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Control of Pd leaching in Heck reactions of bromoarenes catalyzed by Pd supported on activated carbon

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Abstract

Parameters that influence the palladium leaching during and after Heck reactions of aryl bromides with olefins catalyzed by heterogeneous Pd on activated carbon systems are reported. Pd leaching correlates significantly with the progress of the reaction, the nature of starting materials and products, solvent, base and atmosphere. The Pd concentration in solution is highest at the beginning of the reaction and is reduced when the reaction is finished. Reaction procedures were developed that allow easy and practicable control and minimization of the Pd leaching at the end of the reaction: Pd re-deposition by: (i) increased temperature, (ii) addition of reducing agents and (iii) working under inert conditions. The Pd concentration in solution after the reaction is reduced to 0.05 ppm Pd (μg Pd/g solution). The catalyst meets all demands for practical application: high activity and selectivity under ambient conditions, complete separation (filtration) of Pd from the product mixture, easy recovery of Pd and commercial availability. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The olefination of aryl halides (Heck reaction), one of the most important C–C coupling reactions in organic synthesis [1–3], is mostly catalyzed by palladium complexes in homogeneous solution. Important advantages of this reaction are the broad availability of aryl bromides and chlorides and the tolerance of the reaction for a wide variety of functional groups. During the last years, the development of new highly active Pd complexes allowed the activation and conversion even of aryl chlorides to considerable extent [4–8]. However, homogeneous catalysts suffer from the need of ligands (usually phosphine ligands) which are eventually not easy to handle (e.g. air sensitive basic phosphines) and form a difficult removal of the catalyst from the product. This includes the ligand as well as the expensive precious metal. Several experiments have been reported that deal with the separation of Pd from the reaction mixture [4,9–13].

The issue of catalyst separation and Pd recovery has been tried to overcome by immobilization of Pd catalysts (polymer-supported Pd catalysts [14]) and by the use of heterogeneous Pd catalysts [15,16] (Pd on activated carbon [13,17–19], Pd on metal oxides [20–22], and Pd on zeolites [23]). However, these systems do not reach the excellent activities that are observed with homogeneous catalysts. In addition

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to supported Pd catalysts (mainly Pd/C) often suffer from substantial Pd leaching (e.g. 14% of Pd is leached from Pd/C [24]). Since the use of supported Pd catalysts is motivated by the ease of catalyst separation, Pd leaching is the most important issue. The aim of the present investigations was to control and minimize the Pd content in solution at the end of Heck reactions catalyzed by Pd/activated carbon systems to allow an as complete as possible separation of the noble metal from the reaction mixture.

Pd/C catalyzes Heck reactions of aryl iodides as published by Arai and coworkers [17]. In the case of aryl bromides low activities and dehalogenation were found by these authors. However, Pd/activated carbon catalysts were also reported recently to convert non-activated and deactivated aryl bromides with very high activity and selectivity to the Heck coupling products [25,26]. (This optimized Pd/C system will be the subject of the present studies about leaching control and minimization.) Besides Heck coupling, very promising results about Suzuki cross coupling reactions catalyzed by Pd/C have been reported recently [27,28].

Whereas the catalytic performance in the Heck reaction of the catalysts has been studied in several papers thoroughly, less attention was paid to Pd leaching and the understanding of the parameters that affect this unwanted precious metal loss. Besides the problems arising for catalyst separation, Pd leaching is also closely related to questions concerning the mechanism of Pd/C catalyzed Heck couplings. Several papers discuss mechanistic aspects of Pd/C catalyzed Heck couplings since it is yet undecided whether the reaction takes place on the solid Pd surface [27,29] or the true catalysts are dissolved Pd colloids [30,31] or complexes that have been leached from Pd/C which acts just as a reservoir of Pd [18,22,32].

Starting from a detailed study of the parameters that influence the palladium concentration in solution during and after the Heck reaction of arylbromides catalyzed by highly active Pd/C systems, the present paper reports for the first time easily practicable methods to control and minimize the Pd leaching at the end of the reaction (Pd re-deposition). The findings made it possible to tune the Pd concentration in solution after the reaction down to 0.05 ppm Pd and allowed the practically complete separation of the precious metal after Pd/C catalyzed Heck reactions.

2. Experimental

2.1. Catalyst preparation

The 5 wt.% Pd on activated carbon catalyst (Degussa nomenclature: E 105 CA/W 5% Pd) was prepared using H_2PdCl_4 at a constant Pd loading of 5 wt.% [33,34]. The support material (specific surface area by BET 1120 m^2/g; mean grain size 23 μm) was first suspended in distilled water. Then an aqueous solution of the Pd compound was added. After impregnation and heating to 80 °C the suspension was adjusted to pH 10 by adding sodium hydroxide. After further agitation the slurry was filtered and washed with distilled water.

2.2. Procedures for catalytic tests

2.2.1. General

Preparations and manipulations were performed in ambient atmosphere. The catalytic reactions were carried out in pressure tubes in air or under argon. All reactants and solvents were obtained from Sigma–Aldrich/Fluka or Merck (grade p.a.) and were used as-received without further purification or drying. The qualitative and quantitative analysis of the reactants and products was performed by gas-liquid chromatography (GLC) and GC–MS, respectively. Products were identified by comparison with authentic samples. Conversion and selectivity are represented as product distribution (=relative area of GLC signals) and GLC yields (=relative area of GLC signals referred to an internal standard calibrated to the corresponding pure compound, $\Delta_{rel} < \pm 10\%$).

2.2.2. Catalytic tests

The 10 mmol bromoarene, 15 mmol styrene, 12 mmol base (usually sodium acetate), 500 mg diethylene glycol–*n*-butylether (as internal standard for GC analysis) and 0.005–1.0 mol% of Pd as heterogeneous catalyst were introduced in a pressure tube. The 10 ml of solvent (usually *N*,*N*-dimethylacetamide (DMAc) or *N*-methylpyrrolidone (NMP)) were added. For experiments with a palladium content of 0.005 mol%, 20 mmol bromobenzene, 30 mmol styrene, 24 mmol sodium acetate, 1 g diethylene glycol–*n*-butylether and 20 ml NMP were used. The mixture was optionally de-aerated by purging with argon for 5 min. The reactor was placed in a pre-heated oil bath at reaction temperature (60–160 °C) with vigorous stirring of the reaction mixture. After the reaction has completed a small sample of the reaction mixture was collected for GLC analysis and the remaining reaction mixture is separated by hot filtration (near reaction temperature). A sample was taken from the filtrate for Pd analysis. For the GLC analyses the sample (1 ml) taken from the reaction mixture was quenched with 2 ml water in a test tube. This mixture was extracted with 2 ml of methylene chloride, the organic layer was filtered and dried over $MgSO_4$. The resulting dry organic layer was analyzed by GLC or GC–MS. The gas-liquid chromatograms were recorded on a chromatograph HP 6890 series equipped with an FID detector and a HP-1 column (cross-linked methylsiloxane, $30\,m \times 0.25\,mm \times 0.25\,\mu m$ film thickness). GC–MS analysis was performed on a HP 5890 instrument with a HP 5970 mass detector and a HP-1 column.

For investigations of activity and Pd leaching as a function of reaction time 200 mmol bromobenzene, 240 mmol sodium acetate or sodium formiate, 10 g diethylene glycol–*n*-butylether and 1.0 mol% Pd (4.26 g Pd/C catalyst) were introduced with 200 ml DMAc in a three-necked flask (500 ml) equipped with a septum and a reflux condenser. After the mixture was de-aerated by purging with argon for 20 min, the reactor was placed in a pre-heated oil bath at reaction temperature (140 °C) with vigorous stirring of the reaction mixture. Starting 60 min (20 min with sodium formiate) after the reaction temperature has reached 140 °C inside the flask, 300 mmol styrene were added. The 8 ml of the reaction mixture were taken in defined time intervals and analyzed by GLC as well as by inductively coupled plasma-optical emission spectroscopy (ICP-OES) or inductively coupled plasma-mass spectroscopy (ICP-MS) for the Pd content in solution.

2.3. Investigation of Pd leaching

For the determination of the Pd content in solution a maximum amount of the clear filtrate was collected for precise Pd analysis (usually half of the reaction mixture, i.e. 4–5 ml). The defined amount of the clear filtrate was collected in a glass vessel immediately after hot filtration. After careful evaporation of the organic compounds the sample was dissolved by aqua regia, diluted and the solution was filtered and analyzed by atomic spectroscopy (ICP-OES or ICP-MS). Multiple analyses were applied for each sample for better accuracy. The palladium content in solution was determined by ICP-OES on a Perkin Elmer Optima 3300 DV spectrograph and ICP-MS by a VG Elemental Plasmaquad 2 + spectrograph.

2.4. TEM investigations

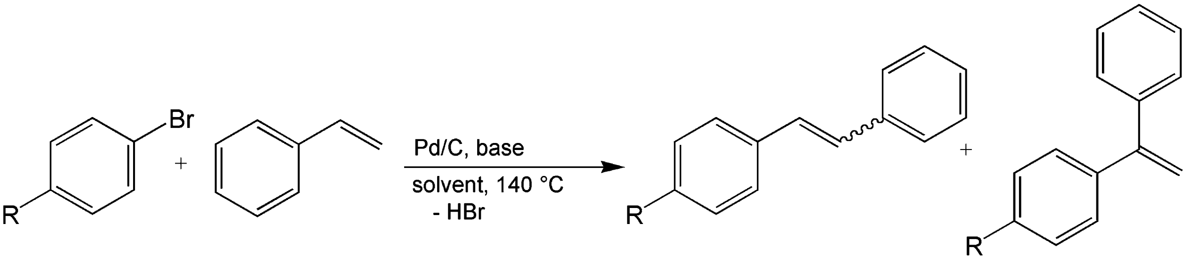
The fresh Pd/C catalyst and a sample of the used one (after Heck reaction) were studied by transmission electron microscopy (TEM). The used catalyst was washed with methylene chloride and water to remove organic compounds like *E*-stilbene and inorganic compounds like base or sodium bromide. The investigations were carried out on a Hitachi H 500 H microscope.

3. Results and discussions

3.1. Correlation of reaction parameters with Pd leaching (and activity)

According to the focus of the investigations, i.e. to control and minimize the Pd content in solution at the end of the reaction and to allow an as complete as possible separation of the noble metal from the reaction mixture, the influence of various reaction parameters on the Pd leaching was studied first. An optimized Pd/activated carbon catalyst, which was recently reported to convert non-activated and deactivated aryl bromides with very high activity and selectivity to the Heck coupling products [25,26] has been chosen for the studies. The catalyst is characterized by high Pd dispersion (36%), low Pd reduction degree (about 100% Pd(II)) and a high water content (>50 wt.%) [25,26]. The catalyst was used without thermal treatment and reduction. In addition to the catalytic activity and selectivity, the Pd content in solution was determined after hot filtration of the solid catalyst at the end of the reaction for each experiment.

In a first series of experiments, the Pd/C catalysts were tested in the Heck coupling of bromobenzene and of *p*-bromoacetophenone with styrene (Scheme 1, R = H, $COCH_3$) varying the parameters: solvent, reaction temperature, Pd amount (mol%) and base.



1 **2**

R = H, OCH_3, $COCH_3$

E- und *Z*-isomers
respectively **3** and **4**

5

Scheme 1. Heck coupling of bromoarenes with styrene.

The Pd/activated carbon catalyst studied converts bromobenzene with high yields without dehalogenation (Table 1, entry 1; conversion 92% in the coupling of bromobenzene with styrene, 20 h, sodium acetate, DMAc). This is in contrast to Arai and coworkers [17] where up to 80% of benzene formation via dehalogenation was observed.

The most pronounced influence of the reaction temperature on the Pd concentration in solution is found in the Heck reaction of *p*-bromoacetophenone and styrene. As expected, activated bromoarenes as *p*-bromoacetophenone can be converted at lower temperatures than non-activated ones like bromobenzene (Table 1, entries 1 and 3). At reaction temperatures as low as 80 °C *p*-bromoacetophenone was converted almost quantitatively showing the highest Pd leaching of 18 ppm (entry 3). At higher temperatures (>80 °C) the Pd content in solution is reduced to 0.8 ppm (entries 4 and 5) with quantitative conversion. No Heck coupling product was found at 60 °C (entry 2) and almost no Pd leaching was detected. The decrease in Pd leaching at higher temperatures was confirmed in the coupling of bromobenzene with styrene (Table 1, entries 6 and 7). At 140 °C the Pd

Table 1
Variation of reaction conditions: Heck coupling of different bromoarenes with styrene (Scheme 1; R = $COCH_3$, H)[a]

Entry	R	Catalyst (mol% Pd)	Solvent	Base	*T* (°C)	Pd fraction in solution[b] (%)	Pd in solution[c] (ppm)	Conversion[d] (%)	Yield **3**[d] (%)
1	H	1.0	DMAc	NaOAc	140	0.4	3.1	92	83
2	$COCH_3$	0.1	DMAc	NaOAc	60	0.5	0.3	7	6
3	$COCH_3$	0.1	DMAc	NaOAc	80	21.9	17.8	98	93
4	$COCH_3$	0.1	DMAc	NaOAc	100	1.1	0.8	100	95
5	$COCH_3$	0.1	DMAc	NaOAc	120	1.0	0.8	100	95
6	H	0.1	DMAc	NaOAc	160	1.1	0.9	69	62
7	H	0.1	DMAc	NaOAc	140	1.9	1.6	87	77
8	H	0.1	Toluene	NaOAc	140	0.5	0.4	0	0
9	H	0.1	NMP	NaOAc	140	1.8	1.5	99	91
10[e]	$COCH_3$	0.1	DMAc	NaOAc	100	26.3	20.0	100	94
11	H	0.2	NMP	NaOAc	140	0.3	0.5	96	86
12	H	0.2	NMP	$^{n}Bu_3N$	140	0.3	0.5	35	30
13	H	1.0	DMAc	$NaHCO_2$	140	0.05	0.4	81	23[f]

[a] Reaction conditions: bromoarene, styrene, base, solvent, 0.10–1.0 mol% Pd; $T = 60$–$160\,^{\circ}C$, $t = 20\,h$.
[b] Pd in solution/total amount of Pd introduced.
[c] Pd in solution/total amount of solution.
[d] Conversion of bromoarenes and yields of product **3** from GLC analysis.
[e] Without exclusion of air (no purging with argon).
[f] Small yield of **3** due to dominating dehalogenation and homo-coupling.

content in solution was found to be 1.6 ppm compared to 0.9 ppm at 160 °C. A first tentative interpretation of the interdependence of reaction temperature and Pd leaching might result from (catalytically active) species in solution that are less stable (soluble) at higher temperatures (such as 160 °C) resulting in a decreased Pd leaching.

The choice of the solvent also effects the Pd content in solution at the end of the reaction. In the coupling of bromobenzene and styrene, DMAc, NMP and toluene were selected as solvents. The Pd content in solution (1.5 ppm, Table 1, entries 7 and 9) was the same for the solvents NMP and DMAc, whereby an increase in catalytic activity was observed for NMP (conversion 99%, compared to 87% in DMAc). Almost no leaching (0.4 ppm) was detected performing Heck reactions in toluene (or THF, 1,4-dioxane, not shown) but also no catalytic activity was found (Table 1, entry 8). This indicates that Pd in solution actually is the catalytically active species under the conditions used. The influence of the solvent is again most pronounced for the reaction of *p*-bromoacetophenone (both NMP and DMAc resulted in high Pd dissolution from the support: 22% for NMP and 26% for DMAc, respectively, not shown).

For the Pd/C catalysts investigated here, almost no influence of the atmosphere (argon or air over the reaction mixture) on catalytic activity was observed. However, a significant difference in Pd leaching was detected when argon or air were used for the reaction of *p*-bromoacetophenone with styrene. Without exclusion of air about 26% of the total palladium amount were lost from the catalyst and found in solution (20 ppm Pd) compared to 1.1% under argon atmosphere (Table 1, entries 10 and 4).

A significant correlation of the catalytic activity and the base was found: higher activities were obtained using sodium acetate compared to other bases like amines. In the reaction of bromobenzene with styrene conversions up to 98% using sodium acetate were obtained compared to 36% for tributylamine under identical reaction conditions (Table 1, entries 11 and 12). The Pd content in solution was the same for both bases. Significantly lower Pd leaching (0.05%) was observed for the reducing base sodium formiate (Table 1, entry 13). However, the selectivity is dramatically decreased in this reaction: dehalogenation (formation of benzene) and aryl–aryl coupling (formation of biphenyl) are the dominating reactions.

The palladium concentration in solution was not affected by the filter-type used for catalyst separation. This is connected with the excellent filterability of the carbon support used (optimized particle size distribution, attrition resistance, morphology).

In summary, the Pd concentration in solution correlates with the nature of the starting materials and products, the temperature, the solvent, the base and the atmosphere (argon or air). Lower temperatures, higher concentrations and stronger interactions of the bromoarenes with Pd(0) clearly increase Pd leaching. Higher temperatures seem to favor (re-)precipitation. *p*-Bromoacetophenone is known to be a more oxidizing species, i.e. oxidative additions to Pd(0) surface species proceeds more readily than, e.g. by bromobenzene due to the electron withdrawing nature of the acetyl substituent. These observations are thus in agreement with results and interpretations of Biffis et al. [22], who showed that dissolution of Pd from solid catalysts is due to an oxidative attack to the metal. In addition, *p*-bromoacetophenone is expected to form more stable complexes with Pd(II) after oxidative addition in solution [35].

For complete Pd separation after the reaction, the parameters atmosphere, temperature and (reducing) base are useful to minimize the Pd leaching. In addition, the reduction of the absolute amount of Pd catalyst could be interesting. In fact, the high catalytic activity of the Pd/C catalysts allowed to decrease the typical Pd amount down to 0.01 mol% keeping the catalytic activity at the same high level. Corresponding investigations are reported in Section 3.3.

3.2. *Pd leaching during the reaction*

All determinations of the Pd concentration in solution described above were performed after hot filtration of the solid catalyst from the reaction mixture at the end of the reaction (after 20 h). However, it is important to understand how the catalytic reaction proceeds by determination of the Pd concentration in solution during the reaction at a given time and to correlate this with the corresponding catalytic activity.

Therefore, 25 samples of the reaction mixture were taken during the reaction of bromobenzene and styrene and analyzed by GLC as well as by ICP-OES (to

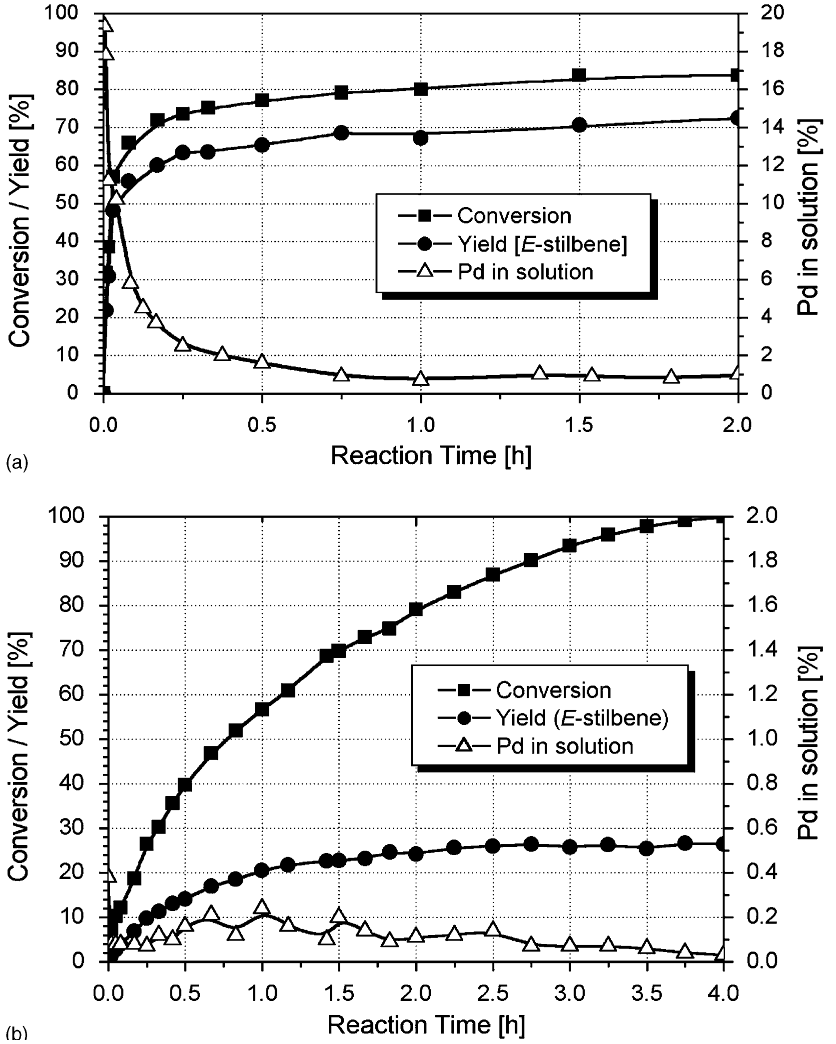


Fig. 1. Kinetic investigations of activity and Pd leaching: Heck coupling of bromobenzene with styrene as a function of reaction time; reaction conditions: (a) 200 mmol bromobenzene, 300 mmol styrene, 240 mmol sodium acetate, 1.0 mol% Pd/C catalyst, 200 ml DMAc; $T = 140\,^{\circ}\mathrm{C}$ (60 min pre-heated before addition of styrene) and (b) 200 mmol bromobenzene, 300 mmol styrene, 240 mmol sodium formiate, 1.0 mol% Pd/C catalyst, 200 ml DMAc; $T = 140\,^{\circ}\mathrm{C}$ (20 min preheated).

ensure higher accuracy in this experiment 1.0 mol% Pd were used; reaction conditions: DMAc, 140 °C and sodium acetate). Fig. 1a shows that the palladium concentration in solution was the highest at the beginning of the reaction (20% of the total palladium content). It is reduced to about 0.3% of the total palladium content when the reaction is finished. The conversion per time decreased to the same extent as the Pd concentration in solution decreased. This supports the hypothesis that Pd in solution is catalytically active in the reaction under study (a distinction between molecular Pd complexes and small clusters is not possible) [18,22,32]. One could also conclude that there is a direct correlation between reaction rate and Pd concentration in solution. However, the conversion–time behavior observed is expected (at least qualitatively) for the Heck reaction independent on the Pd concentration in solution. The obvious analogy of conversion and Pd concentration can also be understood by the influence of the educt concentration on the Pd leaching (educt molecules as potential ligands). In addition, the obvious dissolution–re-precipitation of Pd during the reaction (see also below) should cause a progressive decrease in Pd dispersion and thus a reduced Pd leaching [25,26].

Completely different results were obtained using sodium formiate instead of sodium acetate as base (Fig. 1b). The reaction rate (conversion per time) is still high. However, the yield of *E*-stilbene decreased dramatically to 25% due to dominating dehalogenation and formation of biphenyl (Table 1, entry 13). The palladium content is very low even at the beginning of the reaction (0.4% of the total palladium content) and it is further reduced to 0.02% when the reaction is finished.

Whereas the reduction of the Pd concentration in solution under reducing conditions (formiate) is not surprising, the reduced selectivity (with comparable activity) under these conditions is interesting to discuss: as found by Arai and coworkers [17], dehalogenation is the dominating reaction for Pd on activated carbon with low Pd dispersion. In particular, this is true for higher reaction temperatures (160 °C), where re-precipitation of Pd onto the support is favored as also in the presence of sodium formiate. The observations of Arai and coworkers and of our work indicate that the side reactions (dehalogenation, aryl–aryl coupling) are catalyzed by supported Pd crystallites, i.e. their solid surfaces, whereas the Heck coupling is due to Pd leached into solution.

The reaction is accompanied by Pd dissolution/re-precipitation processes [18]. This mechanism of catalyst evolution is also reflected by TEM investigations of the Pd/C catalyst before and after the reaction (Fig. 2). The fresh catalyst (Fig. 2, top) clearly exhibits a higher Pd dispersion and more uniform distribution than the same catalyst (Fig. 2, bottom) after Heck coupling of bromobenzene and styrene under standard reaction conditions (DMAc, sodium acetate, 140 °C, 20 h). The used catalyst was washed with methylene chloride and water before TEM investigations. The average Pd crystallite size is increased by one order of magnitude from 2.4 to 23 nm. The TEM figures indicate the agglomeration of small primary Pd crystallites to large “grapes” (Fig. 2).

As expected, this dramatic decrease in Pd dispersion during the reaction leads to a significant decrease in catalytic activity when the catalyst is re-used in Heck reactions. This was found in recycling studies [25,26]. For close to complete conversions 20 h or more are necessary making the re-use of the catalyst rather unattractive.

3.3. Control and minimization of Pd leaching

As mentioned above (Table 1, entries 7 and 9) palladium in solution is found to be about 2% of the total palladium content (for palladium concentrations of 0.1 mol%) in Heck reactions of bromobenzene with styrene under standard reaction conditions (NMP, sodium acetate, 140 °C) after 20 h. After 4 h under identical reaction conditions (NMP, sodium acetate and 140 °C) and with further decreased palladium concentration to 0.01 mol% Pd, 24% of the total palladium content was found in solution in Heck coupling of bromobenzene with styrene (Table 2).

In order to reduce the Pd leaching, the Heck reaction was performed at optimized reaction conditions until (almost) quantitative conversion followed by conditions favoring re-precipitation onto the carbon support. Palladium in solution was found to be re-precipitated after longer reaction times and complete conversion (Fig. 1a), by higher reaction temperatures (Table 1, entries 2–7), by exclusion of air/oxygen (purging with argon; Table 1, entries 4 and 10) and by the use of reducing agents like sodium formiate (Table 1, entry 13 and Fig. 1b). Due to the correlation of reaction atmosphere and Pd leaching all further experiments for minimization of leaching were performed with exclusion of air (purging with argon). As expected, the Pd content in solution can be reduced from 24% of the total palladium content (after a 4 h reaction) to 7% by additional treatment for 2 h at 140 °C and to 5.6% by 2 h treatment at 160 °C (Table 2, entries 1–3) for the coupling of bromobenzene with styrene. The lowest Pd content in solution (1.7%) was obtained by addition of sodium formiate to the reaction mixture after 4 h (complete conversion) and additional “reaction” of 2 h at 140 °C (Table 2, entry 4). The absolute Pd concentration in solution was found to be as low as 0.13 ppm (without any side reactions, i.e. no dehalogenation). Even if all palladium in solution was found quantitatively in the Heck product *E*-stilbene only (worst case

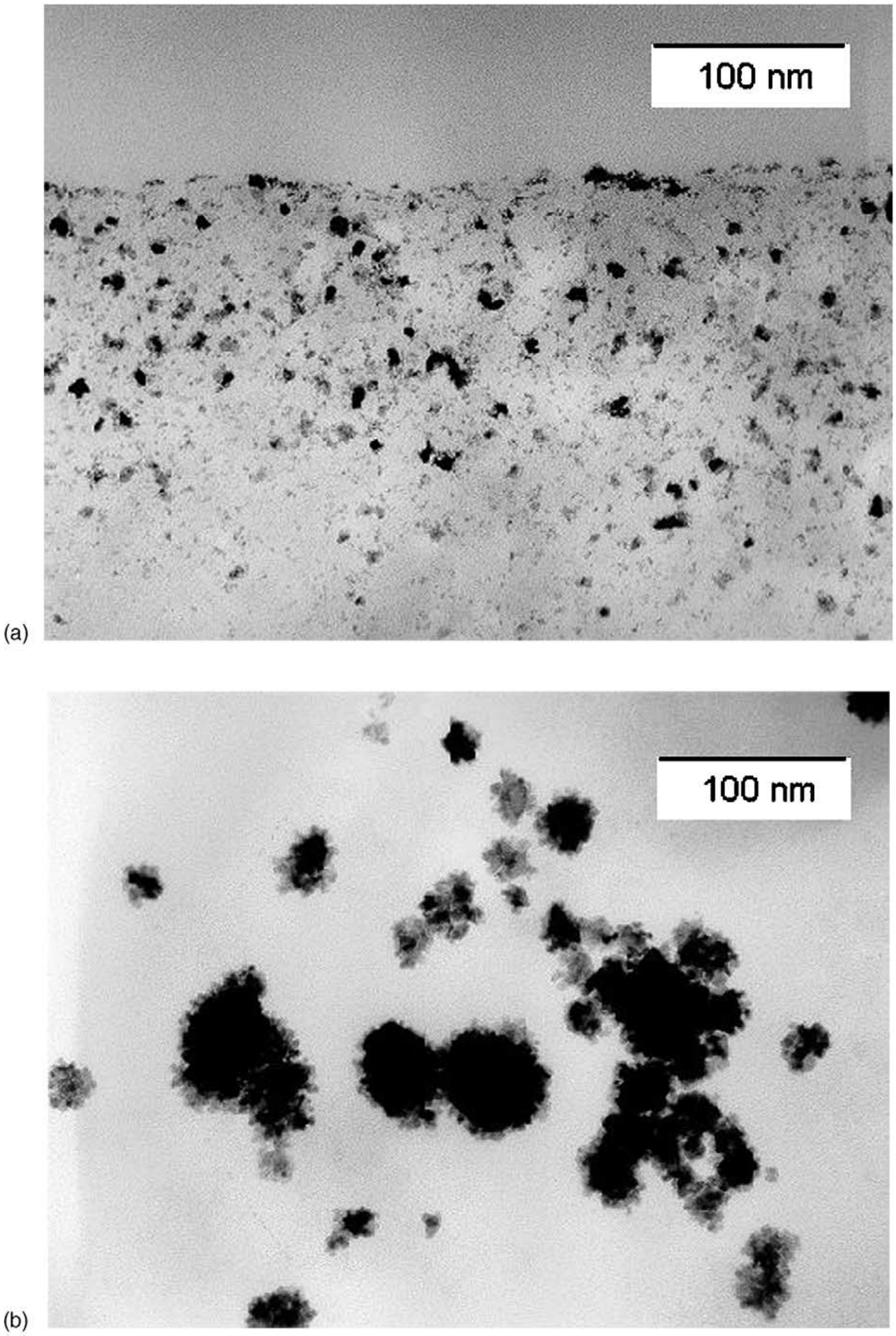


Fig. 2. Transmission electron micrograph of the Pd/C catalyst before Heck coupling of bromobenzene with styrene (magnification 1:400,000; top) and catalyst after the Heck reaction (magnification 1:400,000; bottom). Reaction conditions: 10 mmol bromobenzene, 15 mmol styrene, 12 mmol sodium acetate, 1.0 mol% Pd, 10 ml DMAc; $T = 140\,^{\circ}\mathrm{C}$; reaction time 20 h.

Table 2
Minimization of Pd leaching: Heck coupling of different bromoarenes with styrene (Scheme 1; R = H, $COCH_3$, OCH_3)[a]

Entry	R	Additional treatment (after 4 h at 140 °C)	Pd fraction in solution[b] (%)	Pd content in main product **3**[c] (ppm)	Pd in solution[d] (ppm)	Conversion[e] (%)	Yield **3**[e] (%)
1	H	–	24.2	28.6	2.0	95	87
2	H	2 h, 140 °C	7.1	8.4	0.55	95	88
3	H	2 h, 160 °C	5.6	6.6	0.45	96	89
4	H	12 mmol $NaHCO_2$ and 2 h, 140 °C	1.7	1.9	0.13	96	89
5	$COCH_3$	–	30.4	30.7	2.3	100	93
6	$COCH_3$	12 mmol $NaHCO_2$ and 2 h, 140 °C	0.7	0.7	0.05	100	92
7	OCH_3	–	25.8	48.7	2.1	66	57
8	OCH_3	12 mmol $NaHCO_2$ and 2 h, 140 °C	1.2	1.5	0.09	95	85

[a] Reaction conditions: bromoarene, styrene, NaOAc, 0.01 mol% Pd, NMP; $T = 140\,°C$; $t = 4\,h$. After 4 h, 12 mmol of sodium formiate were added to the reaction mixture (optionally) and the reaction mixture was replaced in the oil bath for another 2 h.

[b] Pd in solution was determined by ICP-MS (Pd in solution/total amount of Pd introduced).

[c] Calculation based on the assumption that all the Pd is found in the main product **3**.

[d] Pd in solution/total amount of solution.

[e] Conversion of bromobenzene and yields of product **3** from GLC analysis.

scenario, i.e. solvent and other coupling products were absolutely free of palladium), a maximum Pd content below 2 ppm would result.

The minimization of Pd in solution in the Heck reaction of bromobenzene and styrene is in line with the decrease of Pd leaching in Heck coupling of activated and de-activated bromoarenes as well (Table 2, entries 5–8). The Pd leaching without the addition of reducing agents at the end of the reaction corresponds to 24–30% of total Pd content (Table 2, entries 1, 5 and 7), whereas 0.7–1.7% of the Pd were found in solution after 4 h with addition of sodium formiate for additional 2 h (Table 2, entries 4, 6 and 8). The Pd content in solution can be decreased dramatically down

Table 3
Variation of the amount of sodium formiate added at the end of the reaction: Heck coupling of bromobenzene with styrene (Scheme 1; R = H)[a]

Entry	Extended time (min) (after 4 h at 140 °C)	Sodium formiate (mmol)	Pd fraction in solution[b] (%)	Pd in solution[c] (ppm)	Conversion[d] (%)	Yield **3**[d] (%)
1	–	–	24.5	1.10	97	89
2	15	8	8.1	0.32	98	90
3	30	8	5.3	0.21	97	89
4	45	8	4.9	0.21	97	90
5	60	8	2.9	0.12	97	89
6	15	16	6.1	0.23	97	91
7	30	16	4.6	0.18	96	89
8	45	16	2.8	0.11	97	90
9	60	16	1.6	0.07	97	90
10	15	24	6.4	0.25	98	90
11	30	24	3.1	0.12	97	90
12	45	24	3.2	0.13	97	89
13	60	24	2.0	0.08	97	90

[a] Reaction conditions: bromobenzene, NaOAc, 0.005 mol% Pd, NMP; $T = 140\,°C$; $t = 4\,h$. After 4 h, sodium formiate was added to the reaction mixture and the reaction mixture was replaced in the oil bath at 140 °C.

[b] Pd in solution was determined by ICP-MS (Pd in solution/total amount of Pd introduced).

[c] Pd in solution/total amount of solution.

[d] Conversion of bromobenzene and yields of product **3** from GLC analysis.

to 0.05 ppm (Table 2, entry 6) compared to 141 ppm (without treatment, not shown) for the coupling of *p*-bromoacetophenone with styrene by useful choice of the reaction parameters. Even with de-activated bromoarenes like *p*-bromoanisole almost quantitative conversions can be obtained without dehalogenation after 6 h (Table 2, entry 8) and Pd concentrations <0.1 ppm.

Finally, various amounts of sodium formiate were used in the Heck reaction of bromobenzene and styrene with Pd concentrations of 0.005 mol% (reaction conditions: NMP, NaOAc, 140 °C) and the Pd concentration was measured every 15 min during "extended" reaction time (up to 1 h). The longer the reaction time in the presence of sodium formiate the lower is the Pd content in solution (Fig. 1b). Almost no difference in Pd leaching was found for 16 and 24 mmol sodium formiate (Table 3, entries 6–13). The Pd content in solution can be decreased to 1.6% after 1 h with 16 mmol sodium formiate (Table 3, entry 9) and to 1.7% after 2 h with 12 mmol sodium formiate (Table 2, entry 4). This corresponds to absolute Pd contents of 0.13 ppm (Table 2) and 0.07 ppm (Table 3), respectively.

4. Conclusions

The palladium concentration in solution (leaching) in Heck reactions of aryl bromides with olefins catalyzed by heterogeneous Pd on activated carbon catalysts correlates with the progress of the reaction, the nature of the starting materials and products, the temperature, the solvent, the base and the atmosphere (argon or air). The Pd concentration in solution is highest at the beginning of the reaction and decreased when the reaction is finished. Useful reaction procedures allow easy and practicable control and minimization of the Pd leaching at the end of the reaction. Pd re-deposition is achieved by: (i) additional treatment at reaction or increased temperatures, (ii) addition of reducing agents (sodium formiate) and/or (iii) working under inert atmosphere. The Pd concentration in solution after the reaction can be reduced down to 0.05 ppm Pd and thus allows practically complete separation of the noble metal. The catalysts meet all demands for practical application: high activity and selectivity under ambient conditions (air and moisture), simple and complete separation of Pd from the product mixture, easy recovery of Pd (combustion of the carbon support) and commercial availability. The investigations show also that non-activated as well as de-activated bromoarenes can be converted quantitatively with Pd/activated carbon catalysts without dehalogenation within 2–6 h using extremely low palladium concentrations (0.005–0.01 mol% with respect to the bromoarene). The experimental results indicate a (quasi-)homogeneous reaction mechanism, i.e. Pd complexes or colloidal particles in solution act as the catalytically active species.

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