Preparation of benzylamine by highly selective reductive amination of benzaldehyde over Ru on an acidic activated carbon support as the catalyst

Silvia Gomez[a], Joop A. Peters[a], Jan C. van der Waal[a,b], Wuzong Zhou[c] and Thomas Maschmeyer[a,*]
[a] *Laboratory of Applied Organic Chemistry and Catalysis, DelftChemTech, Delft University of Technology, Julianalaan 136, 2628 BL, Delft, The Netherlands*
[b] *Avantium Technologies B.V., Zekeringstraat 29, 1014 BV, P.O. Box 2915, 1000 CX Amsterdam, The Netherlands*
[c] *School of Chemistry, University of St. Andrews, St. Andrews, Fife KY16 9ST, United Kingdom*

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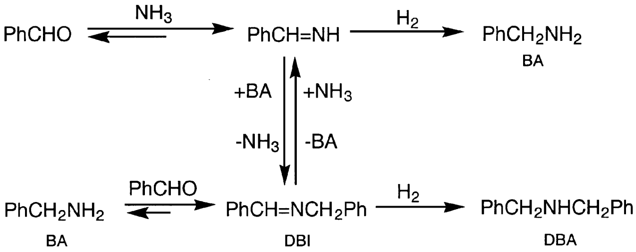
Ruthenium supported on activated carbon, on which acidic groups were introduced by pre-treatment with $(NH_4)_2S_2O_8$, is a highly active and selective catalyst for the synthesis of benzylamine *via* the reductive amination of benzaldehyde.

KEY WORDS: benzaldehyde; reductive amination; supported catalysts; ruthenium; selectivity.

1. Introduction

Both benzylamine (BA) and dibenzylamine (DBA) are industrially interesting compounds with applications in rubber compounding, as corrosion inhibitors and as intermediates in the pharmaceutical industry. These compounds can be synthesized by the reductive amination of benzaldehyde with ammonia [1–4]. Primary, secondary and tertiary amines may be formed during this reaction. In addition, benzyl alcohol and toluene, resulting from the direct hydrogenation of benzaldehyde, may be obtained (scheme 1). Although it is obvious that the selectivity towards either BA or DBA can partly be controlled by the molar ratio of benzaldehyde and ammonia applied in the reaction, this alone does not make the system sufficiently selective.



Scheme 1. Mechanism of the reductive amination of benzaldehyde with ammonia.

Furthermore, the conversion and selectivity are strongly dependent on the choice of the catalyst. Raney Ni was commonly applied as a catalyst for the reductive amination of benzaldehyde in the presence of ammonia [1,2]. However, it has various disadvantages, including the relatively low selectivity. Supported or unsupported noble metal catalysts are more resistant and allow milder reaction conditions than Raney Ni [3–5]. At present, Pd/C is the most frequently used catalyst for the preparation of DBA [6]. Recently, it has been shown that the introduction of carboxylic acid sites on the supporting carbon by oxidation with peroxydisulfate results in a significant increase in the reactivity of this catalyst [7]. This could be attributed to the acid-catalysis of the imine homogeneous equilibria formation, to a decrease in the concentration of the *gem*-diamine inhibiting intermediates and/or to a higher metal surface area and metal dispersion in the catalyst (due to the fact that the new surface functional groups can exchange protons with cationic metal complexes in the impregnation and reduction processes during the preparation of the catalyst).

Herein, we report the use of Ru on a pre-oxidized carbon support as the catalyst for the reductive amination of benzaldehyde with ammonia. With this catalyst, a fully selective synthesis of BA is achieved in a short reaction time. A mechanism that may explain the observed high selectivity of this catalyst will be discussed.

2. Experimental

Benzaldehyde was purchased from Fluka Chemie AG (Buchs, Switzerland). Benzylamine, dibenzylamine, $Pd(NH_3)_4Cl_2{\cdot}H_2O$ and $RuCl_3{\cdot}2.5H_2O$ were obtained from Aldrich (Milwaukee, USA). $(NH_4)_2S_2O_8$ was obtained from Merck KGaA (Darmstadt, Germany). The steam-activated peat-based carbon SX1G was a gift

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[*] To whom correspondence should be addressed.

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from Norit N.V. (Amersfoort, The Netherlands). The 5 wt% Ru/C off-the-shelf catalyst was a gift from Engelhard Italiana S.p.A. (Rome, Italy).

2.1. Carbon-support preparation

The carbon support was prepared by oxidation of the steam-activated peat-based carbon SX1G with $(NH_4)_2S_2O_8$ using the procedure described previously [7]. The carbon treated in this way is denoted as C^{ox}.

2.2. Catalyst preparation

The catalysts were prepared by incipient wetness impregnation of C^{ox} (0.95 g) with aqueous solutions of $Pd(NH_3)_4Cl_2 \cdot H_2O$ (127 mg, 2 ml H_2O) or $RuCl_3 \cdot 2.5H_2O$ (110 mg, 2 ml H_2O), followed by reduction under a 10% H_2/N_2 flow (2 h) at 150 and 350 °C, respectively. The catalysts prepared in this way are denoted as Pd/C^{ox} and Ru/C^{ox}.

2.3. Catalytic reactions

2.3.1. Reductive amination of benzaldehyde with ammonia

A 6.6 M ammonia solution in MeOH (23 ml) was introduced into a 160 ml Parr 4842 autoclave, made of Hastelloy C276. Methanol (57 ml), the catalyst (0.017 g) and benzaldehyde (1.0 g) were added. The reaction mixture was heated to the desired temperature under an N_2 atmosphere and, after 1 h, the H_2 pressure was applied. The experiments were performed at 90 °C and 40 bar H_2. Samples taken during the reaction were analyzed with a Varian Star 3400 gas chromatograph (CP Sil-5 CB column) applying a temperature gradient from 50 to 300 °C.

2.3.2. Hydrogenation of dibenzylimine in the absence of ammonia

Dibenzylimine was prepared from benzaldehyde and benzylamine according to the procedure of O'Donnell *et al.* [8]. The hydrogenation of dibenzylimine was performed in the autoclave described under 2.3.1. Methanol (80 ml), the catalyst (0.017 g) and dibenzylimine (0.9 g) were introduced into the autoclave. The mixture was heated to 90 °C and 40 bar H_2 were applied.

2.4. Catalyst characterization

Pd/C^{ox} and Ru/C^{ox} were characterized by FT-IR, High Resolution Transmission Electron Microscopy (HRTEM), X-ray Diffraction (XRD) and N_2 adsorption.

Transmission infrared spectra were recorded with a Perkin Elmer Spectrum One FT-IR spectrometer and used to study the surface chemistry of the samples. The spectra were obtained by co-addition of 16 scans with a resolution of 4 cm^{-1}. The original spectra were corrected with a curved baseline, using the Perkin Elmer software routine for strongly scattering samples. KBr tablets were used, containing 2 mg of carbon in 250 mg KBr.

The particle diameter and the dispersion of Pd and Ru were studied by HRTEM, which was carried out on a Jeol JEM-2010 electron microscope operating at 200 KeV. To prepare a specimen for the HRTEM studies, the powder sample was dispersed in acetone by an ultrasonic treatment. One drop of the suspension was added on a holey carbon film supported on a copper grid and allowed to dry in air before being transferred into the microscope. The HRTEM images were recorded at magnifications of 800 000× or 1 000 000× using a Gatan 794 CCD camera. Chemical compositions of the particles were examined by Energy Dispersive X-ray microanalysis (EDX) using the Oxford Link ISIS system.

The size of the metallic particles was also estimated by XRD, which was performed on a Bruker D5005 θ–θ diffractometer equipped with a diffracted-beam graphite monochromator, wavelength Cu K_α. The measurement range was 20–90 °2θ, the stepsize 0.1 °2θ and the counting time 8 s. Together with some ethanol, the sample was slightly ground in a mortar. From the resulting slurry, a layer with a weight of *ca* 10 mg and a diameter of *ca* 20 mm was applied to a substrate. The substrate consisted of a single-crystal silicon wafer with orientation ⟨510⟩, which showed no reflections and only a very low background intensity in the measurements.

N_2 adsorption was used to study the effect of the oxidation treatments on the pore structure of the carbons. Prior to the analysis, Pd and Ru samples were dried under vacuum at 120 °C and 150 °C, respectively. After drying, the N_2 adsorption and desorption isotherms were measured at 77 K on a Quantachrome Autosorb-6B.

3. Results and discussion

3.1. Catalytic measurements

It is clear that many parameters are involved in these reactions and, therefore, we approached the system initially *via* a high-throughput screening of catalysts for reductive amination of benzaldehyde with ammonia [9]. The library of 24 catalysts applied in this study was constructed from four different carbons modified by different oxidative treatments. The noble metals selected for this study were Pd, Pt and Ru. In addition, a set of catalysts was prepared using the same noble metals but now with either 1 wt% Sn or 1 wt% Bi as additives. The reactions were carried out in an array of 24 autoclaves of 3 ml working volume under 30 bar H_2, at

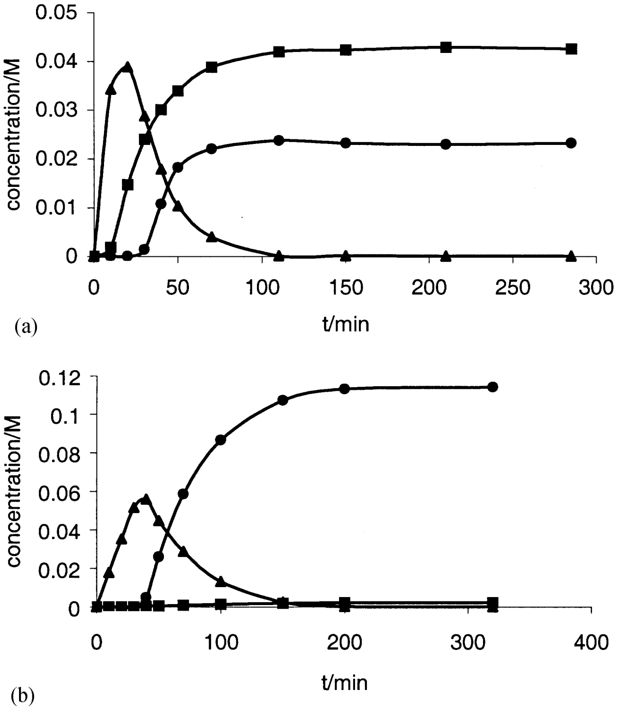

Figure 1. Concentration of BA (●), DBA (■) and DBI (▲) as a function of time in a conventional reaction testing, in which the ratio of ammonia/benzaldehyde is 16 when (a) Pd/C^{ox} and (b) Ru/C^{ox} are used as catalysts for the reductive amination of benzaldehyde with ammonia.

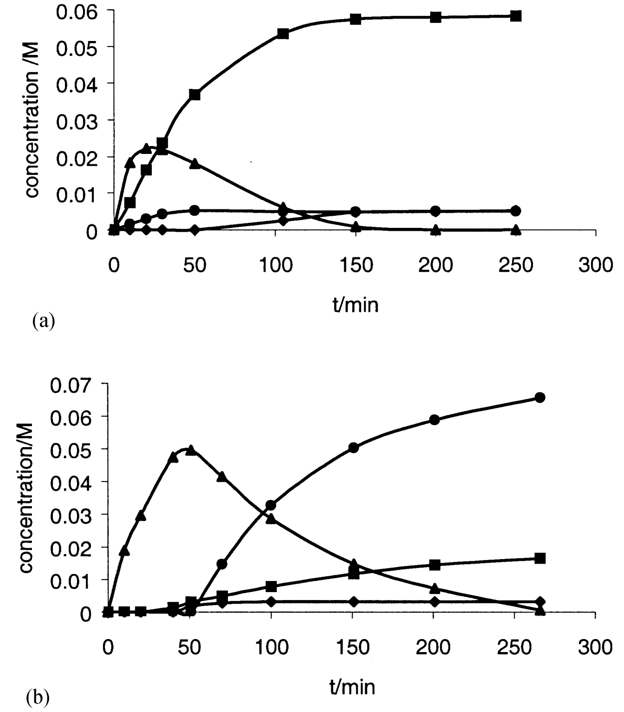

Figure 2. Concentration of BA (●), DBA (■), benzyl alcohol (◆) and DBI (▲) as a function of time in a conventional reaction testing, in which the ratio of ammonia/benzaldehyde is 2 when (a) Pd/C^{ox} and (b) Ru/C^{ox} are used as catalysts for the reductive amination of benzaldehyde with ammonia.

90 °C, with methanol as the solvent and a molar ratio of ammonia/benzaldehyde = 16/1. The large excess of ammonia applied in the high-throughput experiments should bring about a high selectivity towards BA, hence highlighting any selectivity towards DBA.

5 wt% Pd on activated carbon, pre-treated with $(NH_4)_2S_2O_8$, turned out to be the most favorable catalyst for the synthesis of DBA. Surprisingly, the same set of experiments indicated that 5 wt% Ru on the same oxidized carbon support is an extremely active and selective catalyst for conversion toward BA. The activity and selectivity of the catalysts appeared not to be affected by the presence of Sn or Bi.

The most promising catalysts were re-tested by conventional methods using rigorous stirring because the high-throughput protocol presented mass-transfer limitation problems. With the 5 wt% Ru catalyst, almost 100% selectivity toward BA was achieved under reaction conditions identical to those applied with the 5 wt% Pd catalyst (90 °C, 40 bar H_2, molar ratio of ammonia/benzaldehyde = 16/1, in methanol as the solvent).

Figure 1 shows the concentration of BA, DBA and DBI as a function of time for two conventional one-at-a-time reactions, using a molar ratio of ammonia/benzaldehyde = 16/1, with Pd/C^{ox} (a) and Ru/C^{ox} (b) as the catalysts. In both cases, no side-products were detected. With Pd/C^{ox}, 65% DBA and 35% BA were obtained after total conversion, whereas 98% BA and only 2% DBA were the final products of the reaction with Ru/C^{ox}.

The performance of both catalysts was also studied with a ratio of ammonia/benzaldehyde of 2 so as to emphasize any selectivity toward BA (figure 2). Interestingly, Ru/C^{ox} appeared to be very selective to BA even though the reaction conditions for its formation were much less favorable. At total conversion, the reaction mixture consisted of 77% BA, 19% DBA and 4% benzyl alcohol. Under identical conditions, Pd/C^{ox} displayed, as expected, a very high selectivity toward DBA, resulting in 85% DBA, 7.5% BA and 7.5% benzyl alcohol.

3.2. *FT-IR study*

The ratio between the intensity of the band at $1720\,cm^{-1}$ (C=O stretching vibrations of aryl acids [10]) and the band at $1580\,cm^{-1}$ (aromatic bonds polarized by ether-like bonds [11]) in the FT-IR spectra is 0.25 and 0.2 for Pd/C^{ox} and Ru/C^{ox}, respectively, which indicates that the amount of non-ionized carboxylic groups on the surface of the carbons is about 0.5 and 0.4 eq/g carbon [12]. For Ru/C^{ox}, this number is lower because the reduction temperature during the catalyst preparation was higher (350 °C) than in the case of Pd/C^{ox} (150 °C). The loss of carboxylic acid groups upon applying high temperatures has been reported previously [7].

3.3. HRTEM study

Figure 3 shows an HRTEM image of Ru/C^{ox}, revealing the presence of very small Ru particles, approximately 2 nm in size. The particles are highly dispersed and their size distribution is very narrow. Similarly, it has been observed that the particle size of the Pd-catalyst is 12–18 nm.

3.4. XRD study

XRD analysis was in accord with the results observed by HRTEM. Pd/C^{ox} clearly showed Pd reflections. A rough estimation of the mean particle size gave a value between 12 and 18 nm. Ru/C^{ox}, on the contrary, did not show Ru reflections, which indicated that the particle size was much smaller (at least five times) than the abovementioned for the Pd particles. In this case, the presence of the support made the detection of the broad Ru reflections difficult.

3.5. N_2 adsorption study

The BET surface area and the total pore volume for Pd/C^{ox} and Ru/C^{ox} were obtained from the N_2 adsorption and desorption isotherms, which showed a combined type I and IV behavior, indicative of combined microporosity and meso-macroporosity. Pd/C^{ox} displayed an S_{BET} of 745 m^2/g and a pore volume of 0.57 cm^3/g, whereas an S_{BET} of 858 m^2/g and a pore volume of 0.65 cm^3/g were obtained for Ru/C^{ox}.

3.6. Mechanistic causes of the different selectivity of Pd/C^{ox} and Ru/C^{ox}

Ru/C has found very little application in reductive amination processes because, in most cases, only reduction of the aldehyde or the ketone to the alcohol or hydrogenation of the aromatic ring (in the case of aromatic substrates) takes place [3,13]. In the case under study, 5 wt% Ru/C^{ox} is a highly active and selective catalyst (no benzyl alcohol, toluene or any other side-product were detected). Even under more unfavorable conditions for the synthesis of the primary amine (molar ratio of ammonia/benzaldehyde = 2/1), the catalyst is very selective.

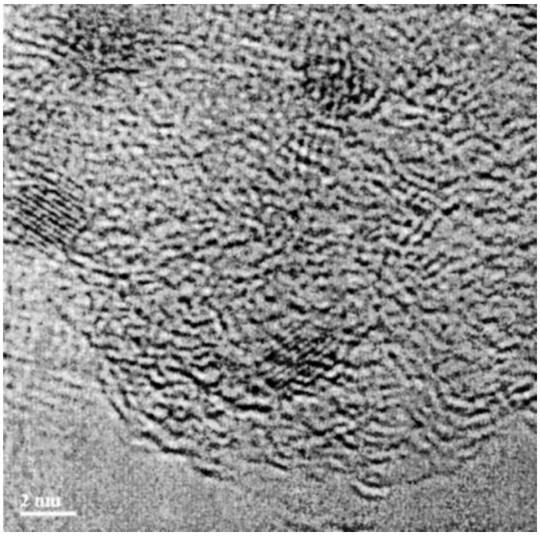

Figure 3. HRTEM micrograph of Ru/C^{ox}.

Comparison of the results obtained with Ru/C^{ox} and Pd/C^{ox} suggests that the selectivity is modulated by the nature of the metal. To support this conclusion, a 5 wt% Ru/C off-the-shelf catalyst was used as a reference. The support was not pre-treated, as confirmed by FT-IR, and the HRTEM analysis displayed Ru clusters, which were larger than 2 nm and very poorly dispersed. This catalyst showed much lower activity but exactly the same selectivity as Ru/C^{ox} in the reductive amination of benzaldehyde with ammonia, hence confirming that the support merely helps to increase the metal dispersion and does not have any significant effect on the selectivity. The fact that the off-the-shelf catalyst contained larger metallic particles than Ru/C^{ox} also ruled out that the difference in selectivity between Ru/C^{ox} and Pd/C^{ox} is due to the difference in the particle size.

The intermediate of the reaction, DBI, is formed at about the same rate and in about the same amount with Ru/C^{ox} and Pd/C^{ox}. Therefore, we suggest that this intermediate has a different behavior toward the two catalysts used. Considering that the chemistry in the liquid phase is independent of the catalyst, we would assume that Ru/C^{ox} is not capable of hydrogenating DBI. Therefore, it most likely desorbs easily from the catalyst to undergo a transimination to benzylimine and BA in solution (see scheme 1), followed by hydrogenation of the former product to BA. In the case of Pd/C^{ox}, on the contrary, DBI would be very reactive toward hydrogenation.

The location of the reaction steps (in the liquid phase or at the surface of the catalyst) is still a matter of challenging research. If we would consider that not only the hydrogenation but also the transimination process occur at the surface of the catalyst, it could also be presumed that Ru/C^{ox} catalyzes both the transimination of DBI and the subsequent hydrogenation of the resulting benzylimine, rather than the direct hydrogenation of DBI to DBA.

Investigations were carried out in order to shed some light on this issue. Le Bris *et al.* observed that, in the reductive amination of acetone with ammonia and an Ni catalyst, isopropylamine is the main product while diisopropylamine is formed nearly exclusively when using a Pt catalyst. It was concluded that Ni is not capable of hydrogenating the secondary imine in the presence of acetone and, therefore, yields selective isopropylamine. When studying the hydrogenation of the secondary imine separately, it was noted that Ni is

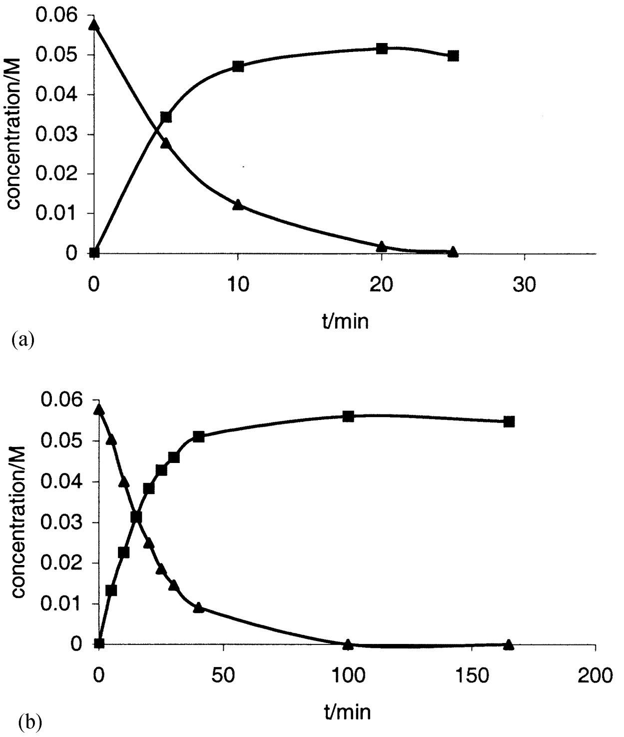

Figure 4. Concentration of DBI (▲) and DBA (■) as a function of time in conventional reaction testing, in the absence of ammonia, when (a) Pd/C^{ox} and (b) Ru/C^{ox} are used as catalysts for the hydrogenation of DBI.

much less effective than Pt for yielding diisopropylamine, in complete agreement with the results obtained from the reductive amination of acetone with ammonia [14].

Following a similar approach, hydrogenation of DBI, in the absence of ammonia, was studied separately (figure 4). Over Pd/C^{ox}, DBI was completely converted to DBA after 20 min of reaction time. With Ru/C^{ox}, however, the reaction was five times slower. This finding confirms that the intermediate DBI adsorbs more readily on the Pd surface. For this reason, it is most likely that DBI undergoes transimination rather than hydrogenation during the Ru/C^{ox} catalyzed reductive amination of benzaldehyde with ammonia.

4. Conclusion

The discovery of the Ru-modified catalysts for the reductive amination of benzaldehyde is of great importance, as it allows a clean synthesis of benzylamine under very mild conditions, with complete conversion of benzaldehyde, in a short reaction time and with excellent selectivity.

Acknowledgments

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