Monolithic Systems: From Separation Science to Heterogeneous Catalysis

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Summary: Recent results that have been obtained in the ring-opening metathesis polymerization (ROMP)-based synthesis of monolithic supports are summarized. We have elaborated a synthetic concept that allows modifying monolithic supports in a way that they can be used both for applications in separation science, for SEC and as supports for catalytically active systems. In all cases, a tailor-made microstructure was accessible due to the controlled character of the transition-metal catalyzed polymerization. Taking advantage of the "living" catalytic sites, an" *in situ*" functionalization was accomplished by subsequently grafting a variety of functional monomers and catalyst precursors onto the rod. Their design and use as supports for high-performance separation devices (e.g. for *ds*-DNA) and catalytic supports (*e. g.* supported Grubbs-type catalysts) is summarized.

Keywords: catalysis; flow reactors; metathesis; ROMP; supports

Introduction

Monolithic separation media evolved from the idea to produce a support with a high degree of continuity that should meet the requirements for fast, yet highly efficient separations.[1] Standard monolithic supports are usually prepared from poly(styrene-divinylbenzene) or poly(acrylate)s and have been used mainly in liquid chromatography including micro-separation techniques.[2] Starting in 1999, our group developed an entirely new concept for the manufacture of

 DOI: 10.1002/masy.200450601

functionalized monolithic supports. It entails the ring-opening metathesis polymerization (ROMP)-based synthesis for these types of materials[3-12] and has lately been extended to the use of these supports in heterogeneous catalysis.[11, 13]

Results and Discussion

Basics and Concepts

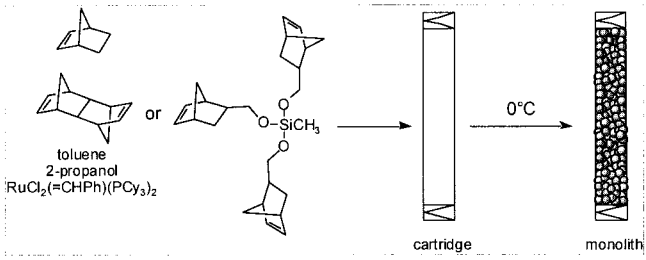
Generally speaking, the term "monolith" applies to any single-body structure containing interconnected repeating cells or channels. In this contribution, the term "monolith" shall comprise crosslinked, organic materials which are characterized by a defined porosity and which support interactions/reactions between this solid and the surrounding liquid phase. Besides advantages such as lower backpressure and enhanced mass transfer[14, 15], the ease of fabrication as well as the many possibilities in structural alteration need to be mentioned.

Until now, a considerable variety of functionalized and non-functionalized monolithic materials based on either organic or inorganic polymers are available. Organic monoliths have mostly been prepared from methacrylates or poly(styrene-*co*-divinylbenzene)[2, 16-19] applying almost exclusively free radical polymerization.[20] Despite the comparably poor control over polymerization kinetics in free radical polymerization-based systems, the porosity and microstructure of monolithic materials has successfully been varied.[2] Due to the broad applicability of ROMP and the good definition of the resulting materials, we investigated to which extent this transition metal-catalyzed polymerization could be used for the synthesis of monolithic polymers.[4] We found that this may be accomplished by generating a continuous matrix by ring-opening metathesis copolymerization of suitable monomers with a crosslinker in the presence of porogenic solvents within a device (column).

Manufacture of Metathesis-Based Monolithic Supports

The choice of the suitable initiator represents an important step in creating a well-defined polymerization system in terms of initiation efficiency and control over propagation. Only in the case where a quantitative and fast initiation occurs, the entire system can be designed on a *stoichiometric base*. This is of enormous importance, since for control of microstructure, the composition of the entire polymerization mixture needs to be varied within very small

increments, being sometimes less than 1%. In terms of monomers, the copolymerization of norborn-2-ene (NBE) with 1,4,4a,5,8,8a-hexahydro-1,4,5,8-*exo-endo*-dimethanonaphthalene (DMN-H6) or tris(norborn-2-en-5-ylmethylenoxy)methylsilane (NBE-$CH_2O)_3SiCH_3$) in the presence of two porogenic solvents, e. g. 2-propanol and toluene worked best (Scheme 1). In all cases, the less oxygen-sensitive ruthenium-based Grubbs-type initiator $RuCl_2(=CHPh)(PCy_3)_2$ was used as catalyst. In contrast to the highly reactive second-generation Grubbs-type catalysts $RuCl_2(=CHPh)(NHC)(PCy_3)$ (NHC=N-heterocyclic carbene), it possesses a balanced reactivity that avoids highly exothermic reactions.



Scheme 1. Synthesis of monolithic supports.

Microstructure of Metathesis-Based Rigid Rods

In order to understand monolithic supports and the effects of polymerization parameters, a brief description of the general construction of a monolith in terms of microstructure, backbone and relevant abbreviations is given in Figure 1.[3, 4] As can be deduced therefrom, monoliths consist of interconnected microstructure-forming microglobules, which are characterized by a certain diameter (d_p) and microporosity (ε_p). In addition, the monolith is characterized by an inter-microglobule void volume (ε_z), which is mainly responsible for the backpressure at a certain flow rate. The volume fractions of both the micropores (ε_p) and voids (intermicroglobule porosity, ε_z) represent the total porosity (ε_t). This value indicates a percentage of pores in the monolith. Together with the pore size distribution, which can be calculated from inverse size exclusion chromatography (ISEC)[21] or mercury intrusion data,[22] it directly translates into a total pore volume, V_p, usually expressed in mL/g. Furthermore, it allows calculation of the specific surface area σ, expressed in m^2/g. For the design of monolithic supports for different tasks, the influence of all components of the polymerization mixture (NBE, DMN-H6 or NBE-$CH_2O)_3SiCH_3$,

solvents, free phosphine and initiator as well as temperature) on microstructure formation was investigated. The relative ratios of all components, i. e. NBE, DMN-H6, porogens and catalyst, allowed broad variations in the microstructure of the monolithic material including structures ideal for heterogeneous catalysis.

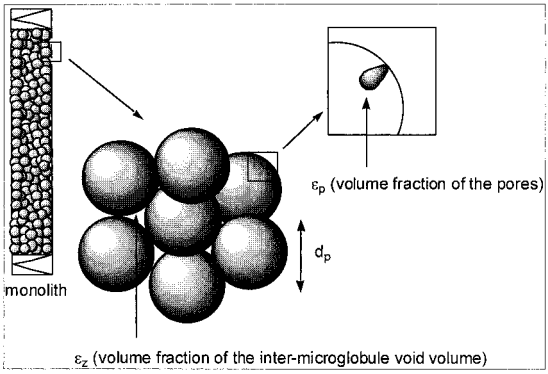


Figure 1. Physical meaning of relevant parameters of monoliths.

In summary, the volume fraction of the interglobular void volume (ε_z) and total porosity (ε_t) were varied within a range of 0 – 50 % and 50 – 80 %, respectively. Figure 2 illustrates some of the microstructures that were generated.

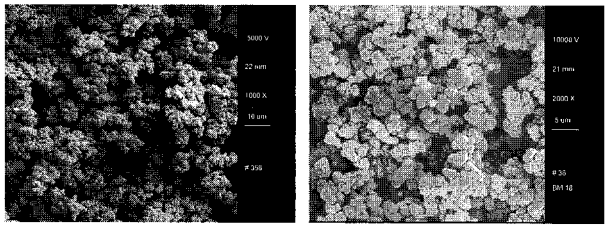
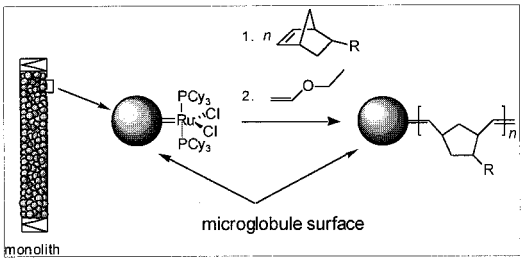


Figure 2. Microstructures of monoliths.

Functionalization, Metal Removal and Metal Content

Using the ROMP-based protocol, the living[23, 24] ruthenium-sites could be used for derivatization after rod-formation was complete. Grafting experiments and ICP-OES-based investigations revealed that more than 98 % of the initial amount of initiator were located at the microglobule surface after microstructure formation.[11] Using the initiator covalently bound to the surface,

functional monomers were grafted onto the monolith surface by simply passing solutions thereof through the mold (Scheme 2).[3, 4, 25]



Scheme 2. Surface-functionalization of monoliths.

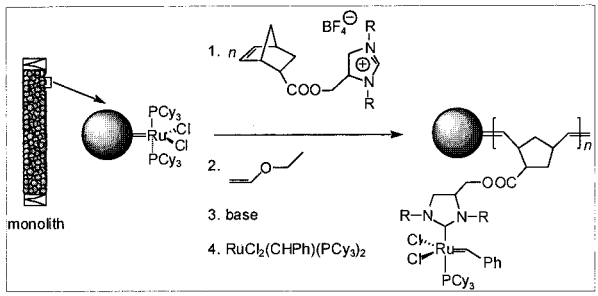
Since no cross-linking can take place, tentacle-like polymer chains attached to the surface were formed. In addition, microglobules were designed in a way that their pore size was < 1.2 nm, which basically restricted functionalization to their surface.[7] The degree of this graft polymerization of functional monomers varies within almost two orders of magnitude, depending on their ROMP activity. Important enough, the structure of the parent monolith was not affected by the functional monomer and could be optimized regardless of the functional monomer used later. Since the initiator was almost quantitatively located at the surface of the microglobules, the efficiency of *metal removal* from the monolith after polymerization was high. ICP-OES investigations revealed that the remaining ruthenium-concentrations after capping with ethyl vinyl ether (EVE) were below 10 µg/g, corresponding to a metal removal of more than 99.8 %.

Applications of Functionalized Metathesis-Based Monoliths in Catalysis

Grafted Supports for Ring-Closing Metathesis (RCM) and Related Reactions

In heterogeneous catalysis, one wants to combine the general advantages of homogeneous systems such as high definition, activity, etc. with the advantages of heterogeneous catalysis such as increased stability, ease of separation, and recycling. The first successful use of metathesis-based monolithic media for heterogeneous catalysis was accomplished by using these supports as carriers for Grubbs-type initiators based on N-heterocyclic carbenes (NHC-ligands).[26] For this purpose, monoliths with a suitable microporosity (40 %) and microglobule diameter (1.5 ± 0.5 µm) were synthesized. Consecutive „in-situ" derivatization was successfully accomplished using

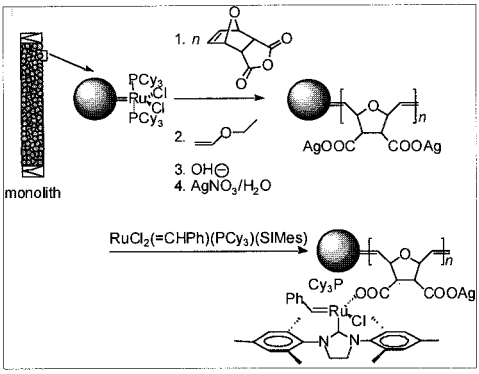
a mixture of NBE and a polymerizable NHC-precursor (Scheme 3).[11, 27-29]



Scheme 3. Immobilization of a second-generation Grubbs catalyst on a monolithic support.

The use of NBE drastically enhanced grafting yields for the functional monomer. Using this setup, tentacles of copolymer with a degree of oligomerization of the functional monomer of 2 – 5 were generated. The free NHC necessary for catalyst formation was simply generated using a strong base such as 4-dimethylaminopyridine (DMAP). In a last step, excess base was removed by extensive washing and the catalyst was immobilized/formed by passing a solution of $Cl_2Ru(CHPh)(PCy_3)_2$ over the rigid rod. Loadings of up to 1.4 % of Grubbs-catalyst on NHC base were achieved. Monolith-immobilized metathesis catalysts prepared by this approach showed high activity in various metathesis-based reactions such as ROMP and RCM. In a benchmark reaction with diethyl diallylmalonate (DEDAM), these properties directly translated into high average turn-over frequences (TOFs) of up to 0.5 s^{-1}.

In an alternative approach, monolith-supported second generation Grubbs catalysts containing unsaturated (e.g. IMes) or saturated (e. g. SIMes) NHCs[30] can be prepared by a synthetic protocol summarized in Scheme 4. Surface-derivatization of a monolith was carried out with 7-oxanorborn-5-ene-2,3-dicarboxylic anhydride followed by conversion of the grafted poly(anhydride) into the corresponding poly-silver salt. This silver salt was used for the halogen exchange with a broad variety of second generation Grubbs catalysts, leading to the catalytic species shown in Scheme 4. In the benchmark reaction with DEDAM, TONs up to 830 were achieved.[31, 32] All monolith-based catalytic systems summarized here were successfully used as pressure stable catalytic reactors.



Scheme 4. Immobilization of a second-generation Grubbs-type catalyst via Cl-exchange.

Bleeding was virtually suppressed, leading even in RCM to basically ruthenium-free products with a ruthenium-content far below 0.1 %.

Monolithic Supports for Separation Science

Due to the pure hydrocarbon backbone, monoliths prepared from NBE and DMN-H6 are strongly hydrophobic. Nevertheless, the resulting materials significantly differ from PS-DVB based resins, in that the latter one contains aromatic systems that are capable of forming π-stacks with analytes possessing aromatic groups.

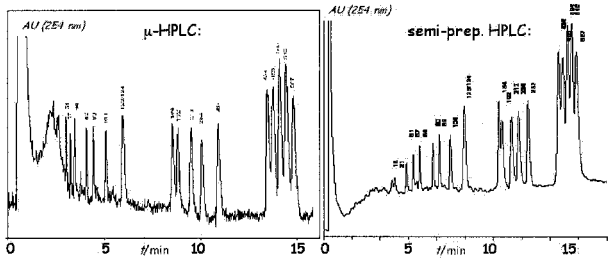


Figure 3. Separation of *ds*-DNA on monolithic supports. A) μ-HPLC, B) semi-preparative HPLC.

The impressive separation capabilities have been demonstrated by the fast separation of biologically relevant compounds such as proteins, double stranded (ds) DNA, oligonucleotides as

well as phosphorothioate oligodeoxynucleotides.[3-5, 33] As an example, the separation of 20 base pairs of *ds*-DNA was accomplished on both standard (i. e. 3x100 mm) and microanalytical (200 mm i. d.) monolithic columns (Figure 3).[6, 34]

Summary

Metathesis-based polymerization techniques have certainly found their place in materials science. This has been made possible by adding well-defined and tolerant initiators to the armor of existing polymerization systems. With these initiators, in particular ROMP has had an enormous impact on the development of both surface-modified and polymeric materials. Applications in catalysis and separation science have been added to the more "traditional" ones in optics and electronics. The ongoing developments in organometallic chemistry, polymer chemistry, and in particular in metathesis polymerization will certainly result in the permanent improvement of existing systems and techniques as well as in new applications in many areas of chemistry and materials science.

Acknowledgement

Our work was supported by the *Austrian Science Fund* (START Y-158).

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