Tetrahedron 66 (2010) 1040–1044

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Pd nanoparticles as catalysts for green and sustainable oxidation of functionalized alcohols in aqueous media

Maria Mifsud, Ksenia V. Parkhomenko, Isabel W.C.E. Arends, Roger A. Sheldon *

Biocatalysis and Organic Chemistry Group, Department of Biotechnology, Delft University of Technology, Julianalaan 136, 2628BL Delft, The Netherlands

ARTICLE INFO

Article history:
Received 3 July 2009
Accepted 18 August 2009
Available online 6 November 2009

Keywords:
Aerobic oxidation of alcohols
Palladium nanoparticles
Steroidal alcohols
Water

ABSTRACT

The previously described catalyst system for the aerobic oxidation of alcohols, comprising palladium(II) acetate in combination with neocuproine in a 1:1 mixture of water and a water-miscible cosolvent such as ethylene carbonate or dimethylsulfoxide, was shown to involve palladium nanoparticles as the active catalyst. The latter are formed in situ or can be preformed by reduction of the palladium–neocuproine complex with hydrogen and they are stabilized by both the neocuproine ligand and the cosolvent. This catalyst system was successfully used for the selective aerobic oxidation of the steroidal secondary alcohols, nandrolone and 5α-pregnan-3α-ol-20-one, to the corresponding ketones.

1. Introduction

The oxidation of primary and secondary alcohols to the corresponding carbonyl compounds plays a central role in organic synthesis.[1] However, standard organic textbooks[2] still recommend classical oxidation methods using stoichiometric quantities of inorganic oxidants, notably chromium VI reagents,[3] which are highly toxic and/or environmentally polluting. According to a recent publication[4] the three most popular oxidants used by Pfizer's medicinal chemists for the oxidation of primary alcohols to the corresponding aldehydes are the Dess–Martin periodinane[5] or its precursor IBX, the Swern reagent[6] and tetrapropyl perruthenate, TPAP.[7] All of these methods have poor atom efficiencies[8] and significant scale-up issues. The Dess–Martin periodinane, for example, is a high energy, potentially explosive molecule that is, prohibitively expensive for use on a multi-kilogram scale. The Swern oxidation is used at pilot plant scale but generates toxic by-products and the stench of dimethylsulfide. The use of stoichiometric TPAP is also prohibitively expensive for large-scale use. A more environmentally friendly and scalable procedure that has become popular in recent years is the use of hypochlorite (household bleach) in conjunction with a stable nitroxy radical such as tetramethylpiperidinyloxy (TEMPO)[9] or its oligomeric equivalent, PIPO.[10]

The ultimate green oxidants are dioxygen (air) and hydrogen peroxide, that form water as the sole coproduct, and catalytic methodologies employing these terminal oxidants are particularly attractive from both an economic and environmental viewpoint.[11] However, as was pointed out by Dunn and Perry and co-workers,[4] there are serious safety issues associated with the use of dioxygen to aerate flammable solvents. It is also worth noting, in this context, that decomposition of hydrogen peroxide leads to the formation of dioxygen. These concerns can be reduced by using a mixture of $<10\%$ oxygen in nitrogen but still these methods lie on the edge of what is acceptable with regard to scalability. An improved safety profile is obtained by performing such oxidations in an aqueous medium, thus avoiding the use of volatile and flammable organic solvents. Hence, we have a longstanding interest in the green, catalytic aerobic oxidation of alcohols[12] in general and employing water as the reaction medium in particular.

Palladium(II) salts have long been known to catalyze the aerobic oxidation of alcohols.[13] The use of $PdCl_2$–NaOAc, for example, was reported in 1977.[14] However, activities were very low, with turnover frequencies of the order of 1 h^{-1}. Other systems, which were subsequently studied include $Pd(OAc)_2$–$NaHCO_3$ in DMSO or ethylene carbonate,[15] $PdCl_2$, in combination with sodium carbonate and a tetraalkylammonium salt as a phase transfer catalyst[16] and $Pd(OAc)_2$ in combination with pyridine and 3 Å molecular sieves in toluene at 80 °C.[17] The best results were turnover frequencies (TOFs) of the order of 10 h^{-1}.

The catalytic mechanism involves the reduction of palladium to the zerovalent state by the alcohol substrate and its subsequent reoxidation to palladium(II) by dioxygen. The transient Pd(0) species is metastable and prone to aggregation to bulk palladium metal (Pd black) with concomitant loss of catalytic activity.[18] One approach to avoid this is to add coordinating ligands, which stabilize the transient Pd(0) species. We previously reported[19] the use of

* Corresponding author. Fax: +31 15 2781415.
E-mail address: r.a.sheldon@tudelft.nl (R.A. Sheldon).

0040-4020/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2009.11.007

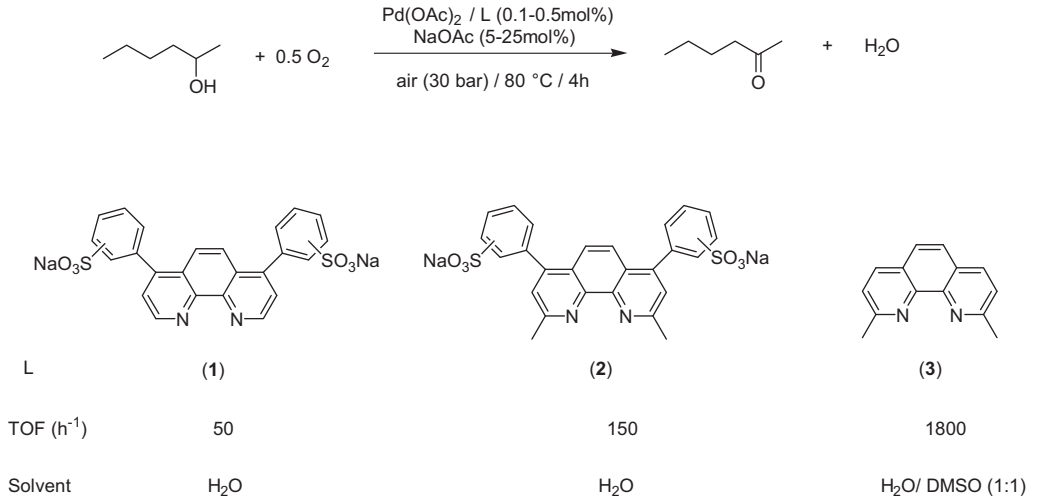

Figure 1. Palladium(II) complexes of dinitrogen ligands.

water-soluble palladium complexes of chelating dinitrogen ligands, notably bathophenanthroline disulfonate (**1**) (Fig. 1) as active, stable and recyclable catalysts for the aerobic oxidation of alcohols in water in the absence of organic solvents. A typical protocol involved the use of 0.25 mol % of a mixture of a 1:1 mixture of $Pd(OAc)_2$ and (**1**) together with 5 mol % of sodium acetate.[19] The latter was shown to stabilize the catalyst by suppressing the formation of palladium black and an amount corresponding to 5 mol % was found to be the optimum. The sodium acetate is not consumed in the reaction, that is, it is a cocatalyst. The palladium(II) bathophenanthroline complex proved to be an active catalyst for the selective aerobic oxidation of a variety of primary and secondary alcohols to the corresponding acids or aldehydes and ketones, respectively. However, alcohols bearing functional groups containing heteroatoms, such as N and S, were unreactive. Hence, we continued our search for an active catalyst that exhibited a broader scope in organic synthesis.

In our original studies[19] of the Pd–bathophenanthroline system we noted that the kinetics were consistent with dissociation of a hydroxyl bridged dimer to give the corresponding monomer, which was the active catalyst. Hence, we reasoned that dimers derived from phenanthroline ligands substituted at the 2 and 9 positions would be sterically crowded and more readily dissociate, resulting in a higher concentration of the active monomer complex. To this end we designed the palladium complexes of ligands (**2**) and (**3**) and measured their activities in the oxidation of a wide variety of primary and secondary alcohols.[20] Reactions were performed in 1:1 mixtures of water with water-miscible organic solvents, mainly DMSO, to ensure dissolution of the substrates and facilitate measurement of relative rates. The 1:1 palladium(II) complex of neocuproine (**3**) was shown to catalyze the aerobic oxidation of alcohols bearing a variety of heteroatom (O, N and S)-containing functional groups under these conditions.[20] Typically 0.1–0.5 mol % of the Pd complex was used together with 5–25 mol % of NaOAc as cocatalyst (see above). We now report a further study of this interesting catalyst.

2. Results and discussion

2.1. Catalyst characterization

A more detailed examination of our previous results[20] revealed a remarkable difference between the Pd(II) complexes of (**1**) and (**3**) in the oxidation of the alcohol (**4**) containing a remote olefinic double bond (Fig. 2). With the complex of (**1**) the major product (75% selectivity) was the keto alcohol (**5**) formed by Pd catalyzed Wacker-type oxidation of the olefinic double bond. We had previously shown that this Pd complex catalyzes the aerobic oxidation of olefins to the corresponding ketones.[21] The diketone (**7**) was formed as a minor product (8%), probably via further oxidation of (**5**). In stark contrast, essentially exclusive (>99% selectivity) formation of (**6**), resulting from the selective oxidation of the alcohol moiety, was observed when the Pd complex of (**3**) was the catalyst.

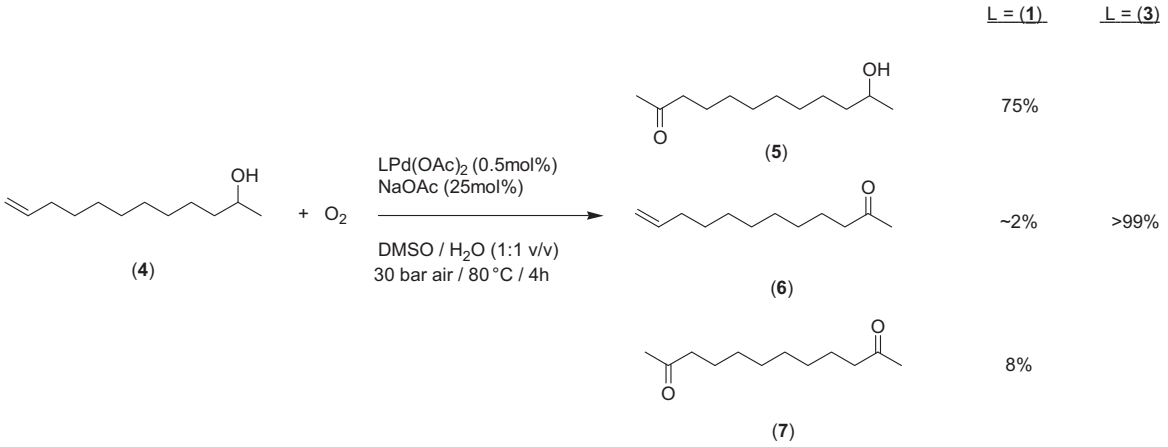

Figure 2.

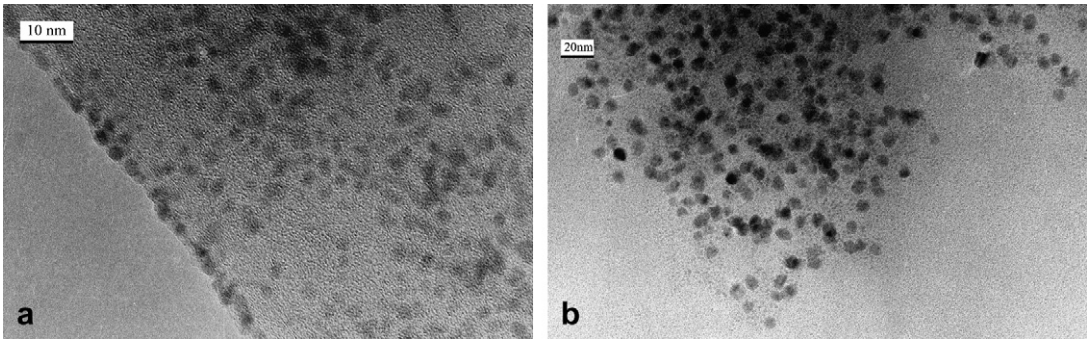

Figure 3. TEM photograph of Pd nanoparticles (a) before and (b) after oxidation reaction.

This remarkable difference led us to suspect that a different mechanism was involved. Indeed, the highly selective oxidation of the alcohol moiety in the presence of an olefinic double bond was reminiscent of earlier reports by Moiseev and co-workers[22,23] who showed that giant Pd clusters (nowadays known as Pd nanoparticles) are effective catalysts for the oxidation of alcohol moieties and are able to selectively oxidize allylic C–H bonds in olefins. More recently, Pd nanoparticles supported on hydroxyapatite,[24] entrapped in aluminium hydroxide,[25] dispersed in a resin[26] or stabilized with poly(ethylene glycol) in $scCO_2$[27] or with microgels in water[28] were shown to catalyze aerobic alcohol oxidations.

We first examined the synthesis of Pd nanoparticles in the presence of neocuproine (**3**) using a standard procedure. To this end a 1:1 mixture of palladium (II) trifluoroacetate and neocuproine, dissolved in a 1:1 mixture of water and a cosolvent, consisting of ethylene carbonate, dipropylene glycol or polyethylene glycol (PEG-600), was reduced with hydrogen gas. The particle size of the resulting nanoparticles was determined with transmission electron microscopy (TEM). The particles had a homogeneous size distribution of 2–4 nm diameter (see Fig. 3a). An oxidation reaction was then performed with these presynthesized Pd nanoparticles and TEM analysis showed an increase in particle size from 2–4 nm before to 4–6 nm after the reaction (Fig. 3b).

Pd nanoparticles were also formed when the separately prepared Pd(II)–neocuproine complex was added to a solution of 2-hexanol dissolved in the water–cosolvent (1:1) and the mixture stirred for 10 min at room temperature. In this case the alcohol substrate acts as the reducing agent that converts the Pd(II) to Pd(0). Our results clearly indicate that, in the presence of (**3**) and an alcohol substrate a Pd(II) salt rapidly forms Pd nanoparticles and that the latter constitute the actual catalyst in aerobic oxidations mediated by the Pd(II) complex of (**3**) in aqueous media. In contrast, the Pd(II) complex of (**1**) is a homogeneous catalyst that does not undergo nanoparticle formation in the presence of an alcohol substrate. A plausible explanation for this difference is that the steric crowding caused by the methyl groups at the 2 and 9 positions in the Pd(II) complex of (**3**) not only facilitates the desired dissociation of the hydroxyl bridged dimer to the catalytically active monomer (see above) but also promotes dissociation of the latter to Pd nanoparticles. By analogy with the known stabilization of palladium nanoparticles by unsubstituted phenanthroline ligands,[22] we assume that neocuproine (**3**) stabilizes the Pd nanoparticles in our system.

2.2. Catalytic activity in 2-hexanol oxidation

The catalytic activity of the presynthesized Pd nanoparticles was determined in the aerobic oxidation of 2-hexanol. The effect of the cosolvent (stabilizing agent), catalyst amount, nature of the palladium salt precursor and Pd/ligand ratio on the reaction rate was investigated and the results are shown in Table 1. Palladium nanoparticles were prepared using different cosolvents: PEG-600, dipropylene glycol and ethylene carbonate. The cosolvent plays a dual role: it acts as a solvent for the oxidation reaction and as an additional stabilizing agent for the nanoparticles. The best conversions were obtained with ethylene carbonate (Entries 1, 3, 4, 5, Table 1). The influence of the anion in the palladium salt precursor was studied by comparing palladium acetate with palladium trifluoroacetate and no differences were observed (Entries 1, 6, Table 1).

Table 1
Oxidation of 2-hexanol to 2-hexanone[a]

Entry	Catalyst	Catalyst amount (mol %)	Conversion (%)
1	$Pd(O_2CCF_3)_2$–neocuproine (1:1) H_2O–ethylene carbonate (1:1)	0.5	72
2	$Pd(O_2CCF_3)_2$–neocuproine (1:1) H_2O–ethylene carbonate (1:1)	0.1	17
3	$Pd(O_2CCF_3)_2$–neocuproine (1:0.25) H_2O–ethylene carbonate (1:1)	0.5	25
4	$Pd(O_2CCF_3)_2$–neocuproine (1:1) H_2O–PEG-600 (1:1)	0.5	54
5	$Pd(O_2CCF_3)_2$–neocuproine (1:1) H_2O–dipropylene glycol (1:1)	0.5	54
6	$Pd(OAc)_2$–neocuproine (1:1) H_2O–ethylene carbonate (1:1)	0.5	73
7	$Pd(OAc)_2$–bathophenanthroline (1:1) H_2O–PEG-600 (1:1)	0.5	30
8	Pd–neocuproine complex H_2O–ethylene carbonate (1:1)	0.5	72
9	Pd–neocuproine complex H_2O–DMSO (1:1)	0.5	67

[a] Reaction conditions: 10 mmol 2-hexanol, 0.5 mmol NaOAc, 100 °C, 2 h, 750 rpm, 50 bar, 8% O_2/N_2; selectivity to 2-hexanone was essentially quantitative.

When the catalyst amount was reduced from 0.5 mol % to 0.1 mol % the conversion decreased from 72% to 17% (Entries 1, 2). A decrease in conversion was also observed when the neocuproine/palladium ratio was reduced from 1:1 to 1: 4 (Entries 1, 3, Table 1) or when bathophenanthroline sulfonate (**1**) was used instead of neocuproine (**3**) as the ligand in the pre-synthesis of the nanoparticles (Entries 1 and 7, Table 1).

We compared the catalytic behaviour of the presynthesized nanoparticles with that of the Pd–neocuproine complex under the same conditions and observed the same conversions after 2 h reaction time (Entries 1 and 8).

2.3. Oxidation of steroidal alcohols

In order to study the catalytic activity of the neocuproine-stabilized palladium nanoparticles with industrially relevant functionalized alcohols as substrates we chose the steroidal alcohols, nandrolone (**8**) and 5α-pregnan-3α-ol-20-one (**9**) (see Fig. 4). With these less reactive alcohols we needed to add more catalyst to

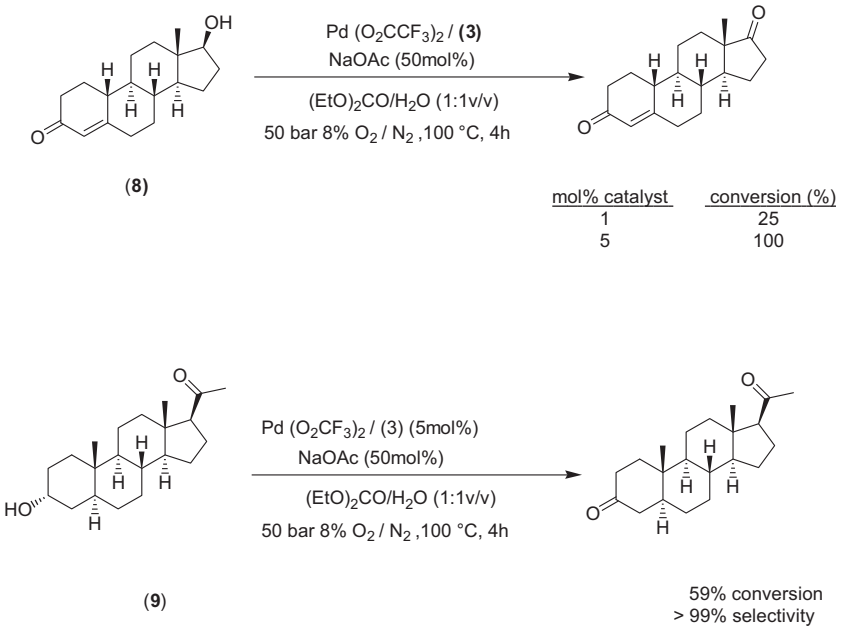

Figure 4. Aerobic oxidation of nandrolone (**8**) and 5α-pregnan-3α-ol-20-one (**9**).

achieve relatively smooth conversions. For example, (**8**) underwent only 25% conversion in 4 h with 1 mol % Pd–neocuproine complex. On increasing the catalyst loading to 5 mol %, in conjunction with 50 mol % NaOAc (not optimized), we observed complete conversion of nandrolone in 4 h. Under the same conditions (**9**) underwent 60% conversion in 4 h with 5 mol % catalyst. In both examples the selectivity to the corresponding ketone was quantitative, no side products were observed.

3. Conclusions

We conclude that the active alcohol oxidation catalyst, formed in situ by reaction of palladium(II) salts with the neocuproine ligand and the alcohol substrate, is not the expected homogeneous Pd(II) complex but rather Pd nanoparticles stabilized by the neocuproine ligand and the cosolvent. It is an effective catalyst for the aerobic oxidation of a broad range of alcohols in aqueous/organic media, from simple aliphatic alcohols such as 2-hexanol to more complicated substrates, such as steroidal alcohols, containing other functional groups. Minor differences in particle size were observed between the palladium nanoparticles generated in situ from the palladium–neocuproine complex and the alcohol substrate and those that were presynthesized by reduction with molecular hydrogen but this did not seriously effect their catalytic behaviour.

4. Experimental section

4.1. General

Neocuproine was purchased from Acros.

Nandrolone and 5α-pregnan-3α-ol-20-one were gifts from Diosynth.

The (neocuproine)$Pd(OAc)_2$ complex was prepared according to the literature procedure.[20]

4.2. Preparation of the Pd nanoparticles

Neocuproine (0.05 mmol, 10.6 mg) was added to a solution of $Pd(O_2CCF_3)_2$ (0.05 mmol, 16.6 mg) in water (12.5 mL). The mixture was stirred for 1 h and the cosolvent (stabilizing agent, 12.5 mL) was added. After 3 min the mixture was reduced under H_2 with vigorous stirring during 15 min.

4.3. Catalyst characterization

The particle size of the Pd catalyst was determined by transmission electron microscopy. The TEM shows a Pd particle size of 2–4 nm. TEM was performed using a Phillips CM30 T electron microscope with a LaB_6 filament as a source of electrons operated a 300 kV. Samples were mounted on Quantifoil® microgrid carbon polymer supported on a copper grid by placing a few droplets of solution on the grid, followed by drying at ambient conditions.

4.4. Oxidation of 2-hexanol

Standard catalytic experiments were carried out in a closed Hastelloy C autoclave (150 mL). 2-Hexanol (10 mmol) and NaOAc (0.5 mmol, 41 mg) were added to a solution of the palladium–neocuproine complex or a suspension of the Pd nanoparticles in the 1:1 water/cosolvent mixture (25 mL) and pressurized with 8% O_2 in N_2 to 50 bar and heated to 100 °C, while stirring at 750 rpm. After the reaction the autoclave was cooled to room temperature and depressurised. The product mixture was extracted with Et_2O and the organic layer was washed with water and dried over $MgSO_4$, *n*-dodecane was added as external standard to the organic solutions and the latter were analysed by GC.

4.5. Oxidation of steroidal alcohols

The reactions were carried out in a closed Hastelloy C autoclave (150 mL). The alcohol (1 mmol, dissolved in 1 mL MeOH) and NaOAc (0.5 mmol, 41 mg) were added to the palladium–neocuproine solution (see in preparation of catalyst) and the mixture pressurized with 8% O_2 in N_2 to 50 bar and heated to 100 °C, while stirring at 750 rpm during 4 h. After the reaction the autoclave was cooled to room temperature and depressurised. The product mixture was extracted with EtOAc, the organic layer was washed with water and

dried over $MgSO_4$. *n*-Dodecane was added as internal standard to the organic solutions and the latter were analysed by GC.

Acknowledgements

M.M. is grateful to the Spanish Ministry of Education and Science for a postdoctoral fellowship. TEM pictures were carried out by V.C.L. Butselaar from National Centre for High Resolution Electron Microscopy in Delft University of Technology.

References and notes

1. Sheldon, R. A.; Arends, I. W. C. E. In *Modern Oxidation Methods*; Bäckvall, J. E., Ed.; Wiley-VCH: Weinheim, 2004; pp 83–114.
2. See organic textbooks, e.g. Clayden, J.; Greeves, N.; Warren, S.; Wothers, P. *Organic Chemistry*; Oxford University Press: New York, NY, 2001; Bruice, P. Y. *Organic Chemistry*, 3rd ed.; Prentice Hall: New Jersey, NJ, 2001.
3. Cainelli, G.; Cardillo, G. *Chromium Oxidations in Organic Chemistry*; Springer: Berlin, 1984.
4. Alfonsi, K.; Colberg, J.; Dunn, P. J.; Fevig, T.; Jennings, S.; Johnson, T. A.; Kleine, H. P.; Knight, C.; Nagy, M. A.; Perry, D. A.; Stefaniak, M. *Green Chem.* **2008**, *10*, 31–36.
5. Dess, D. B.; Martin, J. C. *J. Org. Chem.* **1983**, *48*, 4155–4156.
6. (a) Mancuso, A. J.; Huang, S. L.; Swern, D. *J. Org. Chem.* **1978**, *12*, 2480–2482; (b) Mancuso, A. J.; Swern, D. *Synthesis* **1981**, 165–185.
7. Ley, S. V.; Norman, J.; Griffith, W. P.; Marsden, S. P. *Synthesis* **1994**, 639–666.
8. Trost, B. M. *Science* **1991**, *254*, 1471–1477.
9. de Nooy, A. E. J.; Besemer, A. C.; van Bekkum, H. *Synthesis* **1996**, 1153–1174.
10. (a) Dijksman, A.; Arends, I. W. C. E.; Sheldon, R. A. *Chem. Commun.* **2000**, 271–272; (b) Dijksman, A.; Arends, I. W. C. E.; Sheldon, R. A. *Synlett* **2001**, 102–104.
11. Zhan, B.-Z.; Thompson, A. Tetrahedron report nr. 674 *Tetrahedron* **2004**, *60*, 2917–2935.
12. Sheldon, R. A.; Arends, I. W. C. E.; ten Brink, G. J.; Dijksman, A. *Acc. Chem. Res.* **2002**, *35*, 774–781.
13. For excellent reviews see: (a) Muzart, J. *Tetrahedron* **2003**, *59*, 5789–5816; (b) Stahl, S. S. *Angew. Chem., Int. Ed.* **2004**, *43*, 3400–3420.
14. Blackburn, T. F.; Schwartz, J. *J. Chem. Soc., Chem. Commun.* **1977**, 157–158.
15. Peterson, K. P.; Larock, R. C. *J. Org. Chem.* **1998**, *63*, 3185–3189; van Benthem, R. A. T. M.; Hiemstra, H.; van Leeuwen, P. W. N. M.; Geus, J. W.; Speckamp, W. N. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 457–460.
16. (a) Ait-Mohand, S.; Hénin, F.; Muzart, J. *Tetrahedron Lett.* **1995**, *36*, 2473–2476; (b) Ait-Mohand, S.; Muzart, J. J. *J. Mol. Catal. A: Chem.* **1998**, *129*, 135–139.
17. (a) Nishimura, T.; Onoue, T.; Ohe, K.; Uemura, S. *Tetrahedron Lett.* **1998**, *39*, 6011–6014; (b) Nishimura, T.; Onoue, T.; Ohe, K.; Uemura, S. J. *J. Org. Chem.* **1999**, *64*, 6750–6755; (c) Nishimura, T.; Ohe, K.; Uemura, S. J. *J. Am. Chem. Soc.* **1999**, *121*, 2645–2646.
18. (a) van Leeuwen, P. W. N. M. *Appl. Catal. A: Gen.* **2001**, *212*, 61–81; (b) Tromp, M.; Sietsma, J. R. A.; van Bokhoven, J. A.; van Strijdonk, G. P. F.; van Haaren, R. J.; van der Eerden, A. M. J.; van Leeuwen, P. W. N. M.; Koningsberger, D. C. *Chem. Commun.* **2003**, 128–129.
19. (a) ten Brink, G.-J.; Arends, I. W. C. E.; Sheldon, R. A. *Science* **2000**, *287*, 1636–1639; (b) ten Brink, G.-J.; Arends, I. W. C. E.; Sheldon, R. A. *Adv. Synth. Catal.* **2002**, *344*, 355–369.
20. (a) ten Brink, G.-J.; Arends, I. W. C. E.; Hoogenraad, M.; Verspui, G.; Sheldon, R. A. *Adv. Synth. Catal.* **2003**, *345*, 1341–1352; (b) Arends, I. W. C. E.; ten Brink, G.-J.; Sheldon, R. A. *J. Mol. Catal. A: Chem.* **2006**, *251*, 246–254; (c) ten Brink, G.-J.; Arends, I. W. C. E.; Hoogenraad, M.; Verspui, G.; Sheldon, R. A. *Adv. Synth. Catal.* **2003**, *345*, 497–505.
21. ten Brink, G.-J.; Arends, I. W. C. E.; Papadogianakis, G.; Sheldon, R. A. *Appl. Catal. A: Gen.* **2000**, *194–195*, 435–442.
22. (a) Vargaftik, M. N.; Zagorodnikov, V. P.; Stolarov, I. P.; Moiseev, I. I.; Likholobov, V. A.; Kotchubey, D. I.; Chuvilin, A. L.; Zaikovsky, V. I.; Zamaraev, K. I.; Timofeeva, G. I. *J. Chem. Soc., Chem. Commun.* **1985**, 937–938; (b) Moiseev, I. I.; Vargaftik, M. N. *New J. Chem.* **1998**, *22*, 1217–1227; (c) Pasichnyk, P. I.; Starchevsky, M. K.; Pazdersky, Y. A.; Zagorodnikov, V. P.; Vargaftik, M. N.; Moiseev, I. I. *Mendeleev Commun.* **1994**, 1–2; (d) Vargaftik, M. N.; Zagorodnikov, V. P.; Stolyarov, I. P.; Moiseev, I. I.; Kochubey, D. I.; Likholobov, V. A.; Chuvilin, A. L.; Zamaraev, K. I. *J. Mol. Catal.* **1989**, *53*, 315–348.
23. Kovtun, G.; Kameneva, T.; Hladyi, S.; Starchevsky, M.; Pazdersky, Y.; Stolarov, I.; Vargaftik, M.; Moiseev, I. I. *Adv. Synth. Catal.* **2002**, *344*, 957–964.
24. Mori, K.; Hara, T.; Mizugaki, T.; Ebitani, K.; Kaneda, K. *J. Am. Chem. Soc.* **2004**, *126*, 10657–10666.
25. Kwon, M. S.; Kim, N.; Park, C. M.; Lee, J. S.; Kang, K. Y.; Park, J. *Org. Lett.* **2005**, *7*, 1077–1079.
26. Uozumi, Y.; Nakao, R. *Angew. Chem., Int. Ed* **2003**, *42*, 194–197.
27. (a) Hou, Z.; Theyssen, N.; Brinkmann, A.; Leitner, W. *Angew. Chem., Int. Ed.* **2005**, *44*, 1346–1349; (b) Hou, Z. S.; Theyssen, N.; Leitner, W. *Green. Chem.* **2007**, *9*, 127–132.
28. Biffis, A.; Minati, L. *J. Catal.* **2005**, *236*, 405–409.