & Welding Research Institute,
Osaka University

Yasuo Kousaka, Dr.

Hosokawa Powder Technology Research Institute

Kazue Kurihara, Dr.

Institute of Multidisciplinary Research for Advanced
Materials, Tohoku University

Shun'ichi Kuroda, Dr.

The Institute of Scientific and Industrial Research,
Osaka University

Ken-ichi Kurumada, Dr.

Graduate School of Environment & Information Sciences,
Yokohama National University

Chunliang Li, Dr.

National Institute of Advanced Industrial Science
and Technology (AIST)

Hisao Makino, Dr.

Energy Engineering Research Laboratory,
Central Research Institute of Electric Power Industry

Hiroaki Masuda, Dr.

Department of Chemical Engineering, Kyoto University

Yoshitake Masuda, Dr.

National Institute of Advanced Industrial Science and
Technology (AIST)

Motohide Matsuda, Dr.

Graduate School of Environmental Science,
Okayama University

Tatsushi Matsuyama, Dr.

Faculty of Engineering, Soka University

Shuji Matsusaka, Dr.

Department of Chemical Engineering,
Kyoto University

Reiji Mezaki, Dr.

Nanomateria Center, Institute of Innovation,
The University of Tokyo

Takeshi Mikayama, Dr.

Kohn Patent Office

Kiyotomi Miyajima Mr.

Central Research Institute of Electric Power Industry

Minoru Miyahara, Dr.

Department of Chemical Engineering,
Kyoto University

Yoshinari Miyamoto, Dr.

Joining & Welding Research Institute,
Osaka University

Masaru Miyayama, Dr.

Research Center for Advanced Science and Technology,
The University of Tokyo

Hideki T. Miyazaki, Dr.

National Institute for Materials Science

Hidetoshi Mori, Dr.

School of Engineering, Aichi University of Technology

Tsutomu Morimoto, Dr.

Japan Chemical Innovation Institute

Atsushi Muramatsu, Dr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Norio Murase, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Toshihiko Myojo, Dr.

Institute of Industrial Ecological Sciences
University of Occupational and Environmental Health

Makio Naito, Dr.

Joining & Welding Research Institute,
Osaka University

Noriyuki Nakajima Mr.

Institute of Nanotechnology, Kurimoto, Ltd.

Hachiro Nakanishi Mr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Masami Nakamoto, Dr.

Osaka Municipal Technical Research Institute

Norikazu Namiki, Dr.

Kyoritsu Gokin Co., Ltd.

Kiyoshi Nogi, Dr.

Joining & Welding Research Institute, Osaka University

Yuji Noguchi, Dr.

The University of Tokyo

Toshiyuki Nomura, Dr.

Department of Chemical Engineering,
Osaka Prefecture University

Satoshi Ohara, Dr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Akira Ohtomo, Dr.

Institute for Materials Research, Tohoku University

Hidetoshi Oikawa, Dr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Tomoichiro Okamoto, Dr.

Nagaoka University of Technology

Tatsuya Okubo, Dr.

The University of Tokyo

Kikuo Okuyama, Dr.

Graduate School of Engineering, Hiroshima University

Yoshio Otani, Dr.

Graduate School of Natural Science and Technology,
Kanazawa University

Yasufumi Otsubo, Dr.

Graduate School of Engineering, Chiba University

Fumio Saito, Dr.

Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University

Shuji Sakaguchi, Dr.

National Institute of Advanced Industrial Science and Technology (AIST)

Yoshio Sakka, Dr.

Nano Ceramics Center, National Institute for Materials Science

Takafumi Sasaki, Dr.

Institute of Multidisciplinary Research for Advanced Materials, Tohoku University

Norifusa Satoh, Dr.

Department of Chemistry, Keio University

Haruhide Shikano Mr.

Ibiden Co., Ltd.

Manabu Shimada, Dr.

Graduate School of Engineering,
Hiroshima University

Tetsuya Senda, Dr.

National Maritime Research Institute

Yuichi Setsuhara, Dr.

Joining and Welding Research Institute,
Osaka University

Akihiko Suda, Dr.

Toyota Central R&D Labs., Inc.

Hisao Suzuki, Dr.

Graduate School of Science and Technology,
Shizuoka University

Michitaka Suzuki, Dr.

Department of Mechanical and System Engineering,
University of Hyogo

Takahiro Takada, Dr.

Murata Manufacturing Co., Ltd.

Seiichi Takami, Dr.

Advanced Electronic Materials Center,
National Institute for Materials Science

Hirofumi Takase, Dr.

R&D Division, Takiron Co., Ltd.

Hirofumi Takeuchi, Dr.

Laboratory of Pharmaceutical Engineering,
Gifu Pharmaceutical University

Junichi Tatami, Dr.

Graduate School of Environment & Information Sciences,
Yokohama National University

Kenji Toda, Dr.

Graduate School of Science and Technology,
Niigata University

Hiroyuki Tsujimoto, Dr.

Hosokawa Powder Technology Research Institute

Tetsuo Uchikoshi, Dr.

Nano Ceramics Center,
National Institute for Materials Science

Keizo Uematsu, Dr.

Nagaoka University of Technology

Mitsuo Umetsu, Dr.

Graduate School of Engineering,
Tohoku University

Arimitsu Usuki, Dr.

Toyota Central R&D Labs., Inc.

Fumihiko Wakai, Dr.

Materials & Structures Laboratory,
Tokyo Institute of Technology

Akimasa Yamaguchi, Mr.

Energy Engineering Research Laboratory,
Central Research Institute of Electric Power Industry

Yukio Yamaguchi, Dr.

Department of Chemical System Engineering,
The University of Tokyo

Atsushi Yamamoto, Mr.

National Institute of Advanced Industrial Science and
Technology (AIST)

Hiromitsu Yamamoto, Dr.

University School of Pharmacy,
Aichi Gakuin University

Kenji Yamamoto, Dr.

International Clinical Research Center,
International Medical Center of Japan

Kimihisa Yamamoto, Dr.

Department of Chemistry, Keio University

Masatomo Yashima, Dr.

Department of Materials Science and Engineering,
Tokyo Institute of Technology

Toyokazu Yokoyama, Dr.

Hosokawa Micron Corp.

Susumu Yonezawa, Dr.

Faculty of Engineering, University of Fukui

From the Editors

As the size of a solid particle decreases in the order of one millionth of a millimeter, the number of atoms constructing the particle becomes small and in the order of several hundreds or thousands. At this state, the fundamental physical property such as the melting point can change drastically and ceramic materials may be sintered at a lower temperature. Also, as particles get smaller than the wavelength of visible light, they not only become transparent but also emit special light by plasma absorption. They show completely different electromagnetic or physicochemical properties from their bulk counterparts, although they are made of the same materials.

The authors published a book *Nanoparticle Technology* in Japanese in November 2003, which focused on the technology of handling nanoparticles that have unique properties and enormous potential usefulness. This book has drawn great attention from the readers and a growing demand to publish a handbook has developed, which systematically collects the basic information on nanoparticle technology with recent industrial applications.

Nanoparticle Technology to prepare, process, and apply nanoparticles plays a very important role in the development of nanotechnology. It also pays attention to various applications like life sciences, energy, environment, information technology, new materials, etc. However, there has been no handbook or manual on this technology so far. This is the first handbook written in English for handling nanoparticles and surveying their related processing technologies. It has been long awaited by researchers and engineers interested in nanoparticles or their use in the R&D of advanced materials.

This handbook systematically summarizes the fundamentals and state-of-the-art information in various industrial applications related to nanoparticles. However, since the advancement in the fields of concern is so rapid, not only the application developments but also the new physical properties and measuring methods from fundamental research become available as time goes by. Therefore, we plan to revise the contents of the handbook according to new technology developments in the future.

This handbook consists of fundamental and application sections including processing, evaluation, and application in a way different from other similar conventional handbooks. In the fundamental section, the basic properties, structural control of nanoparticles, nanostructural control, and property characterization with the measuring methods in the dispersed particle system are elucidated in detail mainly from the aspects of material processing and property evaluation. At the end of Fundamental Section, a chapter discussing the environmental and safety impact of nanoparticles is also included.

In the Application Section, various nanoparticle applications in the fields of life sciences, environment, energy, information technology, new materials, and production methods are listed according to their future market potential with focus on the new functionalities of nanoparticles.

To publish this handbook, we invited manuscripts from leading researchers and engineers specialized in a broad range of applications of concern as shown in the list of contributors. We would like to thank all the authors who contributed manuscripts despite their busy schedules and our colleagues in Hosokawa overseas operations as well as the staffs of the publisher for their generous supports. We are also deeply indebted to Dr. Y. Tsuji, Managing Director of Hosokawa Powder Technology Foundation and Dr. C. C. Huang of Hosokawa Micron Powder Systems, who gave us many useful comments on the English manuscripts, and to Ms. S. Nakai for her assistance in the preparation of the manuscript and proof.

Dr. Kiyoshi Nogi
Professor and Director, Joining and Welding Research Institute, Osaka University
Director, Hosokawa Micron Corporation
Director, Hosokawa Powder Technology Research Institute

Table of Contents

<i>Preface</i>	v
<i>List of Contributors</i>	vii
<i>From the Editors</i>	xxi

FUNDAMENTALS

Chapter 1 Basic properties and measuring methods of nanoparticles

1.1 Size effect and properties of nanoparticles	5	1.5 Melting point, surface tension, wettability	18
1.1.1 Definition of nanoparticles	5	1.5.1 Melting point	18
1.1.2 Features of nanoparticles	5	1.5.2 Surface tension	18
1.1.3 Evaluation of size of nanoparticles	5	1.5.3 Wettability	19
1.1.4 Properties of nanoparticle and size effect	6	1.6 Specific surface area and pore	20
1.1.5 Existing conditions of particles and their properties	10	1.7 Composite structure	23
1.2 Particle size	10	1.7.1 Composite structure of nanoparticle	23
1.2.1 Definition of particle size	10	1.7.2 Evaluation method of composite structure using electron microscopy	24
1.2.2 Measuring methods	11	1.7.3 Microstructure evaluation of several types of nano composite particles	25
1.2.3 Key points in the measurements – Reference particles for calibration	11	1.8 Crystal structure	28
1.3 Particle shape	12	1.8.1 Particle size dependence of crystalline phases of zirconia	28
1.3.1 Two-dimensional particle projection image	12	1.8.2 Size effect and crystalline phases of ferroelectric materials	30
1.3.2 Three-dimensional particle image	12	1.9 Surface characteristics	32
1.3.3 Particle shape index using particle diameter ratio	12	1.10 Mechanical property	36
1.3.4 Particle shape expression by fractal dimension	13	1.11 Electrical properties	38
1.3.5 Particle shape analysis by Fourier analysis	14	1.11.1 Introduction	38
1.3.6 Particle shape analysis of nanoparticle	14	1.11.2 Novel characterization method for the dielectric property	39
1.4 Particle density	14	1.11.3 LST relation	39
1.4.1 Density measurement of powders composed of nanoparticles	14	1.11.4 Measurement of the dielectric constant of nanoparticles	40
1.4.2 Density measurement of individual particles	15	1.12 Magnetic properties	42
		1.12.1 Classification of magnetism	42
		1.12.2 Magnetism of metal materials	43

1.12.3	Magnetism of oxide material	43	1.13 Optical property of nanoparticle	45
1.12.4	Magnetic characteristics of nanosized materials	44	1.13.1	Band structure of nanoparticles 45
			1.13.2	Measurement method of optical properties of nanoparticles 47

Chapter 2 Structural control of nanoparticles

2.1 Structure construction and function adaptation of nanoparticles	51	2.4 Composite structure	79
2.1.1	Structures of nanoparticles 51	2.4.1	Gas-phase method 79
2.1.2	Hollow particles 52	2.4.2	Solution method 84
2.1.3	Core-shell particles 52	2.4.3	Supercritical approach 87
2.1.4	Simple inorganic nanoparticles 54	2.4.4	Mechanical processes 91
2.1.5	Simple organic nanoparticles 54	2.5 Pore structure	94
2.1.6	Summary 55	2.5.1	Gas-phase method 94
2.2 Particle size	56	2.5.2	Liquid-phase synthesis 100
2.2.1	Gas-phase method 56	2.6 Nanoparticle design for DDS	105
2.2.2	Liquid-phase method 58	2.6.1	Drug delivery with nanoparticle 105
2.2.3	Supercritical hydrothermal method 61	2.6.2	Design of nano drug carrier 106
2.2.4	Solid-phase method 65	2.6.3	Design of nanoparticle surface and application for DDS 108
2.2.5	Grinding method 69	2.6.4	Pharmaceutical nanotechnology 109
2.3 Particle shape	71	2.7 Nanotubes (CNT)	109
2.3.1	Gas-phase process 71	2.7.1	Production of MWNT by arc discharge method 110
2.3.2	Liquid-phase method 76	2.7.2	Production of SWNT by arc discharge method 110

Chapter 3 Characteristics and behavior of nanoparticles and its dispersion systems

3.1 Introduction of nanoparticle dispersion and aggregation behavior	115	3.2 Single nanoparticle motion in fluid	119
3.1.1	Surface interaction between nanoparticles 115	3.2.1	Single particle motion 119
3.1.2	Difficulty in nanoparticle dispersion control based on DLVO theory 115	3.2.2	Phoretic phenomena 121
3.1.3	Difficulty in nanoparticle dispersion, discussion based on the effect of particle diameter and solid fraction on distance between particle surface 116	3.3 Brownian diffusion	126
3.1.4	Surface molecular-level structure of nanoparticles [3] 117	3.4 Adsorption properties and wettability of nanoparticle surface	127
3.1.5	Basic approach to control nanoparticle dispersion behavior 118	3.5 Interactions between particles	129
		3.5.1	Interactions between particles in gases and control of adhesion 129
		3.5.2	Control of interactions between particles in liquids 139
		3.5.3	Characterization techniques for interactions between particles 146

3.6 Aggregation and dispersion, characterization and control —————	157	3.7.2 Rheological property of nanoparticle dispersed suspension	168
3.6.1 Aggregation and dispersion in gas phase	157	3.8 Simulation of colloidal dispersion system —————	169
3.6.2 Liquid phase	159	3.8.1 Space-time mapping of simulation methods	170
3.6.3 Dispersion in organic solvent and polymer resin	163	3.8.2 Simulation methods in nano/mesoscale	172
3.7 Rheology of slurry —————	165	3.8.3 Recent simulation methods including hydrodynamic interaction	174
3.7.1 Fundamentals of suspension rheology	165	3.8.4 Closing remark	175

Chapter 4 Control of nanostructure of materials

4.1 Assembly of nanoparticles and functionalization —————	179	4.4.5 ECAP	216
4.2 Nanoparticles arranged structures —————	179	4.4.6 Nanostructure control of alloy	220
4.2.1 Photonic fractal	179	4.5 Structure control of nanoparticle collectives by sintering and bonding —————	222
4.2.2 Nanoparticle patterning by nanobiotechnology: Peptide	182	4.5.1 Sintering of nanoparticles	222
4.2.3 Preparation of ceramic films by liquid-phase processing: Electrophoresis	187	4.5.2 Low temperature cofired ceramics (LTCC)	226
4.3 Nanopore structure —————	190	4.5.3 Nanostructure control of a joined interface	230
4.3.1 Microporous material: Zeolite	190	4.5.4 Joining by FSW	233
4.3.2 Preparation of nanoporous material by dry processing	194	4.5.5 Aerosol deposition method for nanostructuring of crystal layer and its applications	236
4.3.3 Ordered porous structures	196	4.5.6 Suppression of particle growth in sintering nanoparticles	242
4.3.4 Nanoporous materials (Titania nanotubes)	199	4.5.7 Fabrication of nanoceramics by colloidal processing	246
4.4 Nanocomposite structure —————	203	4.6 Self-assembly —————	250
4.4.1 Catalyst microstructure	203	4.6.1 Self-organization of nanoparticles	250
4.4.2 Percolation structure	206	4.6.2 Assembling and patterning of particles	256
4.4.3 Structure of filler orientation in matrix	210	4.6.3 Fabrication of organic/inorganic mesoporous materials	262
4.4.4 In situ particle polymerization	213		

Chapter 5 Characterization methods for nanostructure of materials

5.1 Nanostructure and function (characterization of local nanostructure) —————	269	5.2 Crystal structure —————	270
		5.2.1 X-ray diffraction method	270
		5.2.2 Small-angle X-ray scattering	272

5.2.3	Neutron diffraction	274	5.4.3	Capillary condensation phenomenon and PSD analysis	299
5.2.4	Raman scattering	277	5.4.4	Other methods of interest	302
5.3	Surface structure	279	5.5	Grain boundaries and interfaces	303
5.3.1	AFM	279	5.5.1	The role of TEM	303
5.3.2	STM	284	5.5.2	Analytical TEM (AEM)	306
5.3.3	FT-IR	287	5.5.3	Three-dimensional electron tomography (3D-ET)	310
5.3.4	XPS	290	5.6	Evaluation methods for oxide heterostructures	312
5.3.5	Wettability	294			
5.4	Nanopore characterization	297			
5.4.1	Type of nitrogen isotherms and pore characteristics implied	298			
5.4.2	Micropore filling phenomenon and PSD analysis	298			

Chapter 6 Evaluation methods for properties of nanostructured body

6.1	Functionality of nanostructures and their characteristic evaluation	319	6.3.4	Nanosecond thermorefectance method	341
6.1.1	What are nanostructures?	319	6.3.5	Thin film thermophysical property reference material and traceability	341
6.1.2	Examples showing how the functions of nanostructures are performed	320	6.3.6	Summary	342
6.1.3	Functionality and characteristic evaluation	322	6.4	Electric properties	344
6.2	Mechanical properties	324	6.4.1	Dielectric properties	344
6.2.1	Strength, fracture toughness and fatigue behavior	324	6.4.2	Electrical conduction properties	349
6.2.2	Elastic constants: hardness	326	6.4.3	Thermoelectric properties	354
6.2.3	Creep/superplasticity	329	6.5	Electrochemical properties	358
6.2.4	Tribological properties	332	6.5.1	Electrode reaction	358
6.2.5	Nanoindentation	335	6.5.2	Characteristics of sensors	362
6.3	Thermophysical properties	336	6.5.3	Electrochemical reactivity	366
6.3.1	Thermophysical properties related to transfer and storage of heat	336	6.6	Magnetic properties	370
6.3.2	Front-face heating/front-face detection picosecond thermorefectance method	338	6.6.1	Super paramagnetism	370
6.3.3	Picosecond thermorefectance method by rear face heating/front-face detection	339	6.6.2	Material-specific discussion	370
			6.7	Optical properties	372
			6.7.1	Transparency of nanoparticle	372
			6.7.2	Photonic crystal	375
			6.8	Catalytic property	377
			6.9	Properties of gas permeation and separation membranes	380

Chapter 7 Environmental and safety issues with nanoparticles

7.1 Introduction ————— 387 7.2 Nanoparticles and environment ————— 387 7.2.1 Nanoparticles in atmospheric environment 387 7.2.2 Ground water environments and nanoparticles 389 7.2.3 Nanoparticles in exhaust gases 390 7.2.4 Nanoparticles in wastewater 392 7.2.5 Indoor environments and nanoparticles 393 7.2.6 Industrial processes and nanoparticles 396	7.3 Safety of nanoparticles ————— 400 7.3.1 Problems caused by nanoparticles 400 7.3.2 Health effects on nanoparticles 401 7.3.3 Safety assessment for the nanoparticles 406 7.4 Removal of nanoparticles ————— 410 7.4.1 Principle of particle removal 410 7.4.2 Removal of nanoparticles suspended in gas 410 7.4.3 Removal of nanoparticles in liquid 413
--	---

APPLICATIONS

1 Dispersion of fine silica particles using alkoxysilane and industrialization ————— 423 1. Sol-gel hybrid 423 2. Molecular design 423 3. Unmelttable plastics: epoxy resin hybrid 425 4. Tough resin: hybrid of the phenol resin system 426 5. Soft silica hybrid: hybrid of the urethane system 426	6. Cheap engineering plastics in place for imide: hybrid of the amideimide system 426 7. Imide useful for electroless plating: hybrid of the imide system 427
2 Generation of metal nanoparticles using reactive plasma arc evaporation ————— 428 1. Summary of the reactive plasma arc evaporation method 428 2. Nanoparticles by the reactive plasma arc evaporation method 429	3. The nanoparticles generation rate, characteristics, and shape 429 4. Application of the nanoparticle 430
3 Sensing based on localized surface plasmon resonance in metallic nanoparticles ————— 432 1. Localized surface plasmon 432	2. Two sensing method using plasmon 432
4 Microelectronics packaging by metal nanoparticle pastes ————— 434 1. Conductive paste technique and metal nanoparticle paste 434 2. Low temperature firing and fine electronic circuit pattern formation by screen printing 435	3. Direct formation of the electronic circuit pattern by inkjet printing 437 4. Application as the joining materials 438

5	A dye-sensitized solar cell utilizing metal nanoparticle	438
1.	What is a dye-sensitized solar cell? 438	evaporation on the quartz substrate 439
2.	Enhancement of the absorption coefficient of the ruthenium dye, with the silver nanoparticle produced via vacuum	3. Enhancement of the absorption coefficient of silver nanoparticle-ruthenium dye within porous TiO ₂ 440
6	Design of nanoparticles for oral delivery of peptide drugs	442
1.	Particulate design and functions 443	2. Case studies 445
7	Formation of thick electronic ceramic films with bonding technique of crystalline fine particles and their applications	450
1.	Aerosol deposition method (ADM) 450	3. Applications of AD ceramic films 451
2.	Formation of thick electronic ceramic films with ADM 450	
8	Development and multi-functionalization of high-functional separation membranes	453
1.	Gas separation 453	2. Liquid separation 456
9	Development of polymer-clay nanocomposites by dispersion of particles into polymer materials	458
1.	Nylon 6-clay hybrid 458	3. Synthesis and properties of EPDM-clay hybrid 459
2.	Synthesis and properties of polypropylene-clay hybrid 459	4. Morphology control by polymers with clay 459
10	Development of novel ferroelectric materials	460
1.	Crystal structure of bismuth layer-structured ferroelectrics (BLSFs) 460	3. Layered structure, dielectric and leakage current properties of BiT-BBTi crystals 462
2.	Crystal growth and experimental procedure 461	4. Giant polarization in BiT-BBTi crystals 462
11	Development of new phosphors	464
1.	History of development of nanophosphor 464	3. Development trend of new nanophosphor 465
2.	Properties of rare earth nanophosphor 465	
12	Zeolite membrane	467
1.	Characteristics 467	3. Separation properties of zeolite membranes 469
2.	Synthesis 467	