

Microstructure and Properties of High-Temperature Superconductors

Ivan A. Parinov

Microstructure and Properties of High-Temperature Superconductors

With 309 Figures and 44 Tables

 Springer

Ivan A. Parinov

South Federal University
Vorovich Mechanics & Applied
Mathematics Research Institute
Stachki Avenue 200/1
Rostov-on-Don Russia 344090
ppr@math.rsu.ru

Library of Congress Control Number: 2007923179

ISBN 978-3-540-70976-3 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media
springer.com

© Springer-Verlag Berlin Heidelberg 2007

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: by the author and Integra, India using a Springer \LaTeX macro package
Cover design: eStudio Clamar S.L., F. Steinen-Broo, Pau/Girona, Spain

Printed on acid-free paper SPIN: 11802174 5 4 3 2 1 0

To My Wife, NINA

Preface to the English Edition

In 2006, the scientific society is celebrating the twentieth anniversary of the discovery of high-temperature superconductivity by George Bednorz and Alex Müller. Dynamically developing researches in this field give new scientific results. This caused a significant modernization of the English edition compared to the Russian one [808], which has been written in 2003. Considerable changes have been introduced in Chaps. 1–3 and Appendix A, in particular, new Sect. 3.1.2 is devoted to acoustic emission study of BSCCO/Ag tapes under bending. New Chapter 4 is devoted to carbon problem in HTSC and includes “old” text from Sects. 2.6 and 7.7 of the Russian edition, and “new” text (Sections 4.3 and Appendix B), presenting mathematical modeling of the brittle carbonate formation and following fracture during interaction of YBCO with CO₂. The main aims of the monograph have been retained and connected with Material Science of HTSC and their mathematical modeling. Comparatively, less attention has been devoted to Physics of HTSC. The main results as before have been related to the YBCO and BSCCO families, while the main trends in R&D of other superconductors have also been marked. The author would be grateful for reports of typographical and other errors to be sent via the following web page <http://www.math.rsu.ru/niimpm/str1/welcome.en.html>, where an up-to-date errata list will be maintained.

I would like to thank all those who have contributed to the preparation of this manuscript at final stage, especially Jacqueline Lenz and Dhivya Balaraman.

Ivan Parinov
Rostov-on-Don, December 2006

Preface to the Russian Edition

The discovery in 1986 of high-temperature superconductors (HTSC) on the basis of copper oxides with the temperature of superconducting transition, that is greater than the temperature of low-cost, non-toxic and accessible liquid nitrogen (77 K), marked qualitative jump in the development and application of new technical conductors, devices for energy transmission, transformation and storage. Together with enough high critical temperatures T_c , an intrinsic brittleness of oxide cuprates, the layered anisotropic structure and the super-short (~ 1 nm) coherence length, ξ , presenting itself a spatial characteristic of superconducting electrons, are other main features defining HTSC microstructure and properties. Due to the above-mentioned peculiarities, even the existence of an intergranular boundary could be enough to suppress superconductivity, but the structure-sensitive properties of HTSC systems depend very much on the weak links of intergranular boundaries by manufacturing them in the polycrystalline form, demonstrating coexistence of inter- and transgranular currents. Also, superconductivity can be destroyed at the attainment of the critical value of the external magnetic field H_{cm} . The interfaces of the “superconductor–normal metal”, “superconductor–insulator” and other types based on them are the localization places of different defects. The microstructure features, connected with phase composition, domain structure, crystallographic properties, an existence of structure defects, pores, microcracks, inclusions, etc., define directly useful properties of HTSC materials and composites. The main goal of the present monograph is to study microstructure, strength, electromagnetic and superconducting properties. Another aim includes discussion of the optimization directions for the fabrication techniques, superconducting compositions, external loading and thermal treatments to obtain HTSC, possessing improved and more controlled physical and mechanical properties. The link “composition–technique–experiment–theory–model” investigated in the book, assuming considerable HTSC defectiveness and structure heterogeneity, forms the whole picture of modern representations on the microstructure, strength and connected with them the structure-sensitive properties of the materials considered. Special attention in

the book is devoted to Bi–Sr–Ca–Cu–O and Y–Ba–Cu–O families that today are most prospective for applications among HTSC.

The monograph is addressed to students, postgraduate students and specialists taking part in the development, preparation and research of new materials. The author thanks the Russian Foundation for Basic Research, Russian Department of Education and Science, Soros Foundation and the American International Program COBASE (Collaboration in Basic Science and Engineering) grants which during the last decade have rendered considerable financial support and promoted to publish this book.

I am also grateful to colleagues and close scientific workers, who have directly or indirectly contributed to the book. In particular, I wish to thank V.P. Zatsarinny, D.N. Karpinsky, E.A. Dul'kin, E.M. Kaydashev, E.V. Rozhkov, A.A. Polyanskii and D.C. Larbalestier.

Corrections and proposals the book will be considered with thanks. They could be to presented by E-mail: ppr@math.rsu.ru.

I. A. Parinov
September 2003

Contents

1	Superconductors and Superconductivity: General Issues . . .	1
1.1	Superconductivity Discovery	1
1.2	Progress and Prognosis of Superconductivity Applications	5
1.3	Superconductivity Phenomena	16
1.3.1	Critical Field	16
1.3.2	Josephson Effects	16
1.3.3	The Meissner Effect	18
1.3.4	The Isotope Effect	19
1.3.5	Penetration Depth and Coherence Length	20
1.4	Magnetic Properties of Superconductors	21
1.4.1	Magnetic Properties of Type-I Superconductors	21
1.4.2	The Intermediate State	24
1.4.3	Magnetic Properties of Type-II Superconductors	25
1.5	Theories of Superconductivity	26
1.6	High-Temperature Superconductors	33
1.6.1	General Remarks on Type-II Superconductors	33
1.6.2	Doping of Cuprates	35
1.6.3	Coherence Length and HTSC Anisotropy	39
1.6.4	Vortex Structure of HTSC and Magnetic Flux Pinning	42
1.6.5	Interactions of Vortices with Pinning Centers	47
1.7	Weak Links of Josephson Type	49
2	Composition Features and HTSC Preparation Techniques . .	53
2.1	YBCO Films and Coated Conductors	53
2.2	BSCCO Films, Tapes and Wires	63
2.3	Tapes and Wires, Based on Thallium and Mercurial Cuprates	81
2.4	BSCCO Bulks	83
2.5	Y(RE)BCO Bulks	89

3	Experimental Investigations of HTSC	97
3.1	Experimental Methods of HTSC Investigations	97
3.1.1	Special Techniques	97
3.1.2	Acoustic Emission Method	105
3.2	Intergranular Boundaries in HTSC	114
3.3	Superconducting Composites, Based on BSCCO	127
3.3.1	BSCCO/Ag Tapes	127
3.3.2	Irreversibility Lines for BSCCO	140
3.3.3	BSCCO Bulks	144
3.4	Melt-Processed Y(<i>RE</i>)BCO	151
3.4.1	Microstructure Features	151
3.4.2	Growth Processes in Seeded Sample	154
3.4.3	Behavior of 211(422) Disperse Phase	158
3.4.4	Effects of Doping Additives	167
3.4.5	Mechanical and Strength Properties	171
4	Carbon Problem	183
4.1	YBCO System	183
4.2	BSCCO Systems	194
4.3	Carbon Embrittlement and Fracture of YBCO Superconductor	197
4.3.1	Mathematical Model for Carbonate Precipitation and Fracture	198
4.3.2	Discussion of Results	207
4.4	Modeling of Carbon Segregation and Fracture Processes of HTSC	209
4.4.1	Equilibrium Slow and Fast Crack Growth	209
4.4.2	Steady-State Crack Growth	213
4.4.3	Some Numerical Results	216
5	General Aspects of HTSC Modeling	219
5.1	Yield Criteria and Flow Rules for HTSC Powders Compaction	222
5.1.1	HTSC Compaction and Yield Criterion	222
5.1.2	Non-Associated Plasticity of HTSC Powders	225
5.2	Void Transformations During Sintering of Sample	230
5.2.1	Void Separation from Intergranular Boundary	233
5.2.2	Size Trajectories in the Pore/Grain Boundary System During Sintering	239
5.2.3	Estimation of Pore Separation Effects for HTSC	249
5.3	HTSC Microstructure Formation During Sintering	251
5.4	Microcracking of Intergranular Boundaries at Sample Cooling	256
5.5	Study of Statistical Properties of the Model Structures	259
5.6	Modeling of Macrocracks	261

6	Modeling of BSCCO Systems and Composites	269
6.1	Transformation of Bi-2212 to Bi-2223 Phase	269
6.1.1	Edge Dislocations as Channels for Fast Ion Diffusion	270
6.1.2	The Layer-Rigidity Model	272
6.1.3	Dynamics of Bi-2223 Phase Growth	276
6.1.4	Formation Energy of Bi-2223 Phase	278
6.1.5	Effect of Deformation on Bi-2212/Bi-2223 Transformation	280
6.2	Modeling of Preparation Processes for BSCCO/Ag Tapes	283
6.2.1	Sample Texturing by External Magnetic Field	283
6.2.2	Deformation at Tape Cooling	286
6.2.3	Effects of Mechanical Loading	287
6.2.4	Finite-Element Modeling of Deformation Processes	295
7	Modeling of YBCO Oxide Superconductors	301
7.1	Modeling of 123 Phase Solidification from Liquid	301
7.1.1	Heterogeneous Mechanism	301
7.1.2	Models Based on Yttrium Diffusion in Liquid	301
7.1.3	Models Based on Interface Phenomena	309
7.1.4	Models of Platelets-Like Growth of 123 Phase	315
7.1.5	Modeling of Solidification Kinetics	323
7.1.6	Multi-phase Field Method	326
7.2	Stress–Strain State of HTSC in Applied Magnetic Fields	331
8	Computer Simulation of HTSC Microstructure and Toughening Mechanisms	337
8.1	YBCO Ceramic Sintering and Fracture	337
8.1.1	Sintering Model of Superconducting Ceramic	337
8.1.2	Ceramic Cracking During Cooling	341
8.1.3	Formation of Microcracks Around 211 Particles in 123 Matrix	343
8.1.4	Fracture Features at External Loading	347
8.1.5	Microcracking Process Zone near Macrocrack	349
8.1.6	Crack Branching	353
8.1.7	Crack Bridging	356
8.1.8	Some Numerical Results	363
8.2	Twinning Processes in Ferroelastics and Ferroelectrics	370
8.2.1	Domain Structure and Fracture of Ferroelectric Ceramic	371
8.2.2	Fracture Features in Domain Structure of Ferroelectric	374
8.2.3	Thermodynamics of Martensitic Transformation in HTSC	378
8.2.4	About Toughening of Superconducting Ceramics	381
8.3	Toughening Mechanisms for Large-Grain YBCO	385

8.3.1	Model Representations	385
8.3.2	Effect of 211 Particles on YBCO Fracture	387
8.3.3	Some Numerical Results	391
8.4	Small Cyclic Fatigue of YBCO Ceramics	392
8.4.1	Model Representations	392
8.4.2	Microstructure Dissimilitude Effect	393
8.4.3	Fracture Energy and Microstructure Features	395
8.4.4	Some Numerical Results	398
8.5	Residual Thermal Stresses in YBCO/Ag Composite	399
8.6	Toughening of Bi-2223 Bulk, Fabricated by Hot-Pressing Method	401
8.6.1	Microstructure Formation by Processing	401
8.6.2	Bi-2223 Toughening by Silver Dispersion	404
9	Mechanical Destructions of HTSC Josephson Junctions and Composites	407
9.1	Interface Fracture	408
9.2	Thin Films on Substrates	413
9.3	Step-Edge Junctions	417
9.4	Transversal Fracture	420
9.5	HTSC Systems of S-N-S Type	424
9.6	Toughening Mechanisms	426
9.7	Charts of Material Properties and Fracture	428
9.8	Concluding Remarks	432
10	Modeling of Electromagnetic and Superconducting Properties of HTSC	435
10.1	Modeling of Intercrystalline Dislocations	435
10.2	Current-Limiting Mechanisms and Grain Boundary Pinning	440
10.3	Vortex Structures and Current Lines in HTSC with Defects	443
10.4	Non-Linear Current in Superconductors with Obstacles	448
10.5	Current Percolation and Pinning of Magnetic Flux in HTSC	457
10.5.1	Model of Non-linear Resistor Network	458
10.5.2	Simulation of Current Percolation and Magnetic Flux in YBCO Coated Conductors	466
10.5.3	Modeling of Electromagnetic Properties of BSCCO/Ag Tapes	469
10.5.4	Aging at Mechanical Loading	474
10.5.5	Effective Electrical Conductivity of Superconducting Oxide Systems	477
A	Classification of Superconductors	485
A.1	Organic Superconductors	485
A.2	A-15 Compounds	486
A.3	Magnetic Superconductors (Chevrel Phases)	488

A.4	Heavy Fermion Superconductors	491
A.5	Oxide Superconductors without Copper	492
A.6	Pyrochlore Oxides	493
A.7	Rutheno-Cuprates	493
A.8	High-Temperature Superconductors	494
A.9	Rare-Earth Borocarbides	500
A.10	Silicon-Based Superconductors	500
A.11	Chalcogens	501
A.12	Carbon Superconductors	501
A.13	MgB ₂ and Related Superconductors	504
A.14	Room-Temperature Superconductivity	507
B	Finite Element Implementation of Carbon-Induced Embrittlement Model	509
C	Macrostructure Modeling of Heat Conduction	515
C.1	Method of Summary Approximation for Quasi-Linear Equation of Heat Conduction	515
C.2	Heat Conduction of Heterogeneous Systems	518
C.2.1	Effective Heat Conduction of Mixes and Composites . . .	518
C.2.2	Polystructural Model of Granular Material	520
C.2.3	Model of Granular System with Chaotic Structure	523
C.2.4	Heat Flux Through Averaged Element	526
D	Eden Model	531
	References	535
	Index	571