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Monolithic Materials: New High-Performance Supports for Permanently Immobilized Metathesis Catalysts

Monika Mayr, Betina Mayr, and Michael R. Buchmeiser*

Olefin metathesis and variations thereof are among the most important tools for C–C bond formation.[1] Polymer chemistry and materials sciences have seen the introduction of new trends by metathesis-based techniques, such as ring-opening metathesis polymerization (ROMP) or acyclic diene polymerization (ADMET). Complementary, cross-metathesis and ring-closing metathesis find ample application in organic chemistry.[2] Molybdenum- and ruthenium alkylidenes (the latter based on N-heterocyclic carbenes, NCH ligands) are used for this purpose but, until recently, only in homogeneous catalysis.[3] The first heterogeneous ruthenium systems have already been described by Grubbs et al. but these in particular turned out to be less suited to polymerization.[4] Meanwhile, a few non-permanently immobilized Grubbs catalysts have been reported,[5–7] although the system described by Blechert et al. basically represents the only recyclable heterogeneous Grubbs catalyst.[8] Despite the good catalytic data that has been reported for RCM, we investigated a new method to reach heterogeneous metathesis catalysts. The final goal was to combine the advantages of homogeneous and heterogeneous catalysis and, simultaneously, eliminate the disadvantages typical for many heterogeneous systems, such as diffusion-controlled reactions and catalyst bleeding, among others. Again, NHC ligands appeared highly attractive for these purposes. On one hand they allow the generation of highly active ruthenium carbenes,[9–12] on the other hand the corresponding NHC/phosphane-based systems are quite sta-

[*] A. Univ.-Prof. Dr. M. R. Buchmeiser, M. Mayr, Mag. B. Mayr
Institut für Analytische Chemie und Radiochemie
Universität Innsbruck
Innrain 52a, 6020 Innsbruck (Austria)
Fax: (+43) 512-507-2677
E-mail: michael.r.buchmeiser@uibk.ac.at

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ble. Since the dissociating ligand is always the phosphane, an enhanced stability and reduced catalyst bleeding may be expected. Finally, a major way to a one-way cartridge as well as reusable reactor systems could be generated by the manufacture of pressure-stable supports. While this goal is comparably hard to achieve with standard organic supports such as divinylbenzene-crosslinked polystyrene (PS-DVB), we were able to take advantage of the latest developments in organic monolithic supports. Monolithic materials prepared by radical polymerization have been known since the 1970s[13, 14] and have been further developed since mainly by Fréchet and Svéc. They developed modern monolithic high-performance separation media,[15, 16] as well as scavenger- and reagent-bearing supports.[17, 18] The main advantage of monolithic media, a result of their unique structure and pore size distribution, is the comparatively fast mass transfer between the support and liquid phase that may be accomplished. In combination with a suitable interparticle porosity, high flow rates (>1 cm min^{-1}) may be achieved. We already reported on the tailor-made synthesis and functionalization of monolithic systems using ring-opening metathesis polymerization (ROMP) and on selected applications in separation science (HPLC).[19, 20] Because of their highly attractive properties, the extension of the area of functionalized monolithic supports to the synthesis of supported catalytic systems appeared a logical consequence.

The synthetic protocol entails the generation of a continuous matrix through ring-opening metathesis copolymerization of norbornene (NBE) and 1,4,4a,5,8,8a-hexahydro-1,4,5,8-*exo*-*endo*-dimethanonaphthalene (DMN-H6) in the presence of dichloromethane and 2-propanol within a borosilicate column (Figure 1, step 1). In order to achieve the above-mentioned permeability and to avoid any intraparticle diffusion, a sufficient macroporosity had to be achieved yet microporosity had to be avoided. In terms of functionalization as well as in view of the final application, monolithic structures with a microglobule diameter of 1.5 ± 0.5 μm (Figure 2) and an interparticle porosity of 40% turned out to be optimal. The determination of structurally relevant parameters was accomplished by inverse gel-permeation chromatography (IGPC).[21] Swelling of the organic support is drastically reduced by the lack of basically any microporosity, which consequently is a basic requirement for functionalization. This consecutive in situ functionalization is accomplished by feeding the "living" ruthenium termini with a solution of **1** and norbornene in dichloromethane (Figure 1, step 2). The number of the active termini may be determined separately by termination and elution of the ruthenium moiety with ethyl vinyl ether and subsequent plasma emission spectroscopic analysis (ICP-OES). Interestingly, more than 98% (!) of the ruthenium centers are active and located on the microglobule surface. Despite the comparably low surface of approximately 25 m^2 g^{-1}, high loadings of **1** may be achieved by taking advantage of the high number of "living" sites and the "grafting from" approach, that results in surface-bound tentacles. This graft polymerization of **1** is additionally facilitated by addition of approximately 10 equivalents of norbornene. The latter represents a very reactive

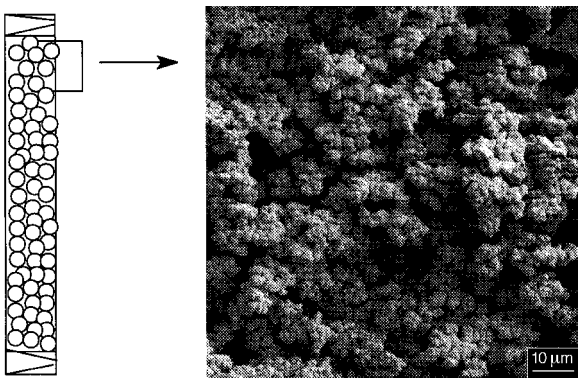

Figure 2. Electron microscopic image of the microstructure of the monolithic support.

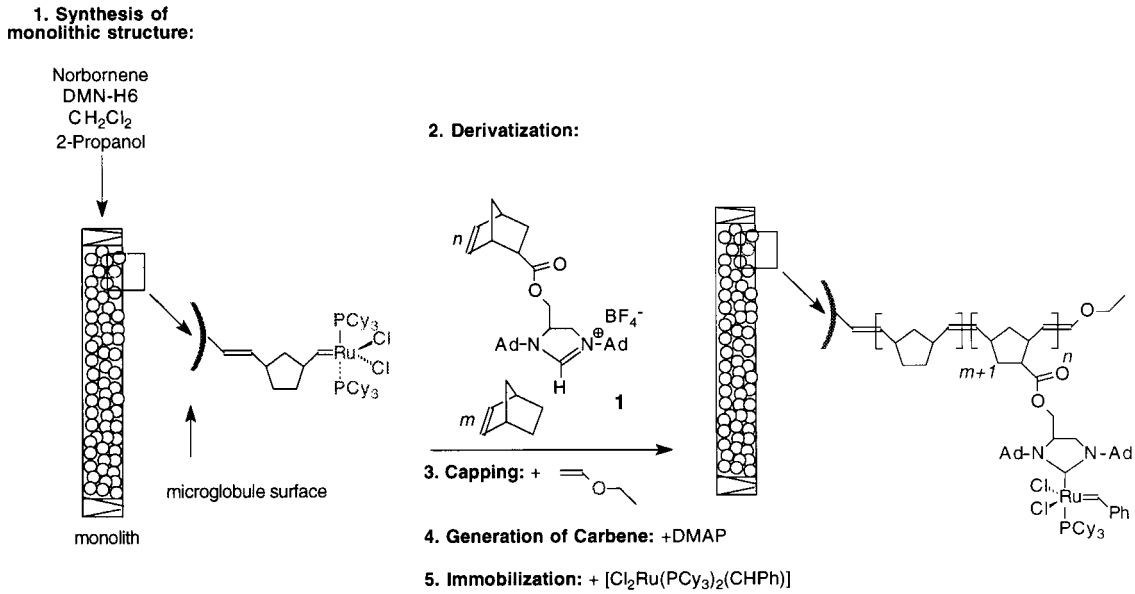

Figure 1. Synthesis and functionalization of a monolithic support and subsequent immobilization of the metathesis catalyst. Ad = adamantyl.

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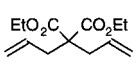
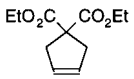
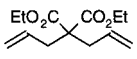
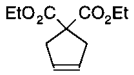
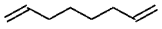
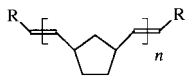
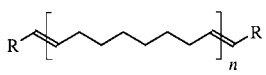
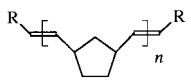
monomer and is therefore grafted first onto the support. Consequently, the active termini are moved away from the structure-forming microglobuli, thus facilitating the consecutive polymerization of the sterically demanding monomer **1**. For grafting experiments based on such a block copolymer approach, the average degree of oligomerization for **1** within the tentacle is 2–5; in the absence of norbornene, lower grafting yields are obtained. These grafting yields may be estimated quite accurately from the amount of nitrogen (as obtained from elemental analysis) and the amount of ruthenium sites active after the structure-forming process. The additionally necessary quantitative initiation of **1** by the $[Cl_2Ru(CHPh)(PCy_3)_n]$-terminated polymer domains was confirmed by preliminary experiments. For this purpose, a $[Cl_2Ru(PCy_3)_2(CHPh)]$-initiated homogeneous polymerization of **1**, carried out at 40 °C in dichloromethane, was terminated with ethyl vinyl ether after 12 h. Due to the insolubility of oligomer in THF and because of the fact that oligo-**1** represents a polycation, the degree of oligomerization was determined by ^{1}H NMR endgroup analysis. Experimental (16.3 ± 1.5) and calculated values (14.6) were in excellent agreement. The last step in the graft polymerization of **1** onto the monolithic supports represents the termination of the ruthenium termini with ethyl vinyl ether (Figure 1, step 3), resulting in the elution of the ruthenium with methylene chloride. Control experiments consisting of an aqua regia digest of the final monolithic structure followed by ICP analysis revealed the basically quantitative removal ($\geq 99\,\%$) of the catalyst. Since the monolithic structures do not tolerate THF, the generation of the carbene necessary for catalyst immobilization is accomplished with (dichloromethane soluble) 4-dimethylaminopyridine (DMAP), a strong base (Figure 1, step 4). Published procedures consist of the synthesis of *tert*-butoxide-protected carbenes, which are thermally converted to the free carbene in the presence of a Grubbs catalyst.[8, 9] In the present system, heterogenization and the entailed reduced ligand mobility does not require this protective procedure. Consequently, the last synthetic step involves the careful removal of excess DMAP (ruthenium alkylidenes are base labile) and treatment of the monolith with a solution of $[Cl_2Ru(CHPh)(PCy_3)_2]$ in CH_2Cl_2 (Figure 1, step 5). As determined by ICP, loadings up to 1.4 % of NHC-based Grubbs catalyst may be achieved according to this procedure. A comparison of this value with the nitrogen tenor as determined by elemental analysis reveal that $\geq 42\,\%$ of the NHC ligands present are involved in the formation of the desired catalytic species.

Ruthenium carbene immobilized onto monoliths possess high activity towards RCM as well as towards ROMP. The *cis*/*trans* ratio of the polymers is exactly the same as the one obtained in homogeneous polymerizations (90 % *trans*). Table 1 summarizes the results. For all experiments, chain-transfer agents (CTAs) such as *cis*-1,4-diacetoxybut-2-ene (**I**), diethyldiallylmalonate (**II**), and *cis*-2-hexene (**III**) were used. These compounds allow the regulation of the degree of polymerization in ROMP in particular with cyclooctene. In addition, CTAs rapidly convert intermediary ruthenium methylidenes in RCM to the more stable alkylidenes, thus significantly enhancing the lifetime of the catalyst (Figure 3). In particular, **I** permits loading one single monolithic system consecutively with different substrates and to run the corresponding metathesis reactions. The tentaclelike struc-

Table 1. Results from RCM (No. 1–3) and ROMP (No. 4–6) experiments obtained by flow-through (1, 4, and 5; these experiments were carried out consecutively with the same monolith) and cartridge experiments (2, 3, and 6). [M]/[**I**] = constant (M = monomer). R = CTA-derived group.

No.	Compound	Product	CTA	M:CTA	T [°C]	t[23] [min]	Yield [%]	TON_{max}[a] [min^{-1}]	TOF[a]	M_n	PDI[b]
1				–	43	3	71	62	25		
2			**I**		56	50	100	63	–		
					56	5	92	55	–		
3			**I**		56	30	41	56	1.9		
4			**II**	21:1	40	3				24000	2.4
					40	3				34000	2.2
					40	3				40000	2.1
					40	3				45000	2.0
5			**III**	18:1	40	3				2500	1.2
					40	3				1100	2.6
					40	3				1500	1.9
					40	3				1500	1.7
6			**I**	5:1	56	30				12000	1.4

[a] Heterogeneous conditions. [b] Polydispersity index.

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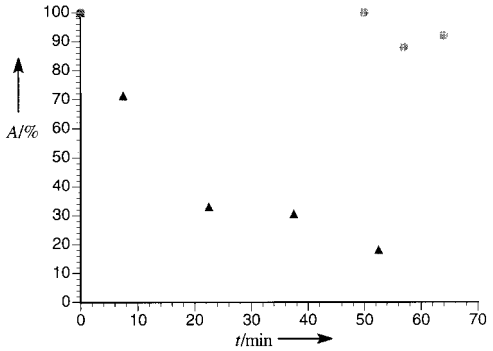

Figure 3. Influence of the chain transfer reagent **I** on the stability of the immobilized catalyst as determined from RCM experiments carried out with diethyldiallylmalonate with (●) and without (▲) CTA. A = Activity of the catalyst.

ture and the lack of basically any microporosity reduce diffusion to a minimum. This results in turnover frequences (TOFs) up to 25 min^{-1}, thus even exceeding homogeneous analogues. In comparison, the TOF for diethyldiethylmalonate using $[Cl_2Ru(Mes_2\text{-}NHC)(PCy_3)(CHPh)]$ is 4 min^{-1} (45 °C).[8]

In terms of a most simple handling, the monolithic systems presented here may be used either as pressure-stable reactors or (in miniaturized form) as cartridges for applications in combinatorial chemistry. The use of NHC ligands even in RCM successfully suppresses any bleeding of the column, thus allowing the synthesis of virtually ruthenium-free cyclization products with a ruthenium content ≤ 70 ppm.

Experimental Section

All experiments were carried out by means of Schlenk techniques using degassed and dried solvents throughout. Borosilicate columns (3×50 mm, 3×150 mm) were surface-derivatized using bicyclo[2.2.1]hept-2-en-5-yltrichlorosilane. Nitrogen and ruthenium contents were determined by elemental analysis and aqua regia decomposition followed by ICP, respectively. Molecular weights were determined by GPC (in THF) using a consecutive UV, refractive index (RI), and light scattering detectors.

Synthesis of monoliths: Solutions of A (NBE/DMN-H6/2-propanol, 25/25/40 wt%) and B (CH_2Cl_2/$[Cl_2Ru(=CHPh)(PCy_3)_2]$, 9.6/0.4)[22] were combined at 0 °C and the reaction mixture was transferred to a borosilicate column prechilled to 0 °C. Polymerization temperature was 0 °C for 15 min and room temperature for 1 h. For functionalization, the monolith was flushed with CH_2Cl_2 and subsequently fed with 2 mL of a solution of **1** (51.8 mg, 0.09 mmol) and norbornene (47.1 mg, 0.5 mmol) in CH_2Cl_2. Columns were closed and kept at 40 °C overnight. The monolith was flushed with CH_2Cl_2 (1 mL), a 10% solution of ethyl vinyl ether in CH_2Cl_2 (2 mL), and finally CH_2Cl_2 (2 mL) again. 4-Dimethylaminopyridine (10.9 mg, 0.09 mmol, dissolved in 1 mL CH_2Cl_2), CH_2Cl_2 (1 mL), and finally $[Cl_2(PCy_3)_2Ru(=CHPh)]$ (10.9 mg, 0.09 mmol, dissolved in 1 mL CH_2Cl_2) were pumped over the column which was then kept for 1 h. at 40 °C. Finally, the monolith was flushed with CH_2Cl_2 for a few hours at a flow rate of 0.1 mL min^{-1}. IGPC data (polystyrene, $M_p = 274$ Da, THF): specific surface area $\sigma = 25\ m^2 g^{-1}$, pore porosity $\varepsilon_p = 17\%$, intergranular porosity $\varepsilon_z = 40\%$, apparent density $\rho_{app} = 0.37\ g\,cm^{-3}$. Electron microscopy: microglobule diameter $d_p = 1.5 \pm 0.5$ μm.

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An Intramolecular Case of Sharpless Kinetic Resolution: Total Synthesis of Laulimalide**

Johann Mulzer* and Elisabeth Öhler*

The Sharpless asymmetric epoxidation (SAE) is an efficient method for resolving racemic mixtures of secondary allylic alcohols: the matched pair of substrate and reagent generates an enantiomerically enriched epoxyalcohol, whereas the mismatched pair remains unreacted (Scheme 1, Eq. (1)).[1] We decided to change this intermolecular selection to an intramolecular one when we embarked on a total synthesis of

[*] Prof. Dr. J. Mulzer, Dr. E. Öhler
Institut für Organische Chemie der Universität Wien
Währinger Strasse 38, 1090 Wien (Austria)
Fax: (+43) 1-4277-52190
E-mail: johann.mulzer@univie.ac.at

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