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Introduction

Immobilization of catalysts is currently a heavily investigated field of research which attracts great attention. It is well known that separation of homogeneous catalysts from the product can be problematic and it is therefore not surprising that various methods allowing for simple catalyst separation and recovery have been developed.^{1,2} In particular if expensive catalysts are used at high loading recycling becomes an important issue. Despite the great achievements in this field development of new concepts and new approaches for catalyst immobilization is still important.

[2.2]-*p*-Cyclophanes are known for more than 60 years.³ During the last decade the interest in these compounds which can be readily polymerized to provide poly(*p*-xylylenes) (PPX) that are robust and highly stable polymers has been steadily increasing.^{4,5} By chemical vapor deposition (CVD) of [2.2]-*p*cyclophanes various surfaces can be coated and thereby modified with very good conformity and uniform thickness. The resulting surfaces covered with poly(*p*-xylylenes) (PPX) are very stable and resistant towards bases, acids and most solvents. By introducing a functional group to the [2.2]-*p*-cyclophane shell, for example an ethinyl substituent, it is possible to prepare *via* CVD coatings bearing the corresponding functionalities.⁶ These functionalized coatings can then be further chemically modified to provide highly valuable materials.⁷

Immobilization of catalysts in poly(*p*-xylylene) nanotubes[†]

Johannes A. M. Hepperle,^a Fabian Mitschang,^b Anna K. Bier,^b Barbara K. Dettlaff,^a Andreas Greiner^{*b} and Armido Studer^{*a}

This paper describes the immobilization of a TEMPO-derivative and a copper catalyst in ethinylfunctionalized poly(*p*-xylylene) nanotubes which are readily prepared by the Tubes by Fiber Templates (TUFT) process. Catalyst conjugation to the nanotubes is achieved *via* the Cu-catalyzed azide alkyne cycloaddition (CuAAC). The TEMPO-functionalized nanotubes are successfully used as recyclable catalysts for oxidation of benzyl alcohol. Recycling studies show that the TEMPO-modified nanotubes can be reused 20 times without loss of catalytic activity. Conjugation of the nanotubes with a bipyridine moiety provides a material that allows for immobilization of metal catalysts. Treatment with a Cu(*i*)-salt leads to a hybrid material, which shows high activity as a recyclable catalyst in the CuAAC. Recycling experiments reveal that these Cu-nanotubes can be reused for 18 runs.

> Recently, we showed that it is possible to immobilize catalysts into electrospun polymer fibers.8,9 Such electrospun nanofibers are also suitable templates for the Tubes by Fiber Templates (TUFT) process which is the basis for the preparation of polymeric nanotubes.10 In this process the template nanofiber is first covered with a PPX layer by CVD of [2.2]-p-cyclophane. Subsequent removal of the soluble core template polymer nanofiber by extraction results in PPX nanotubes. Using this approach we recently showed the successful immobilization of catalytically active and readily recyclable generation 5 PAMAM dendrimers caged in poly(p-xylylene) nanotubes.11 Herein we report preparation of ethinyl-functionalized PPX-nanotubes by applying the TUFT process. Subsequent chemical modification of these PPX nanotubes allows for conjugation of catalysts. The obtained tubes feature a high surface area, show high catalytic activity and are readily recyclable. As first test reactions we investigated the TEMPOcatalyzed oxidation12 of benzyl alcohol and the CuAAC13 of benzyl azide with phenyl propargyl ether.

Results and discussion

Ethinyl-functionalized PPX⁶ was obtained by the TUFT process.¹⁰ The underlying concept is illustrated in Fig. 1.

4-Ethinyl-[2.2]-*p*-cyclophane **5** was readily prepared according to Hopf *et al.*^{6a} starting with [2.2]-*p*-cyclophane **1** (Scheme 1). Bromination of **1** gave 4-bromo-[2.2]-*p*-cyclophane **2** which was further converted in good yield *via* bromine lithium exchange and subsequent addition of dimethyl formamide to 4-formyl-[2.2]-*p*-cyclophane **3**. In the final step the aldehyde was treated with diazocarbonyl phosphonate **4** under basic conditions to provide 4-ethinyl-[2.2]-*p*-cyclophane **5** in 80% yield.

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^aChemistry, WWU Münster, Münster, Germany. E-mail: studer@uni-muenster.de ^bLehrstuhl für Makromolekulare Chemie II, University of Bayreuth, Bayreuth, Germany. E-mail: greiner@uni-bayreuth.de

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Fig. 1 The TUFT-process using electrospun nanofibers as templates and subsequent chemical vapor deposition of ethinyl-functionalized [2.2]-*p*-cyclophane. Solvent extraction of the inner core material leads to the corresponding ethinyl-functionalized PPX tubes.



For template nanofiber formation we chose polyethylene oxide (PEO) which is known in the electrospinning process.⁹ To this end, an aqueous solution of 10 wt% PEO was electrospun to uniform fibers free of beads, as shown in Fig. 2 (left). The average diameter of the fibers was 415 ± 59 nm, featuring a high surface area.¹⁴



Fig. 2 Scanning electron micrographs of electrospun PEO nanofibers (left) and the corresponding core–shell fibers after deposition of ethinyl-functionalized PPX derived from **5** (right).



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 $\mbox{Scheme 2}$ CVD of $\mbox{5}$ to give ethinyl-functionalized PPX $\mbox{6}$ and subsequent CuAAC.

The PEO fibers were then coated with 4-ethinyl-[2.2]-*p*-cyclophane 5 using the CVD process (Scheme 2).⁵ The resulting core–shell fibers (Fig. 2, right) were homogeneously coated and free of visible pores or cracks. The average diameter was 645 ± 15 nm, hence the PPX layer thickness was calculated to lie at around 115 nm.

As opposed to the deposited PPX-type shell, the inner PEO template was soluble in water and could easily be removed *via* solvent extraction in agreement with previous studies which showed that the PPX membrane can be permeated by non globular structures and polymers,¹⁵ whereas sterically demanding dendrimers remain encapsulated inside the PPX confinements.¹¹ Gravimetric measurements confirmed the successful extraction of the PEO template material. Electron scanning micrographs of the resulting sample after freeze-fracturing show both cross- and longitudinal sections of the hollow tubes (Fig. 3).

For conjugation of the PPX-tubes 6, an azidyl functionalized TEMPO-derivative 9 was prepared (Scheme 3). To this end,



Fig. 3 Scanning electron micrographs of the ethinyl-functionalized PPX tubes. As a result of the freeze-fracturing of the sample, both cross-sections and longitudinal sections are visible.



Scheme 3 Synthesis of TEMPO-derivative 9





 ${\rm Scheme}~4$ Oxidation of benzyl alcohol using catalyst A under Anelli conditions. 16

commercially available *N*-acetamido-TEMPO 7 was hydrolysed under basic conditions (KOH). The resulting amine was then acylated with 6-bromo-hexanoic acid chloride to give **8** which was then further converted to azide **9** upon treatment with NaN₃ (Scheme 3).

Conjugation of the azide 9 to the PPX nanotubes 6 via CuAAC turned out to be challenging. Standard click conditions using CuSO₄ 5 H₂O (6 mol%) in the presence of sodium ascorbate as reducing reagent were not suitable for this transformation. Using a Cu(I)-salt (CuI, 6 mol%) was also not effective. A careful literature search revealed that the CuAAC at surfaces is mostly conducted by using azide-functionalized solid phases whereas the alkyne is generally used in excess as soluble component.13b This is opposite to our current case. We assumed that the click reaction at the nanotubes occurs very slowly and that the oxidation of the catalytic active Cu(1)-species might be a problem under the applied conditions. Therefore, the CuAAC was repeated under careful exclusion of air under argon atmosphere using CuI (6 mol%) as catalyst. We were pleased to find that cycloaddition proceeded albeit very slowly. Reaction for 2 days provided catalyst system A, in which about 62% auf the alkyne moieties were functionalized by the TEMPO-derivative 9 via a triazole moiety (for general structure see Scheme 2). The degree of functionalization was estimated gravimetrically and by elemental analysis.

With the catalyst system **A** in hand, we investigated oxidation of benzyl alcohol under Anelli conditions using **A** (around 2.5 mol nitroxide), NaOCl as stoichiometric cooxidant, KBr and NaHCO₃ (Scheme 4, for apparatus used, see ESI†).¹⁶ Benzaldehyde was formed in over 95% yield and the hybrid material **A** was readily recovered (see ESI†). Tube material **A** was successfully reused for 20 runs without loss of activity (yields were determined by GC analysis, Fig. 4). The loss in activity for run 9



Fig. 4 Recycling study: benzyl alcohol oxidation with nanotube **A** as catalyst (nitroxide concentration about 2.5 mol%).



Fig. 5 Scanning electron micrographs of catalyst system A after 20 runs.

(yield dropped to 83%) was caused by using an old and likely partly decomposed solution of NaOCl.¹⁷

After 20 runs the fiber mat was intensively washed and then dried under reduced pressure. To our surprise, despite the high activity only 74% (weight percent) of the initial TEMPO-functionalized nanotubes were recovered. The isolated fiber mat was fragile and brittle. Scanning electron micrographs of the nanotubes showed a large change in morphology (Fig. 5): fiber mats were porous and showed partially coalesced structures (compare with Fig. 3) likely caused by the harsh oxidizing conditions applied.¹⁸ However, despite the partly destructed structure of the tubes, system **A** was still catalytically active in the 20th run.

Encouraged by the successful preparation of the TEMPOfunctionalized system **A**, we decided to conjugate the bipyridine ligand **13** to the PPX nanotubes **6** (Scheme 5). To this end, commercially available bipyridine **10** was first oxidized by SeO_2 to alcohol **11**. O-alkylation with 1,6-dibromohexane provided **12** which was further reacted with NaN₃ to eventually give azido bipyridine **13** that was isolated in 29% over three steps.

The modification of ethinyl-functionalized nanotubes **6** with azido bipyridine **13** was performed in analogy to the TEMPOconjugation discussed above using 20 mol% CuI under argon atmosphere resulting in bipyridine modified nanotubes. To remove the Cu-complexes formed during the CuAAC the bipyridine-functionalized nanotubes were intensively washed with a solution of ethylenediaminetetraacetic acid (EDTA, 0.2 M) in THF. Elemental analysis revealed a degree of functionalization of about 27%.

The successful covalent modification of the alkyne-functionalized tube material with the bipyridine ligand offers a platform for the immobilization of metal salts. Along these



Scheme 5 Synthesis of the azido bipyridine derivative 13.



Scheme 6 CuAAC of phenyl propargyl ether (14) with benzyl azide (15) by using catalyst system **B**.

lines, the nanotubes were stirred for one day in a solution of $Cu(II)SO_4$ to provide Cu-bipyridine complexes covalently bound to the PPX nanotubes which are hereafter called as catalyst system **B**. To remove nonligated physiadsorbed Cu(II)SO₄, the tubes were intensively washed. To test the activity and reusability of catalyst system **B**, we chose the Cu(I)-catalyzed cycloaddition of phenyl propargyl ether (14) with benzyl azide (15) to give triazole 16 as test reaction (Scheme 6).

In order to activate the Cu-catalyst sodium L-ascorbate was added as reducing reagent and a nearly quantitative conversion to the triazole **16** was obtained (at around 5 mol% Cu-loading). Initial reactions were conducted for 19 h but we noted later that high conversion (>90%) is achieved within 3 h. Importantly, catalyst system **B** was successfully recycled 17 times without a significant drop in activity (>90%, see ESI†).

To test whether the cycloaddition is catalyzed by the tube material with immobilized Cu(i) and not by Cu-salt which might have leached out of the tube material into the solution, a control experiment was performed: catalyst system **B** was removed after a conversion of about 25% and stirring was continued for 190 min in the absence of the catalyst. Then the catalyst **B** was added again to the mixture and reaction progress was monitored by gas chromatography (see Fig. 6, black squares). The analysis clearly revealed that the reaction did not stop completely after removal of the tube material **B** indicating that little Cu-salt was leaching out of the tube material, however reaction rate dropped significantly. After addition of catalyst system **B** initial activity was restored.

After 18 runs the fiber mat was intensively washed and then dried under reduced pressure. The isolated fiber mat turned out



Fig. 6 Reaction progress of a standard experiment (red circles) and an experiment (black squares) where catalyst system **B** was removed at about 25% conversion and then readded again after 190 min.



Fig. 7 Scanning electron micrograph of catalyst system **B** which was used for 18 experiments.

to be fragile and brittle. SEM-analysis of the used nanotubes clearly showed that the tube structure is still existing (Fig. 7) in agreement with the experimental findings that the catalyst system **B** was still very active in the CuAAC in the 18th run. In contrast to the TEMPO-bleach process discussed above, the milder conditions of the CuAAC did not lead to a destruction of the tube material.

Conclusion

In this paper we presented a new concept for the immobilization of catalysts into poly(p-xylylene) nanotubes. The novel approach uses the electrospinning technique for the preparation of polymer template nanofibers which are subsequently coated with ethinyl-functionalized PPX via CVD. In the last step the core template fibers are removed by extraction leading to ethinyl-functionalized nanotubes. These nanotubes, which have a high surface area, can be further chemically modified using the CuAAC. Conjugation of a TEMPO-derivative provided a catalyst system which was successfully used as recyclable catalyst for oxidation of benzyl alcohol. The tube material was very robust since after 20 runs under oxidizing conditions (bleach), catalyst activity was still very high. The CuAAC also allowed immobilizing a bipyridine ligand. Cu-complexation gave a tube material which showed activity as recylable catalyst in the CuAAC of phenyl propargyl ether with benzyl azide.

We are confident that the immobilization concept presented should be broadly applicable and will allow immobilizing various catalysts. This is due to the general applicability of the surface CuAAC which we used for conjugation of the catalytically active moieties to the PPX nanotubes. Work along this line is underway.

Experimental section

Electrospinning of poly(ethylene oxide) template nanofibers

An aqueous solution containing 10 wt% PEO ($M_w = 300\ 000\ \text{g}\ \text{mol}^{-1}$) was electrospun using a custom made single-nozzle electrospinning setup. The collector electrode, a round metal plate of 9 cm diameter, was covered with aluminum foil and mounted below a downward facing 1 mL syringe equipped with a 0.9 mm cannula. The gap between the two electrodes was 20 cm and the applied voltage was 20 kV. At room temperature and 20% relative humidity, the feed rate was set to 0.25 mL h⁻¹

resulting in the deposition of PEO nanofibers onto the collector foil.

Chemical vapor deposition of ethinyl-functionalized poly(*p*-xylylene)

Rectangular pieces of 4.5×5.5 cm of the prepared PEO fiber mats were mounted inside the deposition chamber and subsequently coated with ethinyl-functionalized PPX using a custom made CVD setup (see ESI†). The vaporization chamber was filled with 150 mg of the ethinyl-functionalized [2.2]-*p*cyclophane precursor and set to 100 °C. The following pyrolysis zone was set to 580 °C. Whereas the deposition chamber was kept at room temperature, the connecting transportation zone was set to 300 °C. The pressure was kept below 2.0×10^{-2} mbar and after 1 h, the vaporization temperature was raised 10 °C every 30 min until 150 °C. After the CVD setup reached room temperature, the coated fiber mats were flipped and the back layer was subsequently coated as described above. The resulting core–shell fiber mats were homogeneously coated and slightly yellow.

Solvent extraction of the inner polymer template

The prepared core-shell fiber mats were introduced into water in order to extract the inner PEO fibers. The aqueous phase was renewed every 24 h until the weight was consistent.

General procedure for the oxidation of benzyl alcohol using catalyst system A

A solution (3.66 mL) of benzyl alcohol (0.40 M, 1.47 mmol, 1.0 eq.) and hexadecane (0.40 M, 1.47 mmol, 1.0 eq.; internal standard) in dichloromethane was mixed with a solution of KBr (aq., 0.5 M, 0.29 mL, 0.15 mmol, 0.1 eq.) at 0 °C. Then a solution of NaOCl (aq., 0.35 M, 5.24 mL, buffered by NaHCO₃ to pH 8.9, 1.83 mmol, 1.25 eq.) was added at 0 °C. The TEMPO-function-alized PPX-nanotubes **A** (20.0 mg, 36.6 µmol, 2.5 mol% nitro-xide) were fixed in a Teflon holder (see Fig. 1 in the ESI†) and dipped into the reaction mixture. By removal of the catalyst **A** the reaction was stopped and the product was isolated by rinsing the fiber mat with dichloromethane (3 × 5 mL). The combined phases were dried over MgSO₄. Conversion of the reaction was determined by GC analysis.

General procedure for the CuAAC with catalyst system B

Catalyst system **B** (72.0 mg, 12 μ mol, 5 mol% copper) was fixed using the custom made sample mount and a solution of benzyl azide (0.25 mmol, 1.0 eq.) and phenyl propargyl ether (0.27 mmol, 1.1 eq.) in dry methanol (5 mL) were added. In the first reaction cycle after longer storage time of the fiber mat, sodium L-ascorbate (5 mg, 0.02 mmol, 0.1 eq.) was added to the solution to reduce oxidized Cu(II) to Cu(I). The reaction mixture was heated to 60 °C for 3–19 h. Subsequently, the sample mount and the tube material were washed several times with methanol and the washed tube material was dried carefully by passing an argon stream followed by drying under vacuum. After removal of the solvent from the reaction mixture, the obtained residue was dissolved in CDCl_3 and yield was determined by ¹H-NMR-spectroscopy by using dibromomethane as an internal standard.

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- 17 In other experiments we observed a very high yield over 12 runs clearly showing the slightly decreased yield in run 9 was caused by a lower quality of the NaOCl solution as mentioned in the text.
- 18 The insolubility of the tube material makes analysis of the tube material very difficult. IR (FT-ATR) did not give any structural information on how the tube material was damaged. Elemental analysis before (C = 68.74%, H = 7.21, N = 8.00) and after catalysis (C = 68.31%, H = 7.35, N = 7.77) shows that relative amount of C and N slightly decreased. We believe that under the harsh oxidizing conditions CH-oxidation at the benzylic sites and subsequent oxidative C-C-cleavage is slowly occurring which leads to destruction of the material and eventually to material loss as observed in the experiment. The lower N and C content is then caused by a larger content of O (calculated increase is 0.52%). Since the catalyst is covalently bound, the loss of activity after extensive use of the tube material will be caused by a lower concentration of catalyst due to damage and loss of tube material after multiple use.