

Wolfgang Hoffelner

Materials for Nuclear Plants

From Safe Design to Residual Life Assessments

 Springer

Wolfgang Hoffelner
Oberrohrdorf
Switzerland

ISBN 978-1-4471-2914-1 ISBN 978-1-4471-2915-8 (eBook)
DOI 10.1007/978-1-4471-2915-8
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2012935097

© Springer-Verlag London Limited 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, 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.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Contents

1 Nuclear Plants	1
1.1 Current Reactors	1
1.1.1 Pressurized Water Reactors	2
1.1.2 Boiling Water Reactors	2
1.1.3 CANDU Reactors	6
1.1.4 Advanced Gas Reactors	8
1.2 Improvements and Developments of Reactor Concepts	9
1.2.1 Advanced Light Water Reactors	9
1.2.2 Advanced Heavy Water Reactors	11
1.2.3 Small Modular Reactors.	11
1.2.4 Advanced New Reactor Concepts	13
1.3 Neutron Spectrum, Fast Reactors and Fuel Cycles.	16
1.3.1 Neutron Spectrum	16
1.3.2 Fuel Cycles	18
1.4 Generation IV Nuclear Plants	22
1.4.1 Sodium Fast Reactor	22
1.4.2 Lead-Cooled Fast Reactor	29
1.4.3 Very-High-Temperature Reactor System	32
1.4.4 Gas-Cooled Fast Reactor System R&D	41
1.4.5 Supercritical Water Reactor	44
1.4.6 Molten Salt Reactor	47
1.5 Other Advanced Nuclear Plant Concepts	49
1.5.1 Traveling Wave Reactor	49
1.5.2 Accelerator-Driven Systems	51
1.5.3 Space Nuclear Plants.	53
1.5.4 Nuclear Fusion	55
1.6 Conversion of Nuclear Energy into Electricity and Heat	58
References	61

2	Materials	65
2.1	Introduction	65
2.2	Basics	67
2.2.1	Point Defects	69
2.2.2	Linear Defects	71
2.2.3	Planar Defects	73
2.2.4	Diffusion Processes	75
2.2.5	Binary Phase Diagrams	79
2.3	Classes of Materials for Nuclear Applications	81
2.3.1	Steels	84
2.3.2	Superalloys	102
2.3.3	Refractory Alloys	110
2.3.4	Zirconium Alloys	110
2.3.5	Intermetallics	112
2.3.6	Nano-Structured Materials	114
2.3.7	Ceramic Materials	124
2.3.8	Coatings	128
	References	128
3	Components and Its Production	135
3.1	Components of Nuclear Plants	135
3.1.1	Vessel	136
3.1.2	Fuel Elements	141
3.1.3	Control Rods	148
3.1.4	Other Reactor Internals	148
3.1.5	Piping and Steam Generator	151
3.1.6	Intermediate Heat Exchanger	152
3.1.7	Energy Conversion Systems	155
3.1.8	Materials for Nuclear Fission Plants	157
3.1.9	Fusion	157
3.2	Production Techniques	163
3.2.1	Melting	164
3.2.2	Shaping	168
3.3	Powder Metallurgy	172
3.3.1	Powder Production	173
3.3.2	Powder Compaction	174
3.4	Graphite	176
3.5	Fiber Reinforced Materials	179
3.6	Fusion Procedures	181
3.6.1	Submerged Arc and Gas Tungsten Arc Welding	181
3.6.2	Defects in Welds	183
3.6.3	Other Bonding Methods	185

3.7	Coatings and Surface Treatment	188
3.7.1	Lining	188
3.7.2	Chemical Vapor Deposition CVD	190
3.7.3	Physical Vapor Deposition	190
3.7.4	Thermal Spray	192
3.7.5	Other Surface Treatments.	192
	References	192
4	Mechanical Properties of Nuclear Materials	197
4.1	Introduction	197
4.2	Strength of Materials	198
4.2.1	Plastic Deformation of Single Crystals	198
4.2.2	Stress–Strain Curves	200
4.2.3	Hardening Mechanisms	203
4.3	Toughness	206
4.3.1	Impact Testing and Fracture Appearance Transition Temperature	206
4.3.2	Fracture Toughness	208
4.4	Creep	217
4.4.1	Creep Curve	217
4.4.2	Stress Rupture Curve	220
4.4.3	Mechanisms of Thermal Creep in Metals	222
4.4.4	Creep Damage	227
4.4.5	Extrapolation of Stress Rupture Data	228
4.4.6	Creep Crack Growth	232
4.4.7	Thermal Creep of Ceramics for Nuclear Plants	235
4.5	Fatigue	235
4.5.1	Introduction	235
4.5.2	Basic Principles	236
4.5.3	Representation of Fatigue Results	237
4.5.4	Fatigue Crack Growth	241
4.5.5	Phenomenology of Fatigue	244
4.5.6	Creep-Fatigue Interactions	246
	References	251
5	Irradiation Damage	255
5.1	Introduction	255
5.2	Early Stage of Radiation Damage	257
5.3	Reactions of Point Defects Created During Irradiation	261
5.3.1	Influence of Temperature	263
5.3.2	Influence of Lattice Type	265
5.3.3	Influence of Chemical Composition	267

5.4	Other Types of Irradiation Damage	268
5.4.1	Radiation Induced Segregation (RIS).	268
5.4.2	Irradiation Induced (Coherent) Precipitation	270
5.4.3	Amorphization	271
5.4.4	The Production of Foreign Atoms.	272
5.5	Radiation Induced Dimensional Changes	273
5.5.1	Void Swelling	273
5.5.2	Radiation Creep	275
5.6	Radiation Effects at High Temperatures	279
5.7	Influence of Radiation on Mechanical Properties.	281
5.7.1	Strength and Toughness.	281
5.7.2	Influence of Irradiation on Fatigue and Fatigue Crack Growth.	283
5.7.3	Creep and Creep-Fatigue	284
5.8	Radiation Damage in Non-Metallic Structural Materials.	285
5.8.1	Graphite.	285
5.8.2	Silicon Carbide.	287
5.9	Irradiation Damage of Components	288
5.9.1	Light Water Reactors	288
5.9.2	Radiation Damage in Advanced Reactors.	294
	References	302
6	Environmental Damage in Nuclear Plants.	309
6.1	Basic Aspects of Corrosion.	309
6.1.1	Forms of Corrosion.	309
6.1.2	Corrosion Testing	312
6.1.3	Stress Corrosion Cracking (SCC)	316
6.1.4	Corrosion and Fatigue Loading.	317
6.1.5	High Temperature Effects	319
6.2	Environmental Effects in Light Water Reactors.	320
6.2.1	Basics	320
6.2.2	Pressure Boundaries	323
6.2.3	Reactor Internals.	328
6.2.4	Corrosion of Zircaloy Claddings.	331
6.3	Environmental Effects in Advanced Reactors	335
6.3.1	Sodium Fast Reactor	335
6.3.2	High Temperature Gas reactors.	341
6.3.3	Other Advanced Nuclear Plants	345
6.4	Fusion	353
	References	354

7	Advanced Mechanical Testing and Analysis Methods	359
7.1	Introduction	359
7.2	Micro-Mechanical Testing	360
7.2.1	Fatigue Crack Growth Testing	362
7.2.2	Fracture Toughness Testing	363
7.2.3	Shear Punch	366
7.2.4	Micro-Nanohardness Testing	368
7.2.5	Compression and Tensile Tests with Micro-Samples	370
7.3	Advanced Auxiliary Equipment	371
7.3.1	Irradiation	371
7.3.2	Preparation of Miniaturized Samples with Focused Ion Beam	373
7.3.3	Measurement of Changes in Geometry of Microsamples	374
7.4	Microstructural Investigations	375
7.4.1	Scanning Electron Microscope	375
7.4.2	Transmission Electron Microscope	376
7.4.3	Other Analysis Techniques	377
7.4.4	Analysis With Beamlines	377
7.5	Modelling Techniques	386
7.5.1	First Principle Considerations	387
7.5.2	Molecular Dynamics	389
7.5.3	Kinetic Monte Carlo and Rate Theory	390
7.5.4	Dislocation Dynamics	391
7.5.5	Computational Thermodynamics	393
7.5.6	Some Results of Multiscale Modeling	393
7.6	Further Outlook	400
	References	402
8	Design, Life-Time and Residual Life	407
8.1	Introduction	407
8.2	Loads and Stresses in Components	410
8.2.1	Equivalent Stresses	410
8.2.2	Notches	415
8.3	Codes and Design Rules	417
8.3.1	General Structure of Codes	417
8.3.2	Selected Materials Problems	423
8.4	Material Properties Database Needs	430
8.5	Non Destructive Testing/Evaluation	432
8.5.1	General Considerations	432
8.5.2	NDE Techniques	435
8.5.3	Advanced Material Characterization	441
8.5.4	NDE of Advanced Nuclear Systems	445
8.5.5	RPV as an Example	447

8.6 Plant Life Management (PLIM) and Plant Life Extension (PLEX)	451
References	452
Questions and Exercises	457
Solutions	467
Index	475