Available online at www.sciencedirect.com

Journal of Molecular Catalysis A: Chemical 246 (2006) 263–267

www.elsevier.com/locate/molcata

Cinchonidine doped Pd catalysts in the enantioselective hydrogenation of (*E*)-2-methyl-2-butenoic acid

M. Casagrande [a], S. Franceschini [b], M. Lenarda [a], O. Piccolo [c], A. Vaccari [b,*]

[a] *Dipartimento di Chimica, Università Cà Foscari, INSTM-UdR Venezia, Via Torino 155/B, Ve-Mestre, Venezia, Italy*
[b] *Dipartimento di Chimica Industriale e dei Materiali, Università di Bologna, INSTM-UdR di Bologna, Viale del Risorgimento 4, 40136 Bologna, Italy*
[c] *Studio di Consulenza Scientifica, Via Bornò 5, 23896 Sirtori Lecco, Italy*

Received 4 November 2005; received in revised form 7 November 2005; accepted 7 November 2005
Available online 15 December 2005

Abstract

Commercial 5 wt.% Pd-containing catalysts doped with cinchonidine were investigated in the enantioselective hydrogenation of (*E*)-2-methyl-2-butenoic acid ($P = 4.0$ MPa of H_2, $T = 298$ K) with the aim of determining how the activity and enantioselectivity may be affected by specifications of the catalytic system (metal dispersion, support acidity and surface area).

Keywords: Enantioselective hydrogenation; (*E*)-2-Methyl-2-butenoic acid; Tiglic acid; Cinchonidine; Pd/γ-Al_2O_3; Pd/TiO_2; Pd/C; Surface acidity; Surface area; Pd dispersion

---

1. Introduction

The enantioselective hydrogenation of C=C double bond in α,β-unsaturated carboxylic acids, with heterogeneous chirally doped catalysts, remains an important target for investigation, due to the relevance of the enantiopure or enantioenriched products in the pharmaceutical and agrochemical fields [1–4] as well as to the desire to identify economical and recyclable catalytic systems.

This reaction on different α,β-unsaturated carboxylic acids had been investigated in the presence of cinchonidine (CD) doped Pd on different supports such as γ-Al_2O_3, charcoal, SiO_2 and TiO_2 [5–13]. However, a deep comparison among these catalysts on the same unsaturated substrate was still wanting and might be useful to define a fine-tuning and well robust preparation method for the catalysts that would be necessary for future industrial applications. Indeed, it may be expected that numerous factors such as the metal dispersion, the metal crystallite size, the surface acidity of the support and the method of preparation of the catalyst could have an important role. Therefore, the aim of this work was to study the contributions of the specifications of commercial catalysts on activity and enantioselectivity in the hydrogenation of (*E*)-2-methyl-2-butenoic acid (tiglic acid), chosen as a model substrate (Fig. 1).

2. Experimental

The commercial catalysts “40692”, “5220” Engelhard and “11713” Johnson Matthey (5 wt.% Pd/γ-Al_2O_3), “44258” Engelhard (5 wt.% Pd/TiO_2) and “5018” Engelhard (5 wt.% Pd/C) were used. These catalysts were characterised before reaction with X-ray diffraction, H_2 chemisorption, B.E.T surface area by N_2 adsorption and NH_3-TPD analyses. Before the hydrogenation reaction, the catalysts were doped with CD by stirring 1 h under air in the presence of 75 mL of *n*-hexane as solvent [14].

Tiglic acid, CD, undecane and *n*-hexane were purchased from Aldrich Chemicals (purity ≥ 98%) and used without any further purification. The reaction conditions in a 300 mL Parr autoclave for the experiments were: 54 μmol of Pd, 25 mmol of tiglic acid, 170 μmol of CD, 75 mL of *n*-hexane, reaction time 2 h, pressure 4.0 MPa of H_2, temperature 298 K, stirring. Before being heated, the autoclave was purged three times with He at 0.3 MPa. When the system reached the reaction temperature, the H_2 was introduced at the set pressure and the reaction started. Two milliliters of mixture was periodically sampled and diluted to 10 mL with

---

[*] Corresponding author. Tel.: +39 051 2093683; fax: +39 051 2093680/679.
E-mail address: angelo.vaccari@unibo.it (A. Vaccari).

1381-1169/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.molcata.2005.11.010

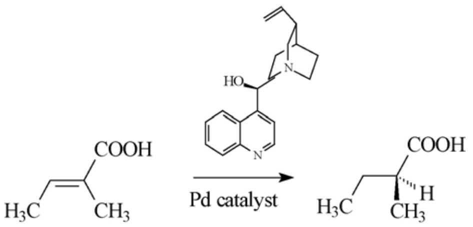

Fig. 1. Pd-catalysed enantioselective hydrogenation of (*E*)-2-methyl-2-butenoic (tiglic) acid with cinchonidine as modifier.

solvent, 100 μL of undecane added as external standard. The products were analysed using a Perkin-Elmer Autosystem XL gas chromatograph, equipped with FID and a wide bore PS086 chiral column (DEtTbuSililBETACDX 25 m × 0.25 mm, film width 0.25 μm). The enantiomeric excess (e.e.) was expressed as: e.e. (%) = [(S − R)/(S + R)] × 100.

X-ray diffraction (XRD) analyses were carried out using a Philips PW 1050/81 diffractometer (40 kV, 25 mA) equipped with a PW 1710 unit, and a Cu Kα radiation ($\lambda = 0.154118$ nm). A 2θ range from 10° to 80° was investigated at a scanning rate of 0.10°/s. The H_2 chemiadsorption and the B.E.T. analyses were carried out using an AUTOCHEM 2910 (Micromeritrics). The samples were pre-treated under H_2/Ar (5:95, v/v) to 673 K for 25 min. Then the samples were treated to 333 K with Ar for 20 min, and then were treated to 333 K with H_2/Ar (5:95, v/v).

The surface acidity was determined using a ThermoQuest TPD/R/O 1100, equipped with TCD. The samples were pre-treated under a 100 mL/min He flow at 673 K for 1 h, then there was added at 433 K of 10 pulses of NH_3 (every 5 min) and maintained at this temperature for 1 h. Finally, under the same He flow, the samples were heated from 433 to 823 K (heating rate 10 K/min) and maintained at the latter temperature for 1 h.

3. Results and discussion

The best performances in the enantioselective hydrogenation of tiglic acid were obtained with CD-doped 5 wt.% Pd/γ-Al_2O_3 catalysts, in particular with “40692” Engelhard, reaching the complete conversion and an e.e. up to 48% [15] (Table 1), in agreement with the best literature data [9]. Comparing all the Pd on γ-alumina catalysts it is possible to observe that “5220” Engelhard and “11713” Johnson Matthey produced a lower enantioselectivity, although with comparable activity (conversion and TON values). On the contrary, Pd on TiO_2 and on charcoal catalysts were much less active and also less enantioselective. It is possible that in the commercial catalysts sometimes-unknown impurities, usually present in low amount, may influence the reaction results in a way not easy to study and to understand. However, a direct analysis only of the species adsorbed on the catalyst surface, that might be possibly relevant, is very difficult. We hypothesise that the influence of these impurities on the surface should not be so important to explain the obtained results, because similar results (activity, e.e.) have been observed when some experiments were repeated with different samples of the same catalyst belonging to a different production lot. Thus, the probability of the same type of impurities on the surface, if any, should be low.

The difference from conversion and yield is probably determined by a small adsorption on the catalyst surface of the reaction product or the formation of small amounts of some volatile by-products (likely C_4H_8 and/or C_4H_{10} hydrocarbons). By GC and TLC analyses other by-products were not observed.

3.1. H_2 chemisorption analysis

The dimension of metal clusters may affect the adsorption of the CD on the catalyst surface, producing either different hydrogenating activity or different enantioselectivity. The more efficient catalyst for both aspects (“40692” Engelhard), presents a dispersion and diameter of metal clusters of 19.3% and 5.8 nm, respectively (Table 2). The decreasing of the activity is particularly evident for the catalysts on TiO_2 and charcoal with small Pd crystallites particles (2.6–3.5 nm). On the contrary, the other Pd/γ-Al_2O_3 catalysts, “5220” Engelhard and “11713” Johnson Matthey, with sizes of Pd clusters of about 8 nm, show high activity, but decreasing enantioselectivity. With this preliminary work, we observed experimentally that a significant importance seems to have also the size of the Pd clusters, affecting the total or partial covering of the catalytic surface by the modifier, in particular the Pd particle size could be between 5.0 and 7.0 nm.

Also the B.E.T. analyses underline how a high surface area combined with small size particles decreases the catalytic activity.

3.2. NH_3 temperature programmed desorption analysis

A study was conducted on the surface acidity of the catalysts by NH_3-TPD analyses, evidencing that the nature of the support determined the catalyst acidity, affecting its activity (Table 3).

The 5 wt.% Pd on γ-alumina “40692” Engelhard catalyst was significantly more acid than the others catalysts. In particular,

Table 1
Hydrogenation of the (*E*)-2-methyl-2-butenoic (tiglic) acid with the different 5 wt.% Pd-containing catalysts (solvent = *n*-hexane; $T = 298$ K; $P = 4.0$ MPa of H_2; reaction time = 2 h)

Catalyst	Conversion (%)	TON[a]	Yield (%)	Selectivity (%)	e.e. (%)
Pd/C “5018” Engelhard	47	7.22	45	96	35
Pd/TiO_2 “44258” Engelhard	77	8.64	70	91	36
Pd/γ-Al_2O_3 “11713” J. Matthey	94	23.74	92	98	38
Pd/γ-Al_2O_3 “5220” Engelhard	>99	30.85	95	96	45
Pd/γ-Al_2O_3 “40692” Engelhard	>99	34.90	95	96	48

[a] mmol of saturated acid obtained/[Pd-metal surface area (m^2) × h].

Table 2
Characterisation data for the investigated 5 wt.% Pd-containing catalysts

Catalyst	Metal dispersion (%)	Pd-metal surface area (m^2/g_{CAT})	Pd-metal surface area (m^2/g_{Pd})	Pd particle size (nm)	B.E.T. surface area (m^2/g)
Pd/C “5018” Engelhard	31.8	7.1	141.6	3.5	425
Pd/TiO_2 “44258” Engelhard	43.5	9.7	193.8	2.6	200
$Pd/\gamma\text{-}Al_2O_3$ “40692” Engelhard	19.3	4.3	86.1	5.8	185
$Pd/\gamma\text{-}Al_2O_3$ “5220” Engelhard	15.8	3.5	70.5	7.1	101
$Pd/\gamma\text{-}Al_2O_3$ “11713” J.Matthey	14.0	3.1	62.3	8.0	148

Table 3
NH_3-TPD data for the 5 wt.% Pd-containing catalysts

Catalyst	Surface acidity (μmol of desorbed NH_3/g_{CAT})
Pd/C “5018” Engelhard	130
Pd/TiO_2 “44258” Engelhard	150
$Pd/\gamma\text{-}Al_2O_3$ “40692” Engelhard	1329
$Pd/\gamma\text{-}Al_2O_3$ “5220” Engelhard	580
$Pd/\gamma\text{-}Al_2O_3$ “11713” J. Matthey	670

when comparing the three catalysts on γ-alumina it is possible to observe that the acidity seems to have a relevant role in the enantioselectivity of the reaction. The importance of the acidity in this reaction is probably determined by the strong acid–base interaction between the CD and the support. The CD is an organic base ($pK_a = 9.18–13.24$) [16], with a quinoline ring that interacts electronically not only with the metal Pd, but also with the support (acid–base interaction).

The interaction with the unsaturated substrate (tiglic acid) and CD would so occur on the catalyst surface in a steric hindered environment, amplifying the energy differences between the two enantiofaces of the double bond. The alternative hypothesis that CD is more stable in presence of an acid support and that no partial hydrogenation of quinoline ring may occur in this condition (so affecting the adsorption of the modified chiral dopant and, hence, the enantioselectivity) is, at our opinion, less probable, since, on the contrary, the hydrogenation of the quinoline ring in these conditions should be easier.

Furthermore, this correlation has been made on catalysts having different supports; the probability that this observed effect may be due to unknown impurities should be low. More important, in our opinion, is the fact that two different Pd on γ-alumina (by Engelhard), having similar structural properties except acidity, gave rise to different enantioselectivity, with higher e.e. for the more acid support.

Thus, a fine-tuning of the surface acidity could implement the e.e. of this reaction. However, our attempts to treat the “5220” Engelhard catalyst with different inorganic and organic acids in order to increase the surface acidity, did not give the wished results, evidencing that the acid characteristics of the support has to be chosen beforehand.

3.3. X-ray diffraction analysis

The XRD powder patterns did not show any difference between the three different Pd on γ-alumina catalysts (Fig. 2) and typical XRD patterns of γ-alumina support (reference code 01-1308 JCPDS) ($2\theta = 37^\circ$, 45° and 66°) and Pd (reference code 01-1310 JCPDS) ($2\theta = 39^\circ$, 46° and 67°) can be observed. The XRD profile of the Pd on TiO_2 (Fig. 3) showed a mixture of both

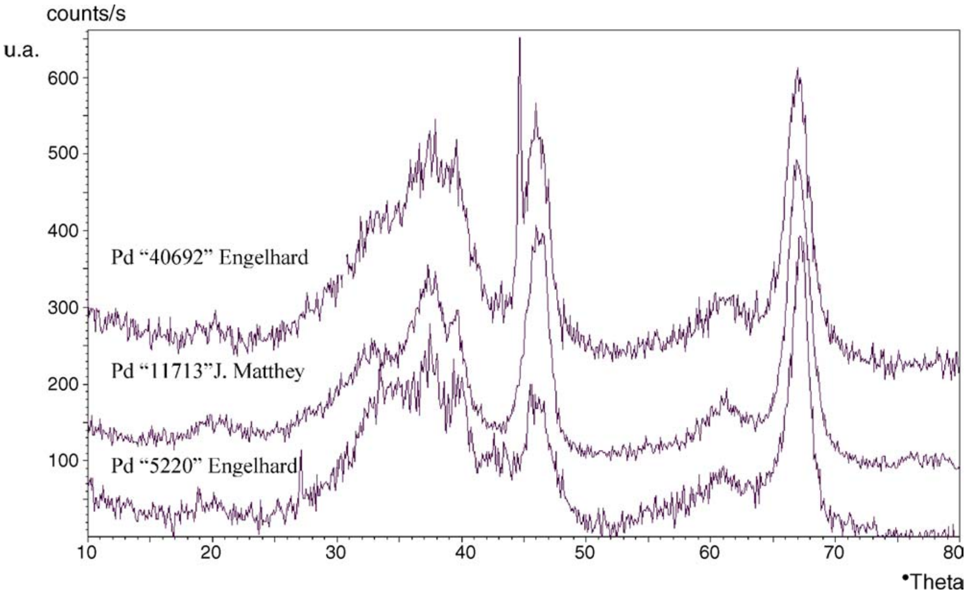

Fig. 2. XRD powder patterns of the different 5 wt.% $Pd/\gamma\text{-}Al_2O_3$ catalysts.

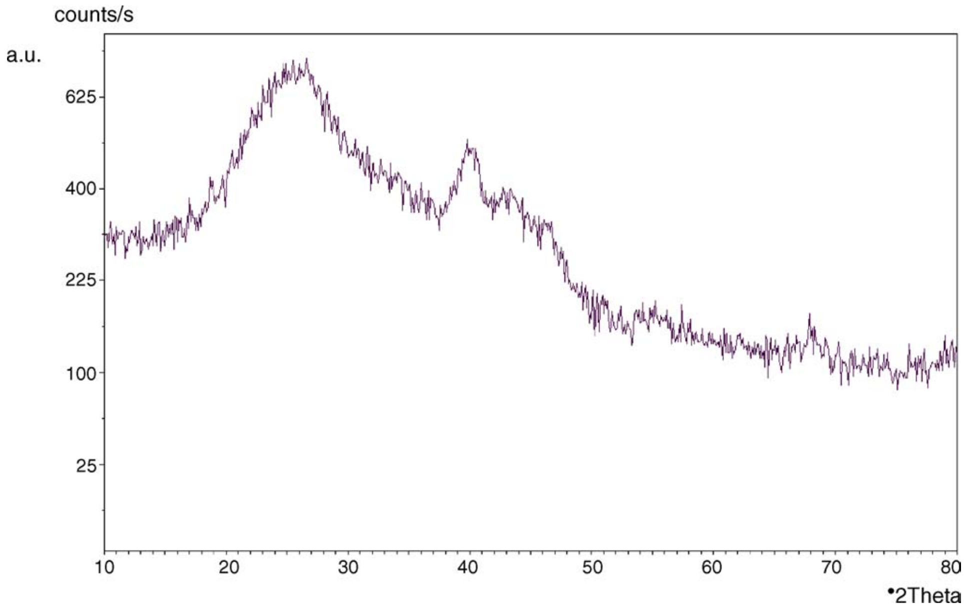

Fig. 3. XRD powder pattern of the 5 wt.% Pd/C catalyst (“5018” Engelhard).

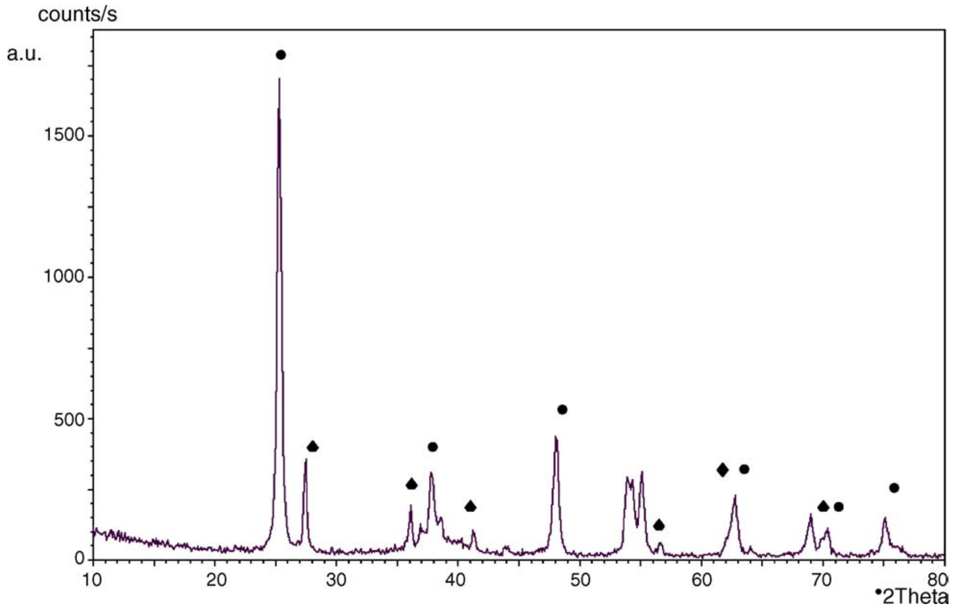

Fig. 4. XRD powder pattern of the 5 wt.% Pd/TiO_2 catalyst (“44258” Engelhard): (●) anatase; (♦) rutile.

anatase and rutile forms, with distinct anatase (reference code 04-0477 JCPDS) and rutile (reference code 76-01317 JCPDS) reflections. Also the XRD pattern of the Pd/C catalyst (Fig. 4) showed the typical reflections (reference code 87-0643 JCPDS) for the C support in graphitic form ($2\theta \approx 26^\circ$ and 44°) and Pd (reference code 01-1310 JCPDS) ($2\theta = 39^\circ$, 46° and 67°) [17].

4. Conclusions

Upon studying the correlation among the catalyst properties, the conversion, TON and e.e. values obtained, we may conclude that none of the chemical–physical properties alone would be able to determine the high enantioselectivity and activity of the catalyst, but, rather, there must be an especially balanced mix of these specifications.

However, of significant importance seems to be the size of the Pd clusters influencing the total or partial covering of the catalytic surface by the modifier (optimum range of the Pd diameter could be between 5.0 and 7.0 nm). Furthermore, the acidity of the support favours the adsorption of cinchonidine, and the stronger this interaction is the more stable the anchoring of the modifier is during the reaction. Work is now in progress with the aim to use or prepare catalysts having fine-tuned specifications.

Acknowledgements

Thanks are due to Engelhard and Johnson Matthey for providing the commercial catalysts and to Mrs. M. Marchiori (University of Venice) for technical assistance. The financial support by the Ministero per l'Istruzione, l'Università e la Ricerca (MIUR, Roma) is gratefully acknowledged.

References

[1] T. Mallat, A. Baiker, Chim. Ind. (Milan) 86 (2004) 110.
[2] H.U. Blaser, Catal. Today 60 (2000) 161.
[3] M. Bartok, G. Szöllösi, K. Balazsik, T. Bartok, J. Mol. Catal. A: Chem. 177 (2002) 299.
[4] K. Borszeky, T. Mallat, A. Baiker, Catal. Lett. 41 (1996) 199.
[5] Y. Nitta, K. Kobiro, Chem. Lett. (1996) 897.
[6] Y. Nitta, T. Kubota, Y. Okamoto, Bull. Chem. Soc. Jpn. 73 (2000) 2635.
[7] Y. Nitta, T. Kubota, Y. Okamoto, Bull. Chem. Soc. Jpn. 74 (2001) 2161.
[8] Y. Nitta, Bull. Chem. Soc. Jpn. 74 (2001) 1971.
[9] K. Borszeky, T. Bürgi, Z. Zhaohui, T. Mallat, A. Baiker, J. Catal. 187 (1999) 160.
[10] K. Borszeky, T. Mallat, A. Baiker, Catal. Lett. 59 (1999) 95.
[11] T.J. Hall, P. Johnston, W.A.H. Vermeer, S.R. Watson, P.B. Wells, in: J.W. Hightower, W.N. Delgass, E. Iglesia, A.T. Bell (Eds.), 11th International Congress on Catalysis Studies in Surface Science and Catalysis, vol. 101, Elsevier, Amsterdam, 1996, p. 221.
[12] R. Strobel, F. Krumeich, W. Stark, S. Pratsinis, A. Baiker, J. Catal. 222 (2004) 307.
[13] T. Yoshida, K. Harada, Bull. Chem. Soc. Jpn. 44 (1971) 106.
[14] S.P. Griffiths, P. Johnston, P.B. Wells, Appl. Catal. A: Gen. 191 (2000) 193.
[15] R. Bisignani, S. Franceschini, O. Piccolo, A. Vaccari, J. Mol. Catal. A: Chem. 232 (2005) 161.
[16] Advanced Chemistry Development (ACD) Software Solaris V4 (1994–2004), www.scifinder.scholar.com.
[17] Diffraction File Inorganic Phases Powder, The International Centre for Diffraction Data, Park Lane, U.S.A., 1991.