

Contents

Preface *ix*

Prelude – A Critical Assessment from an Industrial Point of View 1

Hans-Ulrich Blaser

- 1 Some Introductory Remarks 1
- 1.1 What Is the Motivation for Developing Non-Noble Metal Catalysts? 2
- 1.2 Crucial Parameters for Process Development 3
 - 1.2.1 The Catalyst: Metal Complex, (Chiral) Ligand 4
 - 1.2.2 The Process 5
- 2 Comparison with the Established Catalysts 5
- 2.1 Chemoselective Hydrogenations: Alternatives to Heterogeneous Catalysts 6
 - 2.1.1 Hydrogenation of Esters 6
 - 2.1.2 E-Selective Hydrogenation of Alkynes 7
 - 2.1.3 Selective C=O Reduction of Unsaturated Carbonyl Groups 7
- 2.2 Enantioselective Hydrogenations 8
- 2.3 A Few Remarkable Transformations Using Cu and Co Complexes 9
- 3 Epilogue 10
- References 13

- 1 Iron-Catalyzed Homogeneous Hydrogenation Reactions** 15
- Thomas Zell and Robert Langer*
- 1.1 Introduction 15
- 1.2 Fundamental Differences Between Noble and 3d Metal Complexes 17
- 1.3 Mechanistic Scenarios and the Role of Substrates 22
 - 1.3.1 Nonpolar Substrates 22
 - 1.3.2 Polar Substrates 24
 - 1.3.3 Exceptions 25
- 1.4 Iron-Catalyzed Hydrogenation of C—C Multiple Bonds 26
 - 1.4.1 Hydrogenation of Olefins 26
 - 1.4.2 Hydrogenation of Alkynes 27
- 1.5 Iron-Catalyzed Hydrogenation of C—O Multiple Bonds 28
 - 1.5.1 Hydrogenation of Aldehydes and Ketones 29

- 1.5.2 Hydrogenation of Esters 31
- 1.5.3 Hydrogenation of Amides 32
- 1.6 Iron-Catalyzed Hydrogenation of C—N Multiple Bonds 32
- 1.7 Conclusion 34
- Abbreviations 35
- References 35

- 2 Cobalt-Catalyzed Hydrogenations 39**
Felicia Weber and Gerhard Hilt
- 2.1 Introduction 39
- 2.2 Hydrogenation Reactions 39
 - 2.2.1 Activation of Molecular Hydrogen–Dihydrogen Complexes vs. Dihydride Complexes 39
 - 2.2.2 Hydrogenation of CO₂, Carboxylic Acids, Carboxylic Esters, and Nitriles 40
 - 2.2.3 Hydrogenation of C=O, C=N, C=C, C≡C, and (Hetero)arenes 46
- 2.3 Conclusion 57
- References 57

- 3 Homogeneous Nickel-Catalyzed Hydrogenations 63**
Marlene Bödl and Ivana Fleischer
- 3.1 Introduction 63
- 3.2 Hydrogenation of Alkenes 65
 - 3.2.1 Hydrogenation of Alkyl- and Aryl-Substituted Alkenes 65
 - 3.2.2 Hydrogenation of Electron-Deficient Alkenes 76
- 3.3 Hydrogenation of Alkynes 78
- 3.4 Hydrogenation of Carbonyl Groups 79
 - 3.4.1 Hydrogenation of Ketones 79
 - 3.4.2 Hydrogenation of Carbon Dioxide 81
- 3.5 Conclusions 83
- References 83

- 4 Homogeneous Hydrogenation with Copper Catalysts 87**
Niklas O. Thiel, Felix Pape, and Johannes F. Teichert
- 4.1 Introduction 87
 - 4.1.1 Early Studies on Copper-Catalyzed Hydrogenations 87
- 4.2 Hydrogenation of (α,β-Unsaturated) Carbonyl and Carboxyl Compounds 88
 - 4.2.1 Conjugate Reduction 88
 - 4.2.2 1,2-Hydrogenation of α,β-Unsaturated Ketones and Aldehydes 91
 - 4.2.3 Asymmetric 1,2-Hydrogenation of Simple (Nonconjugated) Ketones and Aldehydes 92
- 4.3 CO₂ Reduction to Formate 93
- 4.4 Allylic Substitutions with a Hydride Nucleophile Generated from H₂ 95
- 4.5 Z-Selective Alkyne Semihydrogenation 98

4.6	Alkyne Transfer Semihydrogenation and Transfer Conjugate Reduction with Ammonia Borane	104
4.7	Dihydrogen-Mediated Cross-Coupling of Internal Alkynes and Aryl iodides	105
4.8	Conclusions and Perspectives	106
	References	107
5	Hydrogenation Reactions Using Group III to Group VII Transition Metals	111
	<i>Matthew L. Clarke and Magnus B. Widegren</i>	
5.1	Introduction	111
5.2	Group III Metals: Scandium and Yttrium	111
5.3	Group IV Metals: Titanium, Zirconium, and Hafnium	112
5.3.1	Asymmetric Hydrogenation Using Titanium and Zirconium Catalysts	115
5.4	Group V Metals: Vanadium, Niobium, and Tantalum	119
5.5	Group VI Metals: Chromium, Molybdenum, and Tungsten	121
5.6	Group VII Metals: Manganese and Rhenium	122
5.7	Summary and Conclusions	137
	References	137
6	Early Main Group Metal Catalyzed Hydrogenation	141
	<i>Heiko Bauer and Sjoerd Harder</i>	
6.1	Introduction	141
6.2	Hydrogenation of C=C Double Bonds	144
6.3	Hydrogenation of C=N Double Bonds	153
6.4	Hydrogenation of C=O Double Bonds	157
6.5	Summary and Perspectives	160
	References	163
7	Frustrated Lewis Pair-Catalyzed Reductions Using Molecular Hydrogen	167
	<i>Jan Paradies and Sebastian Tussing</i>	
7.1	Introduction	167
7.2	Mechanistic Considerations	168
7.3	Influence of the Lewis Acid and Lewis Base on Hydrogenation Reactivity	171
7.3.1	Choice of Lewis Acid	172
7.4	Balance Between Lewis Acidity and Lewis Basicity	173
7.4.1	Hydrogenation of Olefins	178
7.4.2	Dehydrogenative Coupling	179
7.4.3	Acceptorless Dehydrogenation	180
7.4.4	Intramolecular Frustrated Lewis Pairs	181
7.4.5	Air-Stable FLPs	184
7.5	Application of Frustrated Lewis Pairs in Hydrogenations	187
7.5.1	Hydrogenation of Aldimines and Ketimines	187

7.5.2	Hydrogenation of Enamines and Silylenol Ethers	193
7.5.3	Hydrogenation of Ketones	198
7.5.4	Reductive Deoxygenations	198
7.6	Hydrogenation of Heterocycles	201
7.7	Hydrogenation of Enones, Alkylidene Malonates, and Nitroolefins	207
7.8	Hydrogenation of Unpolarized Olefins and Polycyclic Aromatic Hydrocarbons	211
7.9	Electrophilic Phosphonium Cations (EPCs)	215
7.10	Summary	217
	Abbreviations	217
	References	218
8	Recent Advances in Selective Biocatalytic (Hydrogen Transfer) Reductions	227
	<i>Gonzalo de Gonzalo and Iván Lavandera</i>	
8.1	Introduction	227
8.2	Ketoreductases	228
8.2.1	Alcohol Dehydrogenases in “Nonconventional” Media	229
8.2.2	Dynamic Processes Employing Ketoreductases	230
8.2.3	Alcohol Dehydrogenases in Multicatalytic Processes	232
8.2.4	Application of Ketoreductases to the Synthesis of Valuable Compounds	236
8.3	Ene-Reductases	241
8.3.1	Substrate Scope of Ene-Reductases	242
8.3.2	Ene-Reductases in Multicatalytic Processes	244
8.4	Imine Reductases	248
8.5	Carboxylic Acid Reductases	249
8.6	Emerging Enzymes: Nitrile Reductases and Nitroreductases	250
8.7	Summary and Outlook	251
	Abbreviations	252
	References	253
9	Organocatalytic Transfer Hydrogenation	261
	<i>Jie Wang and Yong-Gui Zhou</i>	
9.1	Introduction	261
9.2	Asymmetric Transfer Hydrogenation of C=C Bonds	262
9.3	Asymmetric Transfer Hydrogenation of C=N Bonds	266
9.4	Asymmetric Transfer Hydrogenation of C=O Bonds	273
9.5	Asymmetric Transfer Hydrogenation of Heteroaromatics	274
9.6	Summary and Outlook	280
	Abbreviations	280
	References	281
	Index	285