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Porous Double-Layer Polymer Tubing for the Potential Use in Heterogeneous Continuous Flow Reactions

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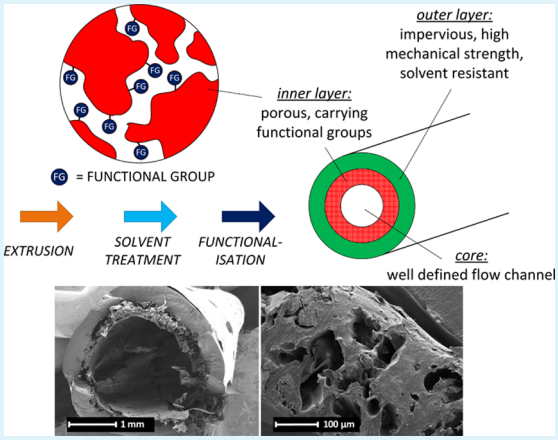
Supporting Information

ABSTRACT: Functional polymer tubing with an OD of 1/16 or 1/8 in. was fabricated by a simple polymer coextrusion process. The tubing was made of an outer impervious polypropylene layer and an inner layer, consisting of a blend of a functional polymer, polyethylene-*co*-methacrylic acid, and a sacrificial polymer, polystyrene. After a simple solvent leaching step using common organic solvents, the polystyrene was removed, leaving behind a porous inner layer that contains functional carboxylic acid groups, which could then be used for the immobilization of target molecules. Solution-phase reactions using amines or isocyanates have proven successful for the immobilization of a series of small molecules and polymers. This flexible multilayered functional tubing can be easily cut to the desired length and connected via standard microfluidic fittings.



KEYWORDS: *polymer extrusion, functional tubing, porous polymer matrix, heterogeneous catalysis, flow chemistry*

INTRODUCTION

In recent years continuous flow microreactor technology has attracted considerable interest for its use in organic and advanced materials synthesis,[1−9] biocatalysis,[10−16] or medical applications.[17,18] The most commonly used reactor designs for liquid- and gas-phase processes are chip-based and tubular devices. The small dimensions of the fluidic pathways (typically between 100 and 1000 μm) result in a well-defined flow regime, high heat and mass transfer rates, and a narrow residence time distribution.[19−21] These favorable processing characteristics allow for reactions to be conducted at quasi-isothermal conditions, often resulting in higher conversions and better selectivity. Several research groups have looked into extending the use of microfluidic devices for solid−liquid phase applications, such as heterogeneous catalysis, which brings along a set of challenges not present in homogeneous liquid or liquid−liquid phase processes. On one hand the solid phase needs to offer a large amount of active sites, which is often addressed by creating small pores; on the other hand, the microfluidic device needs to be designed such that the transport of starting materials and products in and out of the system is efficient, which usually requires larger channels. To create a catalytically active yet practical reactor device, a combination of both is necessary. To date, mainly three different approaches have been utilized for use in heterogeneous catalysis in microfluidic or flow chemistry systems: (a) porous polymer or silica supported beads or other porous particles inside fixed beds,[3,7,10,22−24] (b) porous polymer or silica monoliths,[25−29] and (c) deposition of porous catalytic layers onto chip- or platelet-based devices.[9,12,13,16,30,31] Herein, we describe a new approach using a multilayered tubular reactor system, which could offer strategic benefits over existing technology. This tubular material consists of an outer, impervious, nonreactive polymer layer, an inner, porous, catalytically active polymer layer, a central flow channel, and can be made by a simple polymer extrusion process. The porous layer is formed by a solvent leaching step, whereby a soluble polymer phase is removed from a previously prepared blend consisting of an insoluble functional polymer and a soluble sacrificial polymer (see Figure 1). The central flow channel ensures that pressure

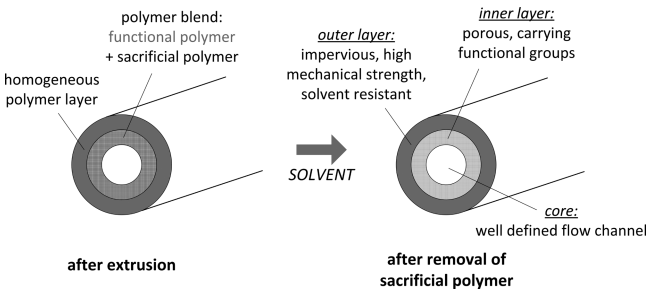


Figure 1. Two-layer polymer tubing, before and after solvent treatment.

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drop is low, easily predictable, and that the flow is regular. This is a big advantage over most monolithic-type materials, which often suffer from high-pressure drops and irregular flow, such as the designs by Ley[25,26] and Haswell.[28,29] These systems are made by a complex, often multistage synthesis and require elaborate preparation and washing protocols.[28] As a result of the synthesis method, the size of monoliths is often limited to small preparative or laboratory scales; for examples, Ingham et al.[25] report that 15 mm is the largest diameter at which the temperature gradient across the column, in which the monolith is made, still allows for an effective polymerization of the monolith. Particle- or bead-based solid-supported reagents suffer from similar problems as monoliths, when used in catalytic bed reactors: The fluid flow through the bed as well as temperature and concentration gradients are highly nonuniform along the cross section of the packed bed column. A tubular device is also much less complex than most chip-based designs, which generally are fabricated by micromachining technologies. Microfluidic chips or plates have a limited fluidic pathway lengths and reactor volume; for example, Rebrov et al.[31] are using stainless steel plates with a length of 8 mm and a width of 4.34 mm. The application of the catalytic material onto the chips or plates also requires complex synthesis steps, such as hydrothermal treatments and calcinations at temperatures of up to 600 °C.[30,31] In contrast, tubular devices can be produced via a very cost-effective extrusion process, which is amenable to large-scale manufacture. Additionally, flexible and standard size polymer tubing has the advantage that it can be easily cut to the desired length, handled without specialist equipment, and connected to "off-the-shelf" fluid handling components such as pumps and valves via standard microfluidic fittings. The investigations herein are based on earlier work,[32] where a functional polymer capillary device was used to conduct palladium-catalyzed hydrogenation reactions. In this earlier work a polymeric multicapillary extrudate made from ethylene vinyl alcohol copolymer was coated directly with the palladium catalyst, without forming a porous layer first. The motivation for the work herein, was to first increase the amount of active sites by introducing a porous layer and second to increase the stability of the tubular extrudate by adding a solvent and temperature resistant outer layer. Especially the lack of the latter limited the use of the catalytic capillary device described previously.[32]

■ EXPERIMENTAL SECTION

Information on sample analysis and imaging procedures as well as on the polymers and chemicals used and the corresponding suppliers can be found in the Supporting Information.

Preparation of Polymer Blends and Sheets. All polymers supplied as beads or pellets were ground in a grinding mill (Glenn Mills, Disc Mill 500) under addition of liquid nitrogen. The polymer powders were then dried overnight in a vacuum oven (National Appliance Company, 58316) at ≤200 mbar and ∼30 K below their melting point (max. drying temperature 360 K). The residual water content was tested on a moisture analyzer (Arizona Instruments, Computrac VaporPro). If the value was below 100 ppm the powder was considered dry enough for extrusion; if not, the drying process was repeated. The polymer blends, consisting of 30 to 70% functional polymer and 70 to 30% sacrificial polymer, were prepared using a 13 mm counter-rotating twin screw mini extruder (Barrell) with a single hole button die. The desired ratio of the two polymers was fed as powder into the hopper of the extruder under dry nitrogen atmosphere. Depending on the polymer mixture used, the die temperature was kept between 160 and 210 °C, The screw speed was set to 150 rpm to maintain the torque at ∼50%. The polymer strand exiting the extruder was then pelletized on a rotary cutter (Isuzu Pelletizer with tungsten carbide cutting blades), yielding small pellets of the desired polymer blend. The pellets were then pressed into sheets on a heated press (Wabash hydraulic press, 12−10−1T) using a Teflon-coated steel frame. Depending on the polymer mixture used, the pressing temperature was set between 200 and 250 °C, and the pressing time varied between 5 and 30 min (at 12 t/in^2). The resulting sheets had a thickness of ∼1 mm, and they were then cut into sample strips of 15 × 30 mm.

Extrusion of Polymer Tubing. For all extrusion experiments, the preparation of the polymer blend and drying of the polymer powders were conducted as described in the previous section. The extrusion of the two-layer polymer tubing was carried out on a two extruder setup. One line using a 13 mm counter-rotating twin screw mini extruder (Barrell) was delivering the molten polymer blend (inner layer); the other line using a 16 mm corotating screw extruder (Prism Eurolab 16) fitted with a gear-driven melt pump (Barrell) was delivering the molten polymer for the outer layer. A third line delivering the core fluid, either air or silicone oil, was attached to a syringe pump (TeledyneIsco 500 D) pumping at a rate of 1 mL/min. The exit temperature of the Barrel mini extruder was kept between 190 and 200 °C, the screw speed was set to 120 rpm maintaining the torque between 30 and 60%. The exit temperature of the Prism screw extruder was kept between 230 and 250 °C, the screw speed was set to 100 rpm, and the torque was between 26 and 28%; the gear pump was set to 12%. All three lines were fed into an annular extrusion die (Guill Tool & Engineering Co., Guill 812 crosshead); the die temperature was set between 220 and 257 °C. Fine adjustments were made during the extrusion process to vary the dimensions of the extrudate and its properties. The tubular extrudate exiting the die was cooled either in air or by passing through a water bath and was then hauled away on a conveyor belt. A diagram of the extrusion dye is shown in the Supporting Information (see Figure S1).

Preparation of Porous Polymer Matrix by Chemical Leaching. Sheet samples made from different polymer blends as described above (dimensions: 30 × 15 × 1 mm) were fully immersed in one of the following solvents: ethyl acetate (EtOAc), dichloromethane (DCM), or acetone. After extensive solvent testing, these three solvents were found to be the most suitable choice to remove the sacrificial polymer phase from the blend (see Supporting Information, Table S1). The sheet sample was agitated by one of four different modes: shaker plate, stirrer bar on magnetic stirrer plate, metal paper clip on magnetic stirrer plate, or two-arm shaker (see Supporting Information, Figure S2). Depending on polymer combination, amount of sacrificial polymer, and solvent used, the leaching process took between 2 and 40 h to complete. The resulting porous samples were washed with copious amounts of solvent (EtOAc or DCM) and then dried in air for a minimum of 6 h. For some experiments, weight measurements were taken at certain time intervals during the process for which the same washing and drying protocol was used. The leaching process was terminated when the mass loss compared to the previous measurement was less than 1 wt %. The preparation of porous tubing samples was analogous to this procedure. The porous samples were then characterized by scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR). After the leaching process, the surface of the porous polymer samples could be functionalized with a range of different compounds, making use of the carboxylic acid groups present in the polymer matrix.

Functionalization of Porous Polymer Matrix with Benzylamine. A rectangular polymer sheet sample (after previous removal of the sacrificial phase), weighing 78.8 mg, was placed inside a 5 mL microwave vial. A solution consisting of 373 mg of benzylamine, 270 mg of 1-ethyl-3-(3-(dimethylamino)propyl)carbodiimide (EDC), and 4.3 mg of *N*-hydroxysuccinimide (NHS) in 5 mL of distilled water was added, and the vial was sealed. The reaction was then conducted in an oil bath at 60 °C over 4 h. After reaction, the polymer sheet sample was rinsed with copious amounts of water followed by three washes in a sealed vial with acetonitrile (MeCN), enhanced by vigorous shaking (see also Figure S2 in the Supporting Information). Finally the sheet was washed overnight in water, followed by drying in air over several

days. The sample was then characterized by FTIR. This procedure was adopted from Hermanson.[33]

Functionalization of Porous Polymer Matrix with 4-Nitroaniline. A rectangular polymer sheet sample (after previous removal of the sacrificial phase), weighing 83.2 mg, was placed inside a 5 mL microwave vial. A solution consisting of 541 mg of 4-nitroaniline, 484 mg of *N*,*N*′-diisopropylcarbodiimide (DIC), and 479 mg of NHS in 5 mL of dry MeCN was added, and the vial was sealed. The reaction was then conducted in an oil bath at 60 °C over 4 h. After reaction, the polymer sheet sample was rinsed with copious amounts of MeCN followed by three washes in a sealed vial with MeCN, enhanced by vigorous shaking. Finally the sheet was dried in air overnight. The sample was then characterized by FTIR.

Functionalization of Porous Polymer Matrix with Polyethylenimine. A rectangular polymer sheet sample (after previous removal of the sacrificial phase), weighing 89.5 mg, was placed inside a round-bottom flask. A suspension consisting of 484 mg of DIC, 479 mg of NHS, 1750 mg of polyethylenimine (branched, average molecular weight: 9800 g/mol), and 20 mL of dry MeCN was added, and the reaction was then conducted in an oil bath at 60 °C over 5 h. After reaction, the polymer sheet sample was rinsed with copious amounts of MeCN followed by three washes in a sealed vial with MeCN, enhanced by vigorous shaking. Finally the sheet was washed over two nights in ethanol, followed by drying in air overnight. The sample was then characterized by FTIR.

Functionalization of Porous Polymer Matrix with 4-Nitrophenylisocyanate. A rectangular polymer sheet sample (after previous removal of the sacrificial phase), weighing 88.7 mg, was placed inside a 5 mL microwave vial. A suspension consisting of 603 mg of 4-nitrophenylisocyanate, 3.5 mg of magnesium chloride ($MgCl_2$), and 5.5 mL of dry MeCN was added, and the vial was sealed. The reaction was then conducted in an oil bath at 60 °C over 4 h. After reaction, the polymer sheet sample was rinsed with copious amounts of MeCN followed by three washes in a sealed vial with MeCN, enhanced by vigorous shaking. Finally the sheet was washed over two nights in dimethyl sulfoxide, followed by rinsing with MeCN and drying in air over several days. The resulting sample had an intense yellow color and was characterized by FTIR. This procedure was based on work described by Gürtler et al.[34]

Functionalization of Porous Polymer Matrix with Polyethylene Glycol. Rectangular polymer sheet samples (after previous removal of the sacrificial phase), weighing between 84 and 140 mg, were each placed inside a 5 mL microwave vial. They were then reacted on a laboratory microwave reactor (Biotage Initiator) following one of three protocols: (a) A suspension consisting of 1050 mg of hexamethylene diissocyanate (HDI), 6 mg of $MgCl_2$, and 5 mL of dry MeCN was added, and it reacted in a first step at 60 °C over 4 h. After washing with dry MeCN, the sheet was reacted in a second step with 2470 mg of polyethylene glycol (PEG, average molecular weight: 8000 g/mol) and 24 mg of dibutyltin dilaurate (DBTDL) in 5 mL of dry MeCN for 2.5 h at 60 °C. (b) A suspension consisting of 1050 mg of HDI, 6 mg of $MgCl_2$, and 5 mL of dry MeCN was added, and it reacted in a first step at 60 °C over 4 h. Then, 2470 mg of PEG (average molecular weight: 8000 g/mol) and 24 mg of DBTDL were added to the mixture and reacted in a second step for 2.5 h at 60 °C. (c) A suspension consisting of 1050 mg of HDI, 6 mg of $MgCl_2$, 2470 mg of PEG (average molecular weight: 8000 g/mol), 24 mg of DBTDL, and 6 mL of dry MeCN was added, and it reacted in one step at 60 °C over 6.5 h. After each of these three reaction protocols, the polymer sheet samples were rinsed with copious amounts of MeCN followed by three washes in a sealed vial with MeCN, enhanced by vigorous shaking. Finally they were washed overnight in MeCN, followed by drying in air overnight. The samples were then characterized by FTIR.

RESULTS AND DISCUSSION

A total of 14 different melt-extrudable polymers were considered and tested initially for use as the outer layer and for the blend; these included polyolefins, poly(vinyl alcohol)s, polyvinyl acetates, poly(lactic acid), and a variety of ethylene copolymers. After solvent stability tests and considering the compatibility of certain combinations of polymers for melt extrusion, a set of six polymers were selected for further investigations, applying the following selection criteria: (a) the polymer for the outer layer should have the highest possible stability to organic solvents, acids, and bases as well as to temperature, and it should have high mechanical strength so that a tubular extrudate could withstand elevated pressures; (b) the functional polymer should have good solvent and temperature stability; swelling when in contact with organic solvents is acceptable to a certain degree, but dissolving or other permanent damage is not; (c) the functional polymer should carry the highest possible amount of reactive groups; (d) the sacrificial polymer should dissolve easily and rapidly in organic solvents or water; (e) all polymers need to be melt-processable, and their melt flow index (MFI) and extrusion temperature range need to be compatible. Following these criteria, we selected the polymers:

- polypropylene (PP), LyondellBasell—PF 814
- polyethylene-*co*-vinyl acetate (PEVAc), DuPont—Elvax 260
- polyethylene-*co*-glycidyl methacrylate (PEGMA), Arkema—Lotader AX 8840
- polyethylene-*co*-methacrylic acid (PEMAA), DuPont—Nucrel 2940
- polylactic acid (PLA), NatureWorks—7000D
- polystyrene (PS), Resirene—HH 112

PP was chosen as the polymer for the outer tubing layer, as it possesses a considerable amount of mechanical strength and has very good stability to all solvents tested; the three copolymers, namely, PEVAc, PEGMA, and PEMAA, which all showed reasonably good solvent stability, were considered as the functional polymer in the polymer blend; PLA and PS, which are readily soluble in a series of organic solvents, were chosen as the sacrificial polymer in the blend. Figure 2 shows

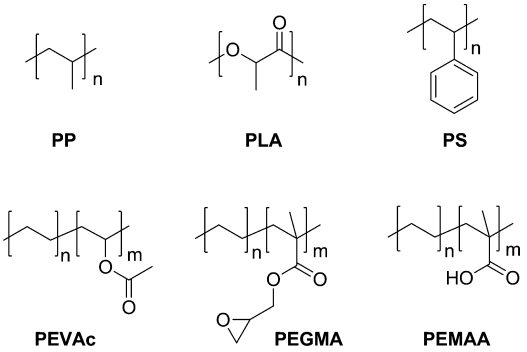

Figure 2. Polymer structures.

the chemical structures of the six polymers, and Table S1 in the Supporting Information lists physical properties, together with the results from the solvent stability tests.

The three functional polymers, PEVAc (functional group: acetate/hydroxyl, after hydrolysis), PEGMA (functional group: epoxide), and PEMAA (functional group: carboxylic acid), were all copolymers of ethylene with varying contents of the functional monomer; while PEVAc had the highest content, PEGMA had the lowest. The solvent stability of PEGMA was the best of the three, while PEVAc performed the worst; PEMAA presented a good compromise, as for both criteria its

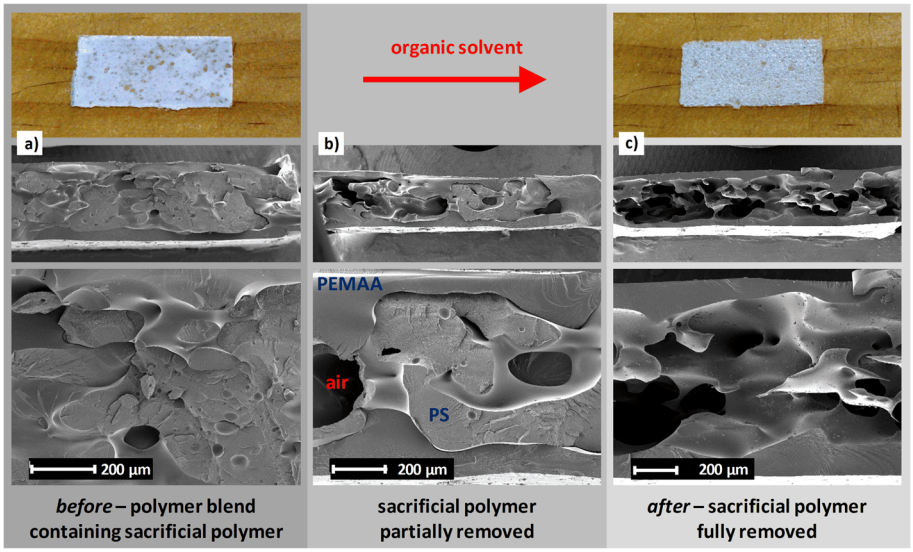

Figure 3. Photos and SEM images of polymer sheets before (a), part way through (b), and at the end of the leaching process (c); blend consists of 50% PEMAA and 50% PS; dimensions of sheet sample: 30 × 15 × 1 mm.

performance was in-between that of the other two copolymers (see Supporting Information, Table S1). To test the compatibility of the three functional copolymers with a sacrificial polymer in a blend, and to investigate the potential of forming a porous matrix, we prepared a set of sheet samples on a hot press. The leaching was then performed in a glass vial filled with either EtOAc, DCM, or acetone (see Experimental Section). Figure 3 shows photographs of polymer sheet samples before and after leaching and SEM images of the cross section of sheet samples before leaching, after leaching, and of a sample where the leaching process was stopped midway—these samples were made from a 50/50 PEMAA/PS blend.

Figure 4 shows SEM images of porous structures created by this leaching process using samples made from various different combinations of functional and sacrificial polymer: Images (a) and (b) show PEMAA/PS samples, images (c) and (d) show PEMAA/PLA samples, image (e) shows a PEGMA/PLA sample, and image (f) a PEVAc/PS sample. It can be seen that the choice of sacrificial polymer has a big impact on the porous structure formed, which is an effect of the miscibility of the two polymers in the molten state. The PEMAA samples with PS had a tortuous and interconnected porous matrix, while the samples with PLA contain isolated spherical pockets where the PLA used to be. These pockets seem less interconnected than the structure created with PS, and these samples might be less suitable for use in heterogeneous catalytic applications. When using blends containing PEGMA and PEVAc systems, another set of difficulties arose that complicated further tests.

PEGMA systems with high contents of the sacrificial polymer (70%) resulted in complete destruction of the sample as it was "flaking apart" during the leaching process; when lower contents of the sacrificial polymer (≤50%) were used, almost no leaching at all occurred. Hence, no porous structure was formed (see Figure S3 in the Supporting Information). For PEVAc systems, the limited solvent stability of the functional polymer presented a problem, as the efficient leaching solvents EtOAc and DCM, which were successfully tested for PEMAA blends, could not be used. Instead we had to resort to acetone, which did not result in satisfactory removal of the sacrificial polymer, even after several days of exposure (see Supporting Information, Figure S3). As a result of these findings, only PEMAA samples were used for all further tests.

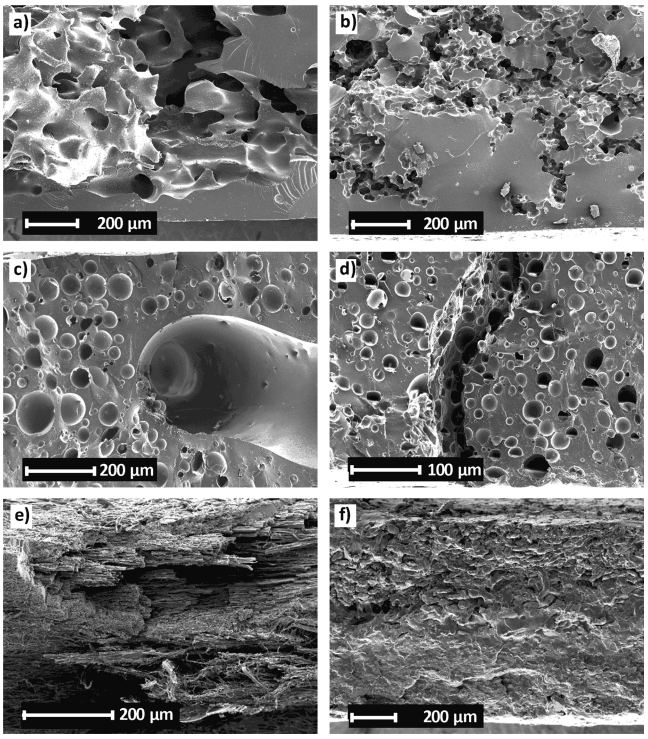

Figure 4. SEM images of polymer sheets from different blends after leaching; (a) PEMAA/PS—60/40, solvent: EtOAc; (b) PEMAA/PS—70/30, solvent: EtOAc; (c) PEMAA/PLA—50/50, solvent: DCM; (d) PEMAA/PLA—70/30, solvent: DCM; (e) PEGMA/PLA—30/70, solvent: DCM; (f) PEVAc/PS—50/50, solvent: acetone.

To characterize the leaching process, a set of experiments using PEMAA/PS and PEMAA/PLA samples were conducted, whereby the sample weight and therefore the leaching progress were monitored over time. The ratio of PEMAA to the sacrificial polymer and the leaching solvent were also varied. Figure 5 shows the results from these experiments.

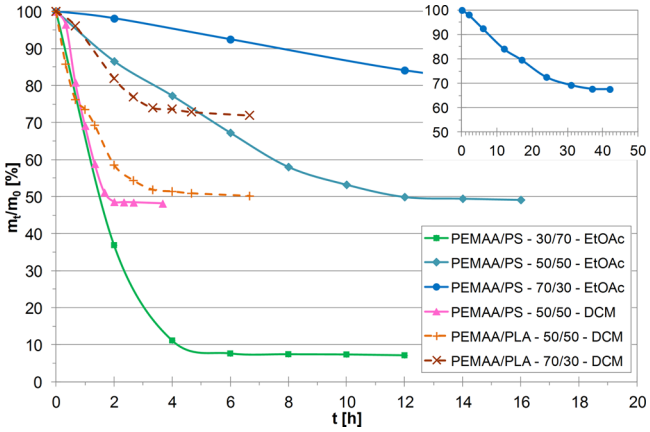

Figure 5. Mass loss of sheet samples over time for different polymer blends; (inset, upper right) The entire curve for PEMAA/PS—70/30, leached with EtOAc.

First, it can be observed that DCM is a better leaching solvent than EtOAc for the herein-investigated systems. While the leaching process was completed with DCM between 2 and 6 h, it took 6 to 40 h with EtOAc. Especially the comparison of the 50/50 PEMAA/PS sample subjected to these two solvents clearly underpins this point. Second, PS was removed slightly faster than PLA, when DCM was used as the leaching solvent (compare 50/50 samples). We further found that samples containing ≥50% PEMAA resulted in the expected mass loss and not more (50/50 samples retained ∼50% of the initial weight at the end of the leaching process, 70/30 samples ∼70%); this was different for samples containing mainly the sacrificial polymer: Of the 30/70 sample (containing 30% PEMAA), only less than 10% of the initial mass was left after leaching. This suggests that large amounts of PEMAA were trapped within the PS phase and subsequently leached out together with the PS. Control samples made from pure PEMAA (no sacrificial polymer) were subjected to the same leaching conditions, to see that there is no partial leaching occurring from this polymer. After 48 h in DCM or EtOAc, the sample weights had not changed measurably (less than ±0.1%).

To demonstrate the activity of the porous polymer matrix for chemical modification, and therefore for use in heterogeneous catalysis applications, we tested a series of solution-phase functionalization procedures—these included the immobilization of small molecules: benzyl amine, **1**, 4-nitroaniline, **2**, and 4-nitrophenylisocyanate, **4**; as well as polymers: polyethylenimine, **3**, and polyethylene glycol, **5**. In all cases, a covalent bond between the target molecules and the PEMAA polymer surface was formed, via one of three routes: reaction of the carboxylic acid groups in PEMAA with either an amine (A), an isocyanate (B), or a diisocyanate linker to hydroxyl groups (C).[33−35] All three routes result in the formation of amide linkages (see Scheme 1); the details of the procedures are presented in the Experimental Section.

Table 1 presents the reaction conditions and analysis results of these experiments. The functionalization with PEG was conducted using three different protocols (see also Experimental Section): first attaching the diisocyanate linker, then removing any excess linker by washing, followed by immobilization of PEG (entry **5-a**); first attaching the diisocyanate linker, followed by immobilization of PEG, with excess linker present (entry **5-b**); immobilization of PEG in a one-step procedure (entry **5-c**). For each experiment in Table 1 the weight gain after functionalization was recorded, and the polymer sample was analyzed by FTIR. The cleaning protocols after functionalization (as described in the Experimental

Scheme 1. Functionalization of the Porous PEMAA Matrix, via One of Three Routes: Reaction with Amines (A), Isocyanates (B), or a Diisocyanate Linker to Hydroxyl Groups (C)

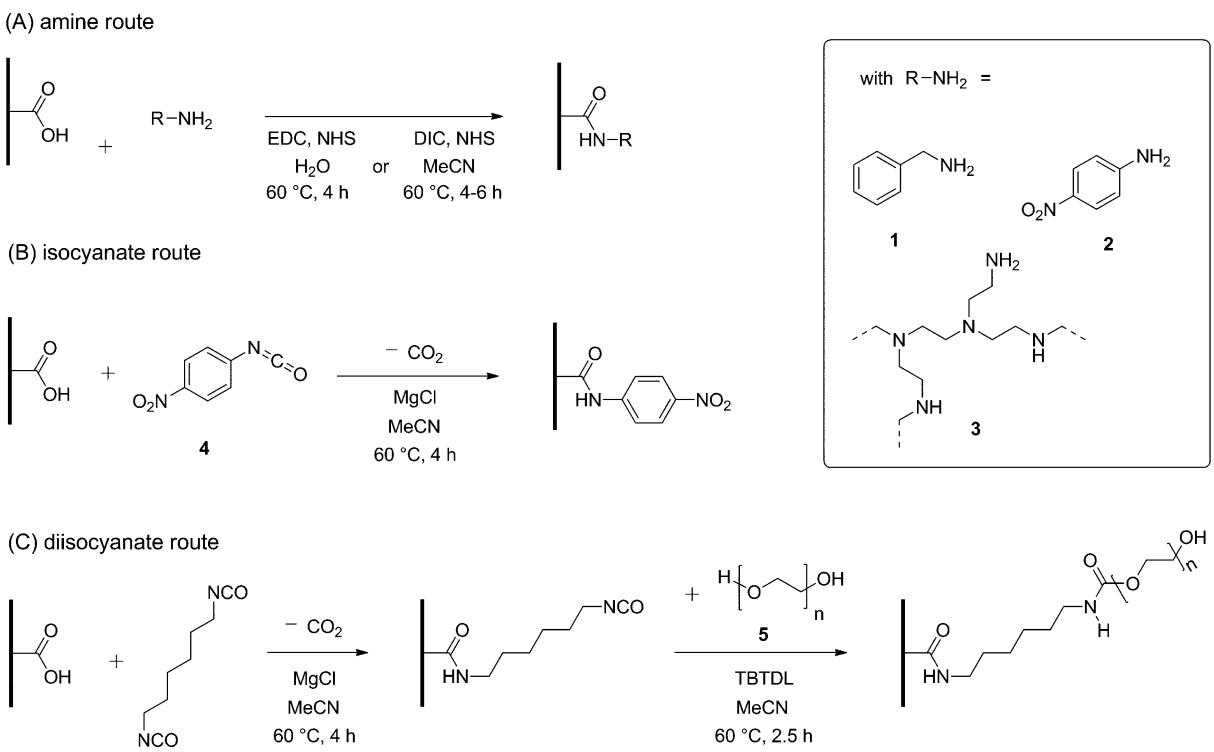

Table 1. Results from the Functionalisation Experiments

immobilized reagent/entry	catalyst and reaction time	weight gain [wt %]	elemental analysis			
			C [wt %]	H [wt %]	N [wt %]	O [wt %]
0[a]			80.24	12.98	0.00	6.78
1	EDC + NHS, 4 h					
2	DIC + NHS, 4 h	3.1	80.72	13.09	0.71	5.48
3	DIC + NHS, 6 h	23.1	76.16	12.73	5.01	6.10
4	$MgCl_2$, 4 h	2.4	73.25	11.02	3.26	12.47
5-a	$MgCl_2$, 4 h/DBTDL, 2.5 h	7.1				
5-b	$MgCl_2$, 4 h/DBTDL, 2.5 h	12.7	78.18	12.77	2.30	6.75
5-c	$MgCl_2$ + DBTDL, 6.5 h	15.3				

[a]Base polymer; **5-a** - functionalization performed in 3 steps: (1) polymer substrate reacted with HDI, + $MgCl_2$, 4 h, 60 °C, (2) removal of excess HDI by washing with solvent, (3) immobilization of PEG, +TBTDL, 2.5 h, 60 °C; **5-b** - functionalization performed in 2 steps: (1) polymer substrate reacted with HDI, + $MgCl_2$, 4 h, 60 °C, (2) immobilization of PEG, +TBTDL, 2.5 h, 60 °C (no removal of excess HDI); **5-c** - functionalization performed in 1 step: polymer substrate reacted with HDI and PEG, + $MgCl_2$ and TBTDL, 6.5 h, 60 °C;

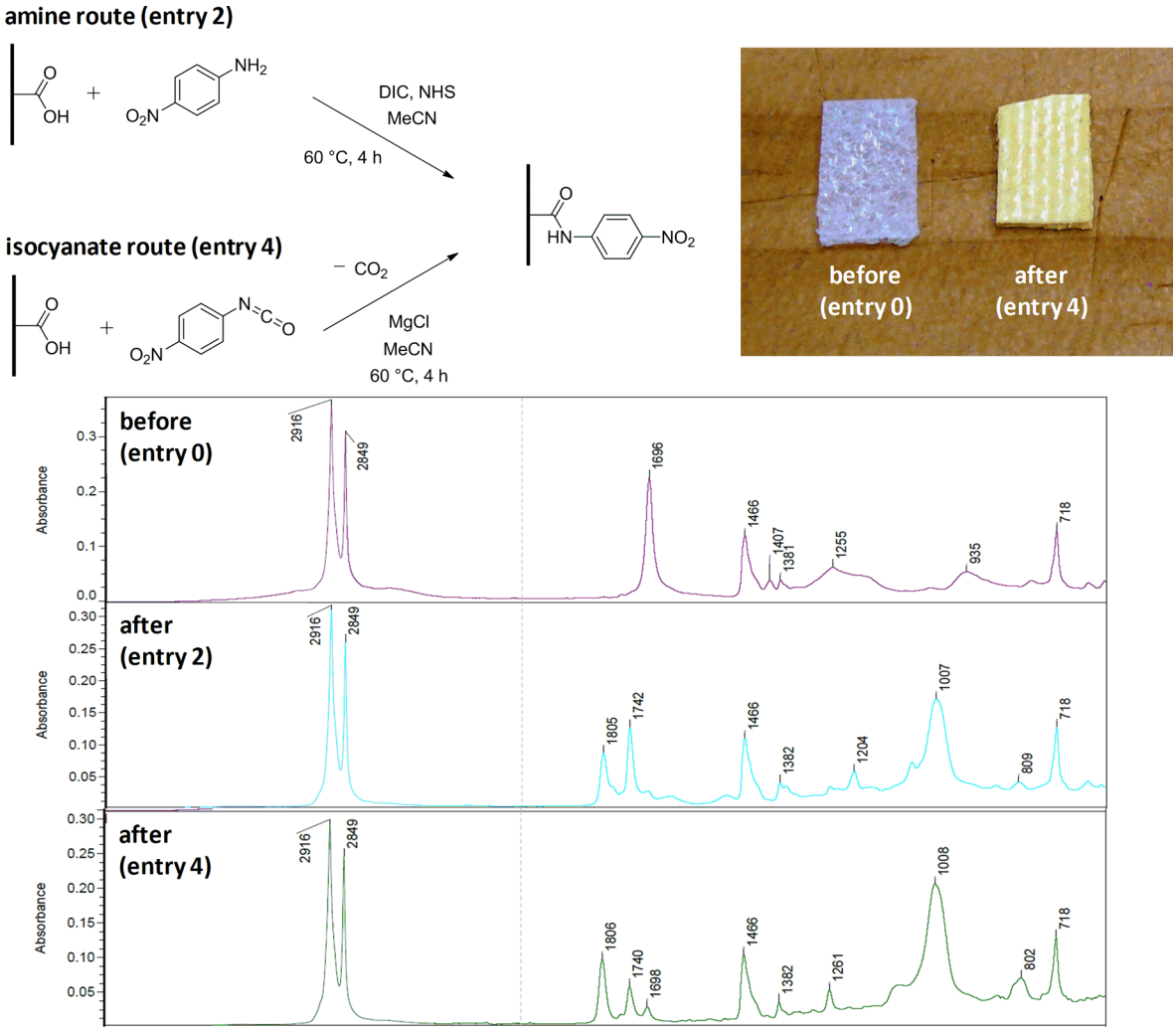

Figure 6. IR spectra of polymer samples (50% PEMAA/50% PS - removed) before and after functionalization with **2** or **4**, photo shows samples before and after functionalization with **4**.

Section) were effective for all samples but entry **1**; as a result, the weight measurement of this sample was inconclusive and is not reported. In all other samples the weight gain lay between 3 and 23% of the untreated sample mass, with the experiments with the polymers PEG and PEI showing the highest values (especially entries **3**, **5-b**, and **5-c**). For entries **2**, **3**, **4**, and **5-b**, an elemental analysis was conducted, which could be compared to the untreated sample (i.e., the base polymer, presented in the first line in Table 1). As we were using a non-nitrogen-containing base polymer, the elemental analysis of the untreated sample resulted in 0% nitrogen, as expected. The value for nitrogen increased in all functionalized samples, which is a clear indication for the success of the immobilization process using nitrogen-containing molecules. The highest

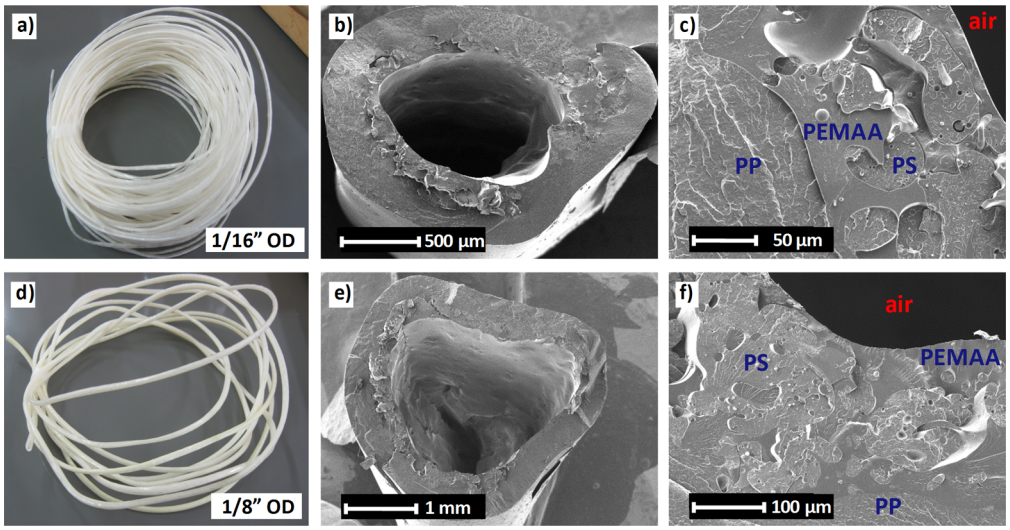

Figure 7. Photos and SEM images of polymer tubing before leaching; (a) to (c) 1/16 in. OD tubing; (d) to (f) 1/8 in. OD tubing.

content of nitrogen was measured in the sample using PEI, entry **3**; here, not only the linking moiety contains nitrogen but also the backbone of the immobilized polymer.

Further evidence for a successful immobilization process could be gathered from the IR results of these samples. Figure 6 shows IR spectra of the untreated base polymer and of the samples from entries **2** and **4**, as well as a photograph comparing an untreated sample to entry **4**. The photo clearly shows the color change associated with the functionalization process: The transparent polymer turned bright yellow after reaction with the highly yellow colored isocyanate **4**. Even after multiple washing cycles, this color did not fade (and the washing solution was not colored), which indicates that **4** is covalently bonded to the polymer matrix. When comparing the IR spectra before and after functionalization, there are a set of characteristic peaks that can be used to identify the immobilized species: the characteristic peaks for the formed amide bond at 1698 and 1740 cm^{-1} are appearing after reaction, while the peak at 1696 cm^{-1}, characteristic for the carboxylic acid and present in the base polymer, is diminished (see, e.g., Pretsch et al.[36]). IR spectra of reactions with **1**, **3**, and **5** gave similar evidence for the formation of amide linkages; these spectra can be found in the Supporting Information (Figures S4–S6). The immobilization of the polymers **3** and **5** was especially easy to follow by IR, as large signals of the immobilized polymers were present in the treated sample, overlaying the base polymer signals.

After protocols for the formation of the porous polymer matrices and for the solution-phase functionalization process were established, we wanted to investigate a polymer coextrusion process to form tubular material, containing a porous inner layer. For the inner layer a 50/50 blend of PEMAA and PS was chosen. An annular extrusion die with two inlets for polymer melts and one inlet for a core fluid (oil or air) was used, together with two polymer extruders (see Experimental Section). The result was a tubular extrudate with outer diameters of either ∼1/16 or ∼1/8 in. These ODs were chosen as they are standard sizes and could be easily connected to existing flow chemistry equipment, using standard plastic or steel fittings. Unfortunately, the tubing we obtained from these experiments showed an irregular shape over its cross section, and it was also varying measurably in diameter along its length. This made the connection to pumps and other tubing impossible using standard fittings. However, we could investigate the leaching process of short sections of the tubing in a beaker in a way similar to that by which the leaching experiments with the sheet samples were conducted. Figure 7 shows a set of photographs and SEM images of both the 1/16 and 1/8 in. OD tubing after extrusion; Figure 8 shows some of these samples after leaching with EtOAc.

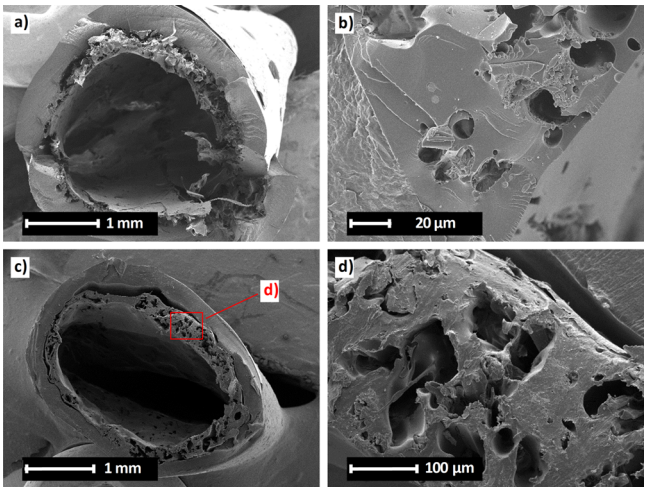

Figure 8. SEM images of 1/8 in. OD polymer tubing after leaching in EtOAc; samples in (a) and (b) were extruded using air as core fluid; the sample shown in (c) and (d) were extruded using silicone oil as core fluid.

Figure 7 shows that the extrudate has formed as expected, with an outer layer consisting of pure PP and an inner layer consisting of a 50/50 blend of PEMAA and PS. The sacrificial PS could then be leached with EtOAc to yield a porous inner layer, surrounded by an impervious outer layer (see Figure 8). The fact that the tubing did not have a round shape could be due to the lack of compatibility of PS with the other two olefinic polymers. While they are relatively soft and elastic, the PS we used was much stiffer and therefore yielded in a stiff and irregular extrudate. Furthermore, the PS was not as miscible with PEMAA as some of the other sacrificial polymers we have

investigated, which might have further complicated the extrusion process. In future experiments, we plan to replace PS with a more compatible polymer, while we keep investigating both PEMAA and PP. We expect that with a suitable sacrificial polymer that is a good match to PEMAA in terms of MFI and miscibility, we should be able to produce regularly shaped polymer tubing for use in heterogeneous catalytic solution-phase applications.

CONCLUSIONS

Herein we have presented preliminary results into the formation of functional polymer tubing that is made by a simple polymer extrusion process. This extrusion setup consists of two polymer feed lines and one core fluid (air or oil), joined in one annular die, and forming a two-layer tubular extrudate. The resulting tubes (1/16 or 1/8 in. OD) contain an outer impervious PP layer and an inner layer, consisting of a blend of a functional copolymer, PEMAA, and a sacrificial polymer, PS. After a simple solvent-leaching step using common organic solvents, the PS is removed, leaving a porous inner layer that contains functional carboxylic acid groups, which can be used for the immobilization of target molecules such as biocatalysts. We have characterized the solvent treatment and the resulting porous structures with a set of polymer sheet samples as well as with the final tubing material. Test reactions using three different chemical immobilization routes (amines, isocyanates, and diisocyanate linkers) have successfully been applied to the porous sheet samples and have resulted in the successful immobilization of small molecules, including highly colored aromatic compounds, as well as the polymers PEG and PEI. Because of an irregular tubing diameter and irregular thickness of the two polymer layers, which were a result of the instabilities of the extrusion process, the extrudate did not meet the requirements for use with standard microfluidic equipment, including pumps and fittings. In future experiments, we plan to replace PS with a more compatible polymer, to improve stability of the extrusion and thus the quality of the tubing. We also plan to characterize porosity of and pore sizes inside the extrdudates by standard techniques such as gas adsorption and mercury intrusion measurements. A catalytic tubing material, with a uniform diameter and thickness, that can offer a large amount of active sites in a porous inner layer, combined with a well-defined central flow channel, which can be manufactured by a simple extrusion process, would offer a series of strategic advantages. Such tubing can be used with a variety of different catalysts, as long as they are amenable to solution-phase immobilization as described herein, and it can be easily cut to the desired length and connected to other components such as pumps and valves via standard microfluidic fittings.

ASSOCIATED CONTENT

Supporting Information

Table containing physical properties of the polymers used within this investigation and results of solvent stability tests; diagrams of the extrusion die; diagrams showing the different stirring mechanisms, applied during the leaching protocols; photos of polymer sheets made from PEGMA and PEVAc blends after leaching; FTIR spectra of polymer samples (50% PEMAA/50% PS - removed) before and after functionalization with **1**, **3**, and **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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