

# Creep-resistant steels

---

Edited by  
Fujio Abe, Torsten-Ulf Kern and R. Viswanathan

**Woodhead Publishing and Maney Publishing  
on behalf of  
The Institute of Materials, Minerals & Mining**

**CRC Press  
Boca Raton Boston New York Washington, DC**

**WOODHEAD PUBLISHING LIMITED**  
Cambridge England

<i>Contributor contact details</i>	<i>xiii</i>
------------------------------------	-------------

<i>Preface</i>	<i>xix</i>
----------------	------------

## Part I General

1	Introduction	3
	F. ABE, National Institute for Materials Science (NIMS), Japan	
1.1	Definition of creep	3
1.2	Creep and creep rate curves	3
1.3	Creep rupture data	7
1.4	Deformation mechanism map	9
1.5	Fracture mechanism map	11
1.6	References	14
2	The development of creep-resistant steels	15
	K.-H. MAYER, ALSTOM Energie GmbH, Germany and F. MASUYAMA, Kyushu Institute of Technology, Japan	
2.1	Introduction	15
2.2	Requirements for heat-resistant steels	18
2.3	Historical development of ferritic steels	19
2.4	Historical development of austenitic steels	42
2.5	Historical development of steel melting and of the purity of heat-resistant steels	64
2.6	Summary	67
2.7	References	70
3	Specifications for creep-resistant steels: Europe	78
	G. MERCKLING, RTM BREDA Milano, Italy	
3.1	Introduction	78

3.2	Specifications and standards	81
3.3	The European Creep Collaborative Committee (ECCC)	85
3.4	European Pressure Equipment Research Council (EPERC)	92
3.5	The latest generation of CEN standards for creep-resistant steels	95
3.6	Future trends	150
3.7	References	151
4	Specifications for creep-resistant steels: Japan	155
	F. MASUYAMA, Kyushu Institute of Technology, Japan	
4.1	Introduction	155
4.2	Types of heat-resistant steels in Japan	155
4.3	Specifications for high temperature tubing and piping steels	158
4.4	Specifications for steam turbine steels	169
4.5	Heat-resistant super alloys	169
4.6	Summary	169
4.7	References	173
5	Production of creep-resistant steels for turbines	174
	Y. TANAKA, Japan Steel Works, Japan	
5.1	Introduction	174
5.2	Overview of production technology of rotor shaft forgings for high temperature steam turbines	175
5.3	Production and properties of turbine rotor forgings for high temperature applications	192
5.4	Future trends	207
5.5	References	212

## Part II Behaviour of creep-resistant steels

6	Physical and elastic behaviour of creep-resistant steels	217
	Y. YIN and R.G. FAULKNER, Loughborough University, UK	
6.1	Introduction	217
6.2	Elastic behaviour	219
6.3	Thermal properties of creep-resistant steels	225
6.4	Electrical resistivity and conductivity of creep-resistant steels	234
6.5	Implications for industries using creep-resistant steels	238
6.6	Future trends	239
6.7	References	239

7	Diffusion behaviour of creep-resistant steels	241
	H. OIKAWA and Y. IJIMA, Tohoku University, Japan	
7.1	Introduction	241
7.2	Diffusion and creep	241
7.3	Diffusion characteristics	243
7.4	Roles of atom/vacancy movement in creep	248
7.5	Influence of some factors on creep through their effects on diffusion	250
7.6	Diffusion data in iron and in some iron-base alloys	255
7.7	Concluding remarks	260
7.8	References	263
8	Fundamental aspects of creep deformation and deformation mechanism map	265
	K. MARUYAMA, Tohoku University, Japan	
8.1	Introduction	265
8.2	Stress-strain response of materials	265
8.3	Temperature and strain rate dependence of yield stress	267
8.4	Deformation upon loading of creep test	269
8.5	Creep behavior below and above athermal yield stress	270
8.6	Change in creep behavior at athermal yield stress $\sigma_a$	271
8.7	Deformation mechanism maps	275
8.8	Concluding remarks	278
8.9	References	278
9	Strengthening mechanisms in steel for creep and creep rupture	279
	F. ABE, National Institute for Material Science (NIMS), Japan	
9.1	Introduction	279
9.2	Basic ways of strengthening steels at elevated temperature	279
9.3	Strengthening mechanisms in modern creep-resistant steels	287
9.4	Loss of strengthening mechanisms in 9–12Cr steels during long time periods	295
9.5	Future trends	301
9.6	References	301
10	Precipitation during heat treatment and service: characterization, simulation and strength contribution	305
	E. KOZESCHNIK and I. HOLZER, Graz University of Technology, Austria	
10.1	Introduction	305

10.2	Microstructure analysis of the COST alloy CB8	306
10.3	Modelling precipitation in complex systems	312
10.4	Computer simulation of the precipitate evolution in CB8	315
10.5	Microstructure-property relationships	320
10.6	The back-stress concept	322
10.7	Loss of precipitation strengthening during service of CB8	324
10.8	Summary and outlook	325
10.9	References	326
11	Grain boundaries in creep-resistant steels	329
	R.G. FAULKNER, Loughborough University, UK	
11.1	Introduction	329
11.2	Ferritic steels	330
11.3	Austenitic steels	341
11.4	Grain boundary properties and constitutive creep design equations	345
11.5	Future trends	346
11.6	References	347
12	Fracture mechanism map and fundamental aspects of creep fracture	350
	K. MARUYAMA, Tohoku University, Japan	
12.1	Introduction	350
12.2	Fracture mechanisms and ductility of materials	351
12.3	Stress and temperature dependence of rupture life	352
12.4	Fracture mechanism maps	355
12.5	Influence of fracture mechanism change on creep rupture strength	356
12.6	Influence of microstructural degradation on creep rupture strength	358
12.7	Change in creep rupture properties at athermal yield stress	359
12.8	Multi-region analysis of creep rupture data	361
12.9	Summary	362
12.10	References	364
13	Mechanisms of creep deformation in steel	365
	W. BLUM, University of Erlangen-Nuernberg, Germany	
13.1	Introduction	365
13.2	Initial microstructure	366
13.3	Creep at constant stress	368
13.4	Transient response to stress changes	370

13.5	Cyclic creep	374
13.6	Microstructural interpretation of creep rate	375
13.7	Dislocation models of creep	385
13.8	<i>In situ</i> transition electron microscope observations of dislocation activity	389
13.9	Discussion and outlook	393
13.10	Acknowledgments	395
13.11	References	395
13.12	Appendix: Microstructural model Mikora	401
14	Constitutive equations for creep curves and predicting service life	403
	S.R. HOLDSWORTH, EMPA – Materials Science & Technology, Switzerland	
14.1	Introduction	403
14.2	Constitutive equations	405
14.3	Constitutive equation selection	405
14.4	Predicting service life	412
14.5	Future trends	416
14.6	Concluding remarks	416
14.7	Nomenclature	416
14.8	References	417
15	Creep strain analysis for steel	421
	B. WILSHIRE and H. BURT, University of Wales Swansea, UK	
15.1	Introduction	421
15.2	Creep-induced strain	422
15.3	Patterns of creep strain accumulation	427
15.4	Practical implications of creep strain analysis	433
15.5	Future data analysis options	441
15.6	References	442
16	Creep fatigue behaviour and crack growth of steels	446
	C. BERGER, A. SCHOLZ, F. MUELLER and M. SCHWIENHEER, Darmstadt University of Technology, Germany	
16.1	Introduction	446
16.2	Creep-fatigue experiments	447
16.3	Stress-strain behaviour	449
16.4	Creep-fatigue interaction, life estimation	449
16.5	Multiaxial behaviour	456
16.6	Creep and creep-fatigue crack behaviour	459

x	Contents	
16.7	Concluding remarks	468
16.8	Acknowledgements	469
16.9	References	469
17	Creep strength of welded joints of ferritic steels	472
	H. CERJAK and P. MAYR, Graz University of Technology, Austria	
17.1	Introduction	472
17.2	Influence of weld thermal cycles on the microstructure of ferritic heat-resistant steels	474
17.3	Weld metal development for creep-resistant steels	482
17.4	Creep behaviour of welded joints	483
17.5	Selected damage mechanism in creep-exposed welded joints	484
17.6	Implications for industries using welded creep-resistant steels	495
17.7	Future trends	496
17.8	References	498
18	Fracture mechanics: understanding in microdimensions	504
	M. TABUCHI, National Institute for Materials Science (NIMS), Japan	
18.1	Introduction	504
18.2	Non-linear fracture mechanics	504
18.3	Effect of mechanical constraint	507
18.4	Effect of microscopic fracture mechanisms	509
18.5	Type IV creep crack growth in welded joints	513
18.6	References	517
19	Mechanisms of oxidation and the influence of steam oxidation on service life of steam power plant components	519
	P. J. ENNIS and W. J. QUADAKKERS, Forschungszentrum Jülich GmbH, Germany	
19.1	Introduction	519
19.2	Mechanisms of enhanced steam oxidation	520
19.3	Steam oxidation rates	525
19.4	Oxidation and service life	530
19.5	Development of steam oxidation-resistant steels	532
19.6	Outlook	533

19.7	Sources of further information	534
19.8	References	534
 <b>Part III Applications</b>		
20	Alloy design philosophy of creep-resistant steels	539
	M. IGARASHI, Sumitomo Metal Industries, Japan	
20.1	Introduction	539
20.2	Creep-resistant steels for particular components in power plants and the properties required	539
20.3	Alloy design philosophies of creep-resistant steels	541
20.4	References	570
21	Using creep-resistant steels in turbines	573
	T.-U. KERN, Siemens AG Power Generation Group, Germany	
21.1	Introduction	573
21.2	Implications for industries using creep-resistant steels	574
21.3	Improving the performance and service life of steel components	583
21.4	Next steps into the future	591
21.5	Summary	593
21.6	References	593
22	Using creep-resistant steels in nuclear reactors	597
	S.K. ALBERT, Indira Gandhi Centre for Atomic Research, India and S. SUNDARESAN, Maharaja Sayajirao University, Baroda, India	
22.1	Introduction	597
22.2	Radiation damage	598
22.3	Embrittlement caused by ageing	611
22.4	Use of heat-resistant steels in major reactor types	613
22.5	Fabrication and joining considerations	629
22.6	Summary	631
22.7	References	632
23	Creep damage – industry needs and future research and development	637
	R. VISWANATHAN and R. TILLEY, Electric Power Research Institute, USA	
23.1	Introduction	637
23.2	Calculational methods for estimating damage	638



xii Contents

23.3	Non-destructive evaluation methods	643
23.4	Accelerated destructive tests	653
23.5	High temperature crack growth	658
23.6	Future trends	662
23.7	References	663
	<i>Index</i>	667