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Communications to the Editor

One-Pot Tandem Synthesis of a Core−Shell Brush Copolymer from Small Molecule Reactants by Ring-Opening Metathesis and Reversible Addition−Fragmentation Chain Transfer (Co)polymerizations

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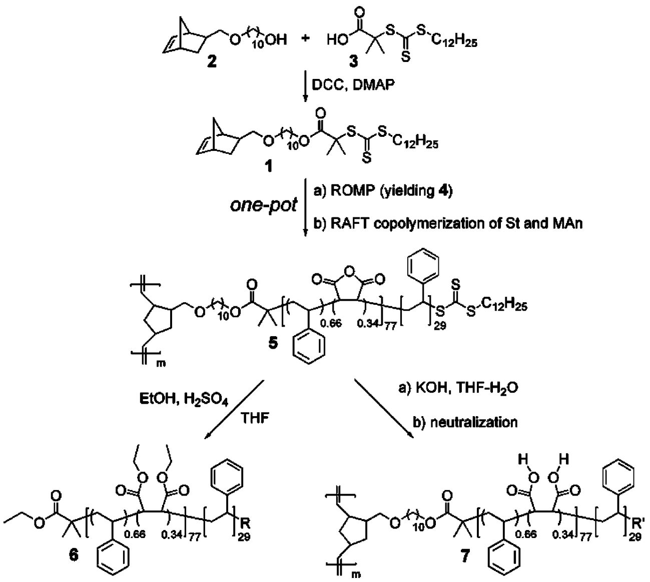
As an important type of nanoscopically sized single macromolecule, brush copolymers have attracted significant attention due to their special properties and interest in the development of elegant synthetic methods for their preparation.[1,2] Brush copolymers can be obtained generally by a "grafting from" (graft growth from a polymer backbone), a "grafting through" (polymerization of macromonomers), or a "grafting onto" approach (polymeric coupling reactions using a polyfunctional coupling agent).[3] With advances in living radical polymerization techniques,[4−9] a variety of brush copolymers have been synthesized by "grafting from" strategies via atom transfer radical polymerization (ATRP),[10−12] nitroxide-mediated polymerization (NMP),[13] or reversible addition−fragmentation chain transfer (RAFT) polymerization.[14] In addition, unique brush copolymers comprised of diblock grafts have also been prepared by "grafting from" approaches via ATRP or NMP.[11−13] Termed as core−shell brush copolymers due to their topological feature, they have been used as single macromolecular templates in the preparation of core−shell nanomaterials.[13,15,16]

We are interested in polymer-based nano-objects having well-defined compositions, structures, and properties. Typically, we have applied a self-assembly and covalent stabilization strategy[17] to produce nanoscale single molecules as spheres, cylinders, and other shapes having a core−shell morphology.[18−22] The dimensions of the resulting nanostructures are thereby determined by the self-assembly processes. Our interest shifted recently to strategies that would allow for a higher degree of control over the entire macromolecular architecture and, therefore, has focused upon brush copolymers and their transformations into other types of nanomaterials.[13]

Because the synthesis of brush copolymers typically requires complicated and time-consuming procedures, we have conducted research to develop facile synthetic methods for the preparation of brush copolymers. On the basis of strategic combination of ring-opening metathesis polymerization (ROMP) and living radical polymerization,[13,23−32] recently we reported the one-pot "grafting from" synthesis of brush copolymers with homopolymer-based grafts by tandem ROMP and ATRP, both catalyzed by Grubbs' catalyst.[33] This work revealed the exceptionally good compatibility between radical polymerizations and ROMP and suggested that there could be significant breadth for the further application of tandem ROMP and radical polymerization methodologies for the facile syntheses of brush copolymers. In this Communication, we describe the one-pot synthesis of a core−shell brush copolymer from small molecule reactants by tandem ROMP and RAFT copolymerization (Scheme 1).

Scheme 1



As a critical agent for the tandem synthesis of core−shell brush copolymer, an *exo*-norbornene-functionalized RAFT agent **1** was prepared in 87% yield by esterification of a norbornene-functionalized alcohol **2** with an acid-functionalized RAFT agent **3** (2.0 equiv),[27,34] using *N,N′*-dicyclohexylcarbodimide (DCC; 2.1 equiv) and 4-(dimethylamino)pyridine (DMAP; 0.2 equiv) in CH_2Cl_2 at room temperature for 20 h.[35] ^1H NMR analysis of **1** showed a series of characteristic resonances (Figure 1a), including those of norbornene alkene protons *a* and *b* (at 6.03−6.16 ppm), CH_2OCO protons *e* (at 4.08 ppm), CH_2OCH_2 protons *c* and *d* and SCH_2 protons *f* (at 3.23−3.53 ppm), and CH_3 protons *g* (at 0.88 ppm). Their integration area ratios of 1.95:2.00:5.95:3.10 were in excellent agreement with the number ratio of protons of 2:2:6:3, verifying the molecular structure of **1**.

One-pot preparation of core−shell brush copolymer from small molecule reactants was then performed by ROMP of the *exo*-norbornene-functionalized RAFT agent **1**, followed by using the resulting polyfunctional RAFT agent and AIBN (as initiator) for "grafting from" via RAFT copolymerization of styrene (St) and maleic anhydride (MAn). The ROMP of **1** (99.7 mg) was conducted using Grubbs' catalyst $RuCl_2(CHC_6H_5)[P(C_6H_{11})_3]_2$

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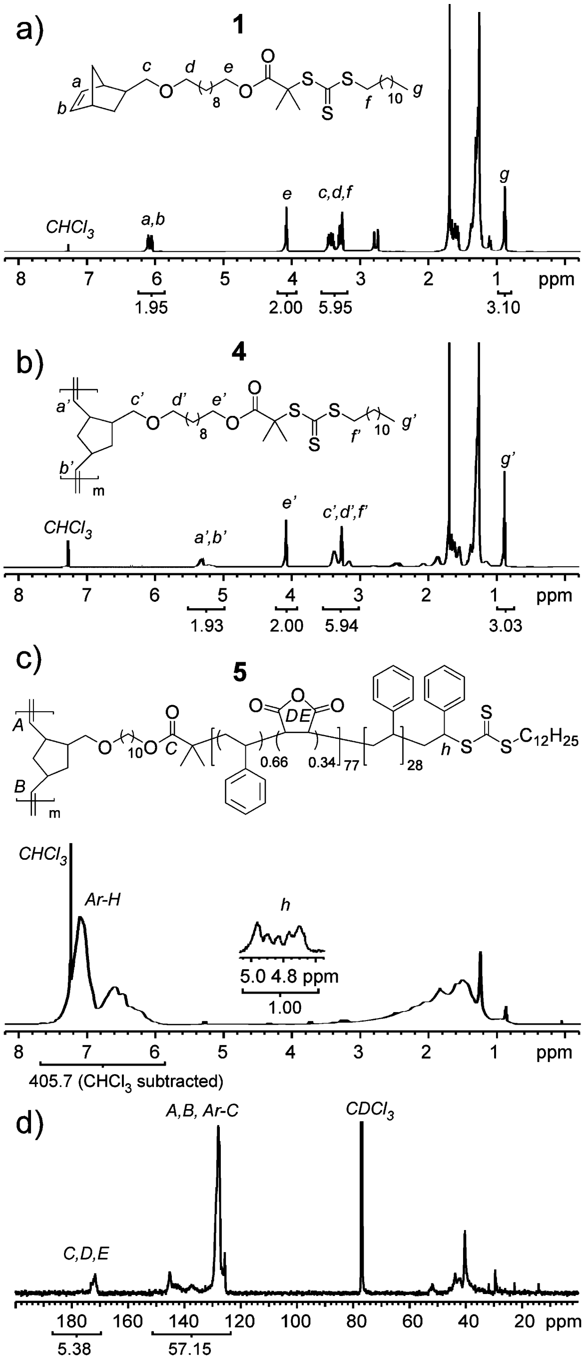

Figure 1. (a) ^{1}H NMR spectrum of norbornene-functionalized RAFT agent **1**. (b) ^{1}H NMR spectrum of polyfunctional RAFT agent **4**. (c) ^{1}H NMR spectrum of core−shell brush copolymer **5**. (d) ^{13}C NMR spectrum of core−shell brush copolymer **5**.

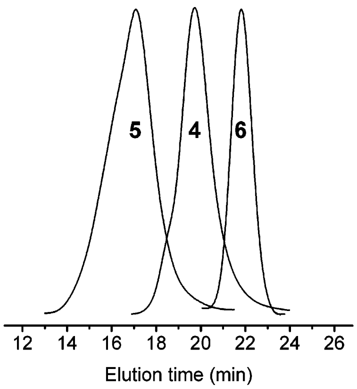

Figure 2. GPC peaks of polyfunctional RAFT agent **4** (M_n = 40.6 kDa, PDI = 1.24), core−shell brush copolymer **5** (M_n = 1200 kDa, PDI = 1.32), and detached ethanolyzed diblock side chain **6** (M_n = 13.0 kDa, PDI = 1.10).

(0.02 equiv) in CH_2Cl_2 at room temperature for 1 h.[36] ^{1}H NMR and GPC analyses of an aliquot of the reaction mixture (19 vol %, terminated by ethyl vinyl ether) determined the successful transformation of **1** into a well-defined polyfunctional RAFT agent. Near complete conversion (>99%) of **1** was verified by the essential absence of ^{1}H NMR resonances of norbornene alkene protons of **1** at 6.03−6.16 ppm (Figure 1b), and the formation of poly(**1**), i.e. **4**, was supported by a series of characteristic resonances, including those of alkene protons *a′* and *b′* of the poly(norbornene)-based main chain (at 5.08−5.49 ppm), CH_2OCO protons *e′* (at 4.08 ppm), CH_2OCH_2 protons *c′* and *d′* and SCH_2 protons *f′* (at 3.10−3.54 ppm), and CH_3 protons *g′* (at 0.88 ppm). Their integration area ratios of 1.93:2.00:5.94:3.03 agreed very well with the number ratios of protons of 2:2:6:3, indicating quantitatively one RAFT functionality per repeat unit of **4**. By GPC, **4** was found to have a M_n of 40.6 kDa and a low polydisperisty index of 1.24 (Figure 2). Relative to a calculated M_n value of 31.5 kDa, the experimental M_n value of **4** indicated an initiation efficiency of 78%.

RAFT copolymerization was subsequently conducted by the additions of St and MAn, 2,2′-azobis(isobutyronitrile) (AIBN), and 1,4-dioxane (50 vol %) directly into the reaction flask ($[St]_0$:$[MAn]_0$:$[AIBN]_0$:$[RAFT\ functionality]_0$ = 480:20:0.1:1), followed by degassing and heating the reaction mixture at 50 °C. Because only traces of residues of Grubbs' catalyst remained in the reaction system, their effects on the RAFT process were not considered. The comonomer pair of St−MAn was chosen due to the very low reported values of monomer reactivity ratios in radical copolymerization ($r_1 = 0.05$, $r_2 = 0.005$),[37] which allow one-pot preparation of poly(St-*stat*-MAn)-*b*-poly(St) and poly(St)-*b*-poly(St-*stat*-MAn)-*b*-poly(St) block copolymers with high feed ratios of St to MAn by living radical polymerization techniques,[38] including RAFT polymerization.[39] A relatively low polymerization temperature of 50 °C was used to maintain low concentrations of radicals and minimize biradical coupling. At time intervals, small aliquots were withdrawn from the polymerization solution and analyzed by ^{1}H NMR spectroscopy to monitor the RAFT process based on the decreased intensities of a vinyl proton of St at 5.76 ppm and the two alkene protons of MAn at 6.99 ppm. As expected, although both comonomers were consumed steadily with the increase of RAFT polymerization time, quantitative conversion of MAn was observed after 16 h of reaction when 8.2% of St was copolymerized, indicating the completion of the "grafting from" formation of the poly(St-*stat*-MAn) first blocks having a molar ratio of St to MAn units of ca. 2:1. The RAFT process was then allowed to continue, and with the absence of MAn comonomer, "grafting from" growth of the poly(St) second block occurred. Finally, the polymerization was quenched at a total RAFT polymerization time of 32.5 h, with a conversion of St of 12.8%. The resulting polymerization solution was precipitated in diethyl ether and then passed through a short column of silica gel (pore size: 150 Å) to remove a small amount of linear polymer species (<10 mass % of all polymers produced, as estimated by GPC), presumably formed by initiation by AIBN and chain transfers (except those to RAFT functionalities). Because of size exclusion, brush copolymer species were eluted much faster than these linear polymer species. Finally, the core−shell brush copolymer **5** was obtained in 61% isolated yield, based on conversions of starting materials.

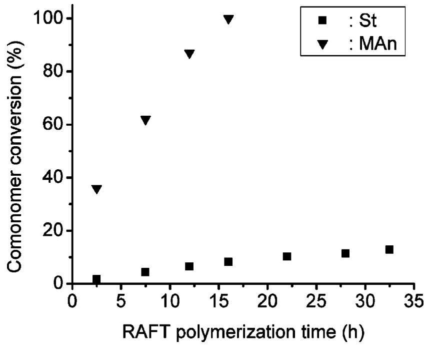

Figure 3. Time dependence of comonomer conversions in RAFT copolymerization of St and MAn.

A number of characterization methods, including ^{1}H and ^{13}C NMR spectroscopies, DSC, and GPC, were utilized to characterize **5**. In the ^{1}H NMR spectrum of **5** (Figure 1c), aromatic protons from St resonated at 5.82−7.90 ppm, and most aliphatic protons (from St, MAn, and **3**) resonated at 0.55−3.70 ppm, with their resonances overlapping. The resonances of the benzylic C*H* proton *h* of the ω-terminal St unit at 4.63−5.04 ppm were unique to the grafted polymer chains and, therefore, were used for quantitative analysis. Comparison of their integration area with that of the resonances for the aromatic protons gave a ratio of 1:406. Relative to the calculated ratio of 1:307 based on St conversion, this experimental ratio indicated an average grafting efficiency of 76%. Quantitative ^{13}C NMR measurement of **5** was performed using a long predelay of 15 s. Resonances of the MAn anhydride carbonyl carbons (with overlap from the fewer ester carbonyl carbons originating from the norbornene-functionalized RAFT agent (ca. 40:1, anhydride carbonyl:ester carbonyl)) concentrated around 172 ppm and resonances of unsaturated carbons (>99% from St, as aromatic carbons) at 124−152 ppm were observed.[40] With their integration area ratio of 1:10.6, the molar fraction of MAn in **5** was estimated as 22%, which was close to the calculated value of 25% obtained from the initial feed ratio and the conversions of the two comonomers. DSC measurement for **5** revealed two glass transition temperatures at 101 °C, which corresponded to the polystyrene blocks, and at 153 °C, which corresponded to the poly(St-*stat*-MAn) blocks. These values were in excellent agreement with the literature values of polystyrene and a 2:1 copolymer of St and MAn prepared by radical polymerization, respectively.[38] By GPC measurement, **5** had a M_n of 1200 kDa and a polydispersity of 1.32. This experimental value of M_n was significantly higher than a calculated value of 590 kDa, presumably due to certain occurrence of biradical coupling (as reflected by an appreciable increase in polydispersity of **5** relative to **4**) and a loss of brush copolymer with small molecular weights during workup.

The grafted structure of **5** was further investigated by cleavage of its grafts through solvolysis in ethanol−THF, using sulfuric acid as catalyst, at 100 °C for 7 days (Scheme 1).[41] The detached grafts **6**, with their MAn units converted into diethyl maleate units, were analyzed by GPC (Figure 3). As compared with a calculated value of 10.0 kDa based on conversions of comonomers and quantitative grafting, an experimental M_n of 13.0 kDa of **6** by GPC indicated a grafting efficiency of 77%, which agreed very well with a grafting efficiency of 76% by ^{1}H NMR (vide supra). The monomodal GPC curve of **6** with a very low polydispersity of 1.10 further confirmed well-controlled formation of diblock grafts by this "grafting from" RAFT copolymerization approach.

By hydrolyzing the MAn units in the poly(St-*stat*-MAn) blocks into hydrophilic maleic acid units, **5** could be further converted into amphiphilic core−shell brush copolymer **7** (Scheme 1). Hydrolysis was attempted under neutral conditions in 10% water−THF, but no reaction was observed even after heating the reaction mixture for 6 h. However, hydrolysis proceeded readily at room temperature under basic conditions using KOH to promote the reaction. Subsequent neutralization of the reaction solution gave **7**.[42] Both ^{1}H NMR and FT-IR spectroscopic characterizations were used to compare **7** with its precursor **5**. ^{1}H NMR resonances of carboxylic protons centered at 12.0 ppm were observed by ^{1}H NMR measurement of **7** in DMSO-d_6, verifying the presence of maleic acid units in **7**. Critical differences between **7** and **5** were revealed by FT-IR. Core−shell brush copolymer **5** showed two C═O stretching frequencies at 1857 and 1778 cm^{-1} for its cyclic anhydride groups and an absence of an O−H stretching absorbance. However, amphiphilic core−shell brush copolymer **7** possessed only one C═O stretching frequency at 1714 cm^{-1} and a broad O−H stretching absorption at 2500−3500 cm^{-1}, indicating functional group transformation from the anhydrides to carboxylic acid groups. Additionally, different solubilities for **7** relative to **5** were found. For example, **5** was soluble in CDCl$_3$, but **7** was insoluble in CDCl$_3$ and could be dissolved by 1:2 CDCl$_3$−CD$_3$OD.

In summary, we have succeeded in the one-pot preparation of core−shell brush copolymers from small molecule reactants by tandem ROMP and RAFT copolymerization. The excellent compatibility of ROMP and RAFT was confirmed, and this work establishes such a stagewise one-pot process for the preparation of many interesting brush block copolymer structures. In this example, a well-defined polyfunctional RAFT agent was prepared by ROMP of a norbornene-functionalized RAFT agent using Grubbs' catalyst, and it was subsequently used, without separation, for the "grafting from" formation of diblock grafts by RAFT copolymerization of St and MAn. Relatively high grafting density was obtained by this synthetic strategy, as confirmed by analysis of the entire brush copolymer structure and also detachment of the grafts for further detailed analysis. Moreover, the resulting core−shell brush copolymer could be readily converted into an amphiphilic core−shell brush copolymer by hydrolysis of the internal MAn units. By combining the high functional group tolerance of ROMP initiated by ruthenium-based catalysts[43−46] with the broad (co)monomer range for RAFT (co)polymerizations,[7,8,18,22,47,48] including during polymer brush growth from surfaces or polymer backbones,[14,49−51] we are pursuing the preparation of a wide variety of brush copolymers having interesting nanoscale frameworks.

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Supporting Information Available: Experimental section. This material is available free of charge via the Internet at http://pubs.acs.org.

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