

# Contents

<i>Contributor contact details</i>	<i>xi</i>
<i>Introduction</i>	<i>xv</i>
<b>Part I Mechanisms of hydrogen interactions with metals</b>	<b>1</b>
1 Hydrogen adsorption on the surface of metals A. A. PISAREV, National Research Nuclear University ‘MEPHI’, Russia	3
1.1 Introduction	3
1.2 Adsorption effect	4
1.3 Elementary processes in adsorption	10
1.4 The structure of the H–Me adsorption complex	15
1.5 Kinetic equations and equilibrium	20
1.6 Conclusions	22
1.7 References	23
2 Analysing hydrogen in metals: bulk thermal desorption spectroscopy (TDS) methods K. VERBEKEN, Ghent University (UGent), Belgium and Max-Planck-Institut für Eisenforschung, Germany	27
2.1 Introduction	27
2.2 Principle of thermal desorption spectroscopy (TDS) measurements	28
2.3 Experimental aspects of thermal desorption spectroscopy (TDS)	31
2.4 Complementary techniques	44
2.5 Conclusion	50
2.6 References	51

3	Analyzing hydrogen in metals: surface techniques P. TROCELLIER, Centre d'Études de Saclay, France	56
3.1	Introduction	56
3.2	Available techniques for analyzing hydrogen	57
3.3	Methods for analyzing hydrogen in metals: basic principles	59
3.4	Applications of hydrogen analysis methods	68
3.5	Ion beam-based methods	79
3.6	Conclusion	84
3.7	References	85
4	Hydrogen diffusion and trapping in metals A. TURNBULL, National Physical Laboratory, UK	89
4.1	Introduction: hydrogen uptake	89
4.2	Solubility of hydrogen in metals	92
4.3	Principles of hydrogen diffusion and trapping	95
4.4	Modelling of hydrogen diffusion and trapping	99
4.5	Measurement of hydrogen diffusion	106
4.6	Hydrogen diffusion data	108
4.7	Conclusions	120
4.8	Acknowledgements	124
4.9	References	124
5	Control of hydrogen embrittlement of metals by chemical inhibitors and coatings J. H. HOLBROOK, AmmPower LLC, USA, H. J. CIALONE, Edison Welding Institute, USA, E. W. COLLINGS, Ohio State University, USA, E. J. DRAUGLIS and P. M. SCOTT, Battelle Columbus Laboratories, USA and M. E. MAYFIELD, US Nuclear Regulatory Commission, USA	129
5.1	Introduction	129
5.2	Chemical barriers to hydrogen environment embrittlement (HEE): gaseous inhibitors	131
5.3	Physical barriers to hydrogen environment embrittlement (HEE)	148
5.4	Conclusions and future trends	149
5.5	Sources of further information and advice	151
5.6	References	152
6	The role of grain boundaries in hydrogen induced cracking (HIC) of steels C. J. McMAHON JR, University of Pennsylvania, USA	154
6.1	Introduction: modes of cracking	154
6.2	Impurity effects	156

6.3	Temper embrittlement and hydrogen	156
6.4	Tempered-martensite embrittlement and hydrogen	160
6.5	Future trends	162
6.6	Conclusions	164
6.7	References	165
7	Influence of hydrogen on the behavior of dislocations I. M. ROBERTSON, M. L. MARTIN and J. A. FENSKY, University of Illinois, USA	166
7.1	Introduction	166
7.2	Dislocation motion	167
7.3	Evidence for hydrogen dislocation interactions	172
7.4	Discussion	195
7.5	Conclusions	199
7.6	Acknowledgements	200
7.7	References	200
	<b>Part II Modelling hydrogen embrittlement</b>	207
8	Modeling hydrogen induced damage mechanisms in metals W. GERBERICH, University of Minnesota, USA	209
8.1	Introduction	209
8.2	Pros and cons of proposed mechanisms	211
8.3	Evolution of decohesion models	218
8.4	Evolution of shear localization models	230
8.5	Summary	239
8.6	Conclusions	241
8.7	Acknowledgements	242
8.8	References	242
9	Hydrogen effects on the plasticity of face centred cubic (fcc) crystals D. DELAFOSSE, Ecole des Mines de Saint-Etienne, France	247
9.1	Introduction and scope	247
9.2	Study of dynamic interactions and elastic binding by static strain ageing (SSA)	248
9.3	Modelling in the framework of the elastic theory of discrete dislocations	257
9.4	Experiments on face centred cubic (fcc) single crystals oriented for single glide	274
9.5	Review of main conclusions	279

viii	Contents	
9.6	Future trends	281
9.7	References	283
10	Continuum mechanics modeling of hydrogen embrittlement M. R. BEGLEY, University of California Santa Barbara, USA, J. A. BEGLEY, TCA Solutions, USA and C. M. LANDIS, The University of Texas at Austin, USA	286
10.1	Introduction	286
10.2	Basic concepts	289
10.3	Crack tip fields: asymptotic elastic and plastic solutions	296
10.4	Crack tip fields: finite deformation blunting predictions	303
10.5	Application of crack tip fields and additional considerations	310
10.6	Stresses around dislocations and inclusions	317
10.7	Conclusions	322
10.8	Acknowledgement	323
10.9	References	323
11	Degradation models for hydrogen embrittlement M. DADFARNIA and P. SOFRONIS, University of Illinois at Urbana-Champaign, USA, B. P. SOMERDAY and D. K. BALCH, Sandia National Laboratories, USA and P. SCHEMBRI, Los Alamos National Laboratory, USA	326
11.1	Introduction	326
11.2	Subcritical intergranular cracking under gaseous hydrogen uptake	330
11.3	Subcritical ductile cracking: gaseous hydrogen exposure at pressures less than 45 MPa or internal hydrogen	356
11.4	Discussion	369
11.5	Conclusions	373
11.6	Acknowledgments	374
11.7	References	374
12	Effect of inelastic strain on hydrogen-assisted fracture of metals M. M. HALL JR, MacRay Consulting, USA	378
12.1	Introduction	378
12.2	Hydrogen embrittlement (HE) processes and assumptions	382
12.3	Hydrogen damage models and assumptions	390
12.4	Diffusion with dynamic trapping	406
12.5	Discussion	420
12.6	Conclusions	422

12.7	References	423
12.8	Appendix: nomenclature	428
13	Development of service life prognosis systems for hydrogen energy devices P. E. IRVING, Cranfield University, UK	430
13.1	Introduction	430
13.2	Current techniques for control of cracking in safety critical structures	433
13.3	Future developments in crack control using prognostic systems	437
13.4	Prognostic systems for crack control in hydrogen energy technologies	442
13.5	Potential future research areas	461
13.6	Conclusions	461
13.7	References	462
<b>Part III The future</b>		<b>469</b>
14	Gaseous hydrogen embrittlement of high performance metals in energy systems: future trends R. JONES, GT Engineering, USA	471
14.1	Introduction	471
14.2	Theory and modeling	472
14.3	Nanoscale processes	473
14.4	Dynamic crack tip processes	474
14.5	Interfacial effects of hydrogen	475
14.6	Measurement of localized hydrogen concentration	477
14.7	Loading mode effects	478
14.8	Hydrogen permeation barrier coatings	479
14.9	Advances in codes and standards	480
14.10	Conclusions	481
14.11	References	481
<i>Index</i>		485