Reversible Redox Cleavage/Coupling of Polystyrene with Disulfide or Thiol Groups Prepared by Atom Transfer Radical Polymerization

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Received July 5, 2002; Revised Manuscript Received September 11, 2002

ABSTRACT: Polymers with chemically labile disulfide groups in the backbone were prepared by atom transfer radical polymerization (ATRP) of styrene using the 2-bromopropionic acid diester of bis(2-hydroxyethyl) disulfide as the initiator and CuBr/*N*,*N*,*N*′,*N*′′,*N*′′-pentamethyldiethylenetriamine as the catalyst at 90 °C. Polymerization kinetics indicated insignificant transfer to the disulfide originating from the initiator. Using a monomer-to-initiator-to-catalyst ratio of 300:1:0.2, radical coupling reactions were suppressed compared to systems with more catalyst (300:1:1), and well-defined (with symmetrical and narrow ($M_w/M_n < 1.1$) molecular weight distribution) disulfide-containing polymers were prepared. The internal disulfide bond was cleaved by reduction with dithiothreitol to yield the corresponding thiol-terminated polystyrene. The thiol end groups were efficiently coupled back to the starting disulfide by oxidation with $FeCl_3$. A dibromo-terminated polystyrene was synthesized under similar ATRP conditions using dimethyl 2,6-dibromoheptanedioate as the initiator and was used as a precursor for dithiol-terminated polymer. Thiodimethylformamide was employed to convert the bromine end groups to thiol functionalities. The obtained difunctional polymer was coupled to a high molecular weight product with internal disulfide bridges upon oxidation with $FeCl_3$.

Introduction

Because of the variety of structures and properties of sulfur-containing functional groups (enriched by the existence of several oxidation states of sulfur and the ability of sulfur atoms to form homopolyatomic chains), polymers with such groups have attracted significant attention. Sulfur atoms can be either a part of the polymer backbone (e.g., in sulfide, polysulfide, sulfoxide, sulfone, thiocarbonate, and sulfonamide polymers) or substituents on the main chain.[1−7] Applications for polymers with sulfur-based functionalities are diverse and include, among others, chemical and light-resistant rubbers,[8,9] ion-exchange and chelating resins,[10] redox (“electron-exchange”) polymers,[11,12] membrane materials,[13] and conductive polymers.[14,15]

Sulfur-containing polymers with di- and polysulfide groups have been the subject of many studies due to their resistance toward aggressive chemical agents (ozone, chlorine, etc.) and UV light. An interesting application of disulfide polymers is the formation of copolymers with vinyl monomers in the presence of radical initiators, which occurs via chain-transfer reaction to the disulfide group. This chain transfer is more efficient with aromatic than with aliphatic disulfides. (The chain-transfer constants for aromatic disulfides are typically around 2 orders of magnitude larger than for the aliphatic ones.[16]) The polymers with disulfide or polysulfide linkages are typically prepared from difunctional halogen-containing low-molecular-weight compounds or oligomers and alkaline metal di- and polysulfide salts.[8,17]

The thiol functionality, which can reversibly form disulfide groups upon oxidation, is of primary importance in biological systems. For example, the major factor determining the tertiary structure of proteins is the formation of a disulfide link, i.e., the oxidative coupling of two cysteine moieties to form a disulfide-bridged cystine group. In addition, thiols play an important role in a variety of redox processes in living organisms.[18]

Low-molecular-weight, oligomeric and polymeric di- and polythiols have been extensively studied in relation to their ability to form linear or cross-linked polymers with internal disulfide linkages upon mild oxidation.[2,17,19] The preparation of thiol-containing polymers is therefore of significant interest. In principle, the thiol functionality can be introduced into a polymer using an appropriate sulfur-containing initiator. However, the direct application of thiol-containing radical sources as initiators for the radical polymerization of vinyl monomers, which would lead to the desired thiol-terminated polymers, is limited because of the large transfer constants of thiols.[20] The use of protected thiols, with protective groups that can be removed after the polymerization, as radical initiators is therefore necessary. Thioether- or disulfide-based initiators can be used as precursors of thiols, because their transfer constants are significantly lower than those of the thiols. (For example, the transfer constant for dibutyl sulfide in the polymerization of styrene at 60 °C is 0.0022; for dibutyl disulfide it is equal to 0.0024, and for buthanethiol it is 22.[20])

A major drawback of conventional radical polymerization systems is that they yield poorly defined polymers with broad molecular weight distributions. The last several years have witnessed the flourishing of controlled/living radical polymerization, and several methods have been developed that produce well-defined (with predicted molecular weight, narrow molecular weight distribution, and high degree of end-functionalization) polymers.[21−23] Among these methods, atom transfer radical polymerization (ATRP)[24−27] is probably the most robust due to its tolerance to a range of monomers and solvents of different polarity and with various functional groups as well as to impurities often encountered in industrial systems.

10.1021/ma021061f CCC: $22.00

Thiol-containing polymers can be prepared in two ways using ATRP. The halogen end groups of the polymers obtained by ATRP[28] can be reacted with a sulfur-containing nucleophilic precursor of the thiol (e.g., (hydrogen) sulfide salts, thiourea,[29,30] thiodimethylformamide, etc.[31,32]) to form thiol end-functionalized polymers. On the other hand, the concept of using of mono- or polyfunctional halide initiators with incorporated protected thiol group can also be applied. For example, a 2,4-dinitrophenyl-protected thiol-containing initiator has already been used for the ATRP of methyl methacrylate.[33] The success of ATRP in the presence of such a thiol precursor relies on the significantly lower transfer constants of thioethers compared to those of thiols. As already mentioned, disulfides are another class of thiol precursors with relatively low transfer constants. Halide initiators with a disulfide bond attached to a gold surface have already been employed for the ATRP of few vinyl monomers.[34,35]

However, no reports on the preparation of thiol-containing polymers via ATRP using disulfide initiators have appeared in the literature. Neither has the transformation of the halide end groups of polymers synthesized by ATRP to mercapto groups been well investigated. The reversible reductive cleavage/oxidative coupling reaction for the disulfide/thiol pair present in well-defined polymers could provide a method for preparing polymers of predetermined molecular weight distributions (for example, by the simultaneous oxidation of mono- and polyfunctional polymeric mercaptans). This approach may also allow the preparation of other materials for important applications (e.g., the reversible formation of gels with polymeric segments of controlled molecular weight, standards for calibration for SEC, etc.) and should be studied.

Herein, we report the ATRP of styrene (Sty) using the diester of 2-bromopropionic acid and bis(2-hydroxyethyl) disulfide (BHEDS(BP)$_2$) as a difunctional initiator. The reversible cleavage (by a redox process) of the internal disulfide bond of the resulting polystyrene (pSty) is also described. In addition, the transformation of a dibromo-terminated pSty to the corresponding dimercapto-terminated polymer, and its oxidative coupling to a high-molecular-weight product with several internal disulfide links, is also reported.

Experimental Section

Prior to use, neat styrene (Sty; 99%, Aldrich) was passed through a column filled with basic alumina in order to remove the inhibitor. The monomer was then purged with nitrogen for at least 1 h. *N*,*N*,*N*′,*N*″,*N*″-Pentamethyldiethylenetriamine (PMDETA; 99%, Aldrich) was distilled under reduced pressure. CuBr (98%, Aldrich) was purified by a modified literature procedure: washing with glacial acetic acid followed by 2-propanol.[36] All other reagents: bis(2-hydroxyethyl) disulfide (BHEDS; TCI, 98%), dicyclohexylcarbodiimide (DCC; 99%), 4-(*N*,*N*-dimethylamino)pyridine (4-DMAP; 99%), 2-bromopropionic acid (99%), FeCl$_3$ (97%), 2,6-dibromoheptanedioate (97%), all from Aldrich, dithiothreitol (2,3-dihydroxy-1,4-butanethiol, DTT; 99%), and thiodimethylformamide (TDMF; 98%), Fluka, and the solvents were used as received.

Synthetic Procedures. a. Synthesis of Bis(2-hydroxyethyl) Disulfide Bis(2-bromopropionate) (BHEDS(BP)$_2$). BHEDS (9.88 g, 6.4×10^{-2} mol) was dissolved in 200 mL of THF. The flask containing the solution was then immersed in ice−water bath, and 2-bromopropionic acid (11.9 mL, 0.128 mol) was added upon stirring, followed by a solution of DCC (26.44 g, 0.128 mol) in 100 mL of THF. The mixture was then stirred for 10 min in the cooling bath, and a solution of 4-DMAP (0.35 g) in 5 mL of THF was added dropwise over 5−10 min. The resulting heterogeneous mixture was stirred at room temperature for 24 h, and the precipitated dicyclohexylurea was filtered off and washed on the filter with 100 mL of THF. Solvent was then removed from the combined filtrates by vacuum evaporation, and the obtained turbid oil was filtered to remove the crystallizing impurities. Yield: 23.4 g (86.2%). (The reaction was initially attempted in methylene chloride, but the alcohol was not fully soluble in this solvent. In addition, since more concentrated mixtures than in the above procedure had been used, after the addition of the solid catalyst, 4-DMAP, an exothermic reaction and vigorous boiling of the solvent occurred.) ^{1}H NMR (methanol-d_4): 4.57−4.38 ppm (slightly overlapping q, 1H, CHBr, and t, 2H, CH$_2$O), 3.02 ppm (t, 2H, CH$_2$S), and 1.80 ppm (d, 3H, CH$_3$). Based on analysis of the spectrum, approximately 2% of unreacted diol remained after the esterification reaction. (The signals of the diol dissolved in methanol-d_4 are situated at 4.73 ppm (broad m, 1H, OH), 3.80 ppm (t, 2H, CH$_2$O), and 2.84 ppm (t, 2H, CH$_2$S).)

b. ATRP of Sty Using BHEDS(BP)$_2$ as the Initiator. A mixture of Sty (50 mL, 0.436 mol), diphenyl ether (20 mL), and PMDETA (0.3 mL, 1.45×10^{-3} mol) was put in a Schlenk flask and degassed by five freeze−pump−thaw cycles. The flask was then filled with nitrogen, and CuBr (0.208 g, 1.45×10^{-3} mol) was quickly added to the frozen mixture. After closing the flask, it was evacuated and back-filled with nitrogen three times. The flask was then immersed in an oil bath and heated to 90 °C. BHEDS(BP)$_2$ (0.4 mL, 1.45×10^{-3} mol) was added via a syringe through the side arm of the flask. Immediately, a sample was withdrawn for GC analysis. Samples were periodically taken during the polymerization, and the monomer conversion and polymer molecular weights were determined by GC and SEC, respectively. The final reaction mixture (73% conversion after 11 h) was diluted with THF, the solution was filtered through a column filled with basic alumina, and the polymer (pSty-SS-pSty) was precipitated in excess of methanol and dried in vacuum at 50−60 °C to constant weight. $M_n = 2.47 \times 10^4$ g/mol; $M_w/M_n = 1.13$.

Another reaction was also performed using a lower concentration of the catalyst (0.042 g (2.9×10^{-4} mol) of CuBr and 61 μL (2.9×10^{-4} mol) of PMDETA) while keeping the amounts of all other components and the reaction conditions the same. The conversion reached 76% after 76 h. $M_n = 2.00 \times 10^4$ g/mol; $M_w/M_n = 1.10$.

c. Reduction of the Disulfide-Containing Thiol-Terminated Polymers. In a typical procedure, the polymer with internal disulfide linkage ($(1.3−2.0) \times 10^{-5}$ mol) was dissolved in 6 mL of deoxygenated solvent, such as THF or DMF, containing 0.2 mL of diphenyl ether (internal standard for the following SEC analysis); DTT (0.154 g, 1×10^{-3} mol)[37,38] was added. The mixtures were stirred under nitrogen at 60 °C. Samples were periodically withdrawn and analyzed by SEC in order to determine the degree of formation of mercapto-terminated polymer (pSty-SH).

d. Oxidation of the Mercapto-Terminated Polymers. Thiols can be easily oxidized by air to the corresponding disulfides,[39] but these reactions were relatively slow in the absence of a catalyst when applied to thiol-terminated polystyrene dissolved in DMF. Therefore, another oxidizing agent, FeCl$_3$, known to efficiently convert mercaptans to disulfides,[39] was used. Thus, thiol-terminated polystyrene (3.5×10^{-6} mol) was dissolved in a mixture of 2 mL of DMF and 0.1 mL of diphenyl ether, and 0.05 g (3.0×10^{-4} mol) of FeCl$_3$ was added. The reaction mixture was stirred at 60 °C for 24 h. Under these conditions, the coupling of the thiol was complete.

e. Synthesis of α,ω-Dibromo-Terminated Polystyrene (Br-pSty-Br). A procedure similar to the one used for the synthesis of polystyrene with internal disulfide bond was employed, but dimethyl 2,6-dibromoheptanedioate was used as a difunctional initiator. The polymer isolated after 48 h (at ca. 50% monomer conversion) was purified as described above. It was analyzed by SEC: $M_n = 1.53 \times 10^4$ g/mol; $M_w/M_n = 1.15$.

f. Preparation of Polystyrene α,*ω*-Dithiol (HS-pSty-SH). Br-pSty-Br of $M_n = 1.53 \times 10^4$ g/mol (0.911 g, 6×10^{-5} mol) was put in a flask, which was then closed with a rubber septum, evacuated, and back-filled with nitrogen three times. TDMF, purged with nitrogen for 20 h in order to remove any dissolved oxygen (5 mL), was added, and the resulting solution was stirred at 80 °C for 24 h. Methanol (deoxygenated by purging with nitrogen; 2 mL) was then added, and the mixture was stirred at 50 °C for 5 h. (The polymer precipitated after the addition of methanol but slowly redissolved.) Finally, a solution of DTT (0.1 g, 6.5×10^{-4} mol) in 30 mL of deoxygenated methanol was added to the mixture, which was stirred at the same temperature for an additional 2 h, and the precipitated polymer was filtered off and washed on the filter with deoxygenated methanol. The SEC analysis of the polymer (polymodal SEC trace) revealed that partial oxidative coupling of the terminal thiol groups occurred even under these conditions. To prepare pure α,*ω*-dithiol-terminated polymer, the reaction product (mixture of thiol- and disulfide-containing polystyrene) had to be reduced using DTT, using a procedure similar to the one described above. Thus, the isolated polymer was dissolved in 10 mL of deoxygenated DMF, containing 0.50 g (3×10^{-3} mol) of DTT and 0.2 mL of diphenyl ether. The solution was stirred at 60 °C under nitrogen for 40 h. After precipitation in ca. 500 mL of methanol, the polymer contained only small amount of dimer and no higher oligomers. $M_n = 1.61 \times 10^4$ g/mol; $M_w/M_n = 1.13$.

g. Oxidation of Polystyrene α,*ω*-Dithiol. To synthesize polystyrene with internal disulfide bonds, the α,*ω*-dithiol-terminated polymer of $M_n = 1.61 \times 10^4$ (0.16 g, 1×10^{-5} mol) was oxidized with $FeCl_3$ (0.162 g, 1×10^{-3} mol) in DMF (5 mL, containing 0.05 mL of diphenyl ether as internal standard for SEC analysis) for 22 h at 60 °C. A high-molecular-weight polymer with internal disulfide links ($(-S\text{-pSty-}S-)_n$) was thus prepared. $M_n = 3.95 \times 10^4$ g/mol; $M_w/M_n = 2.24$.

Analyses and Measurements. Conversions were determined on a Shimadzu GC-14A gas chromatograph equipped with a flame ionization detector and using a capillary column (CEC-Wax, 30 m × 0.53 mm × 1.0 μm, Chrom Expert Co.). The initial temperature was 80 °C (1 min hold), and the final temperature of 180 °C (4 min hold) was reached at a heating rate of 20 °C/min. Diphenyl ether, added initially to the reaction mixtures, was used as internal standard for these measurements.

Prior to determination of molecular weight distributions, the samples were filtered through a short column filled with alumina (for removal of the catalyst) followed by a 0.4 μm PTFE filter, and then the solutions were analyzed by size exclusion chromatography (SEC). The SEC measurements were conducted using DMF as the eluent (flow rate 1 mL/min, 50 °C) and three Styrogel columns in series (10^5, 10^3, 100 Å, Polymer Standard Services) following a guard column. A Waters 2410 differential refractometer was used as the detector. The calibration was based on polystyrene standards with diphenyl ether as the internal standard.

The ^{1}H NMR spectra in methanol-d_4 were taken on a Bruker spectrometer operating at 300 MHz, using tetramethylsilane as the reference compound.

Results and Discussion

Typically, ATRP of Sty is conducted with either 1-phenylethyl halide or 2-haloester as the initiator.[26] The diester of bis(2-hydroxyethyl disulfide) (BHEDS) and 2-bromopropionic acid was used in the current study. Esterification of BHEDS with 2 equiv of 2-bromopropionic acid was conducted in the presence of DCC and 4-DMAP.[40,41] This convenient method, which has already been applied to synthesize various low-molecular-weight and polymeric ATRP initiators,[42] gives high yields of the desired difunctional initiator with an internal disulfide functionality and does not require the use of the moisture-sensitive and malodorous 2-bromopropionyl bromide—a widely utilized reagent for the synthesis of esters of 2-bromopropionic acid.[43]

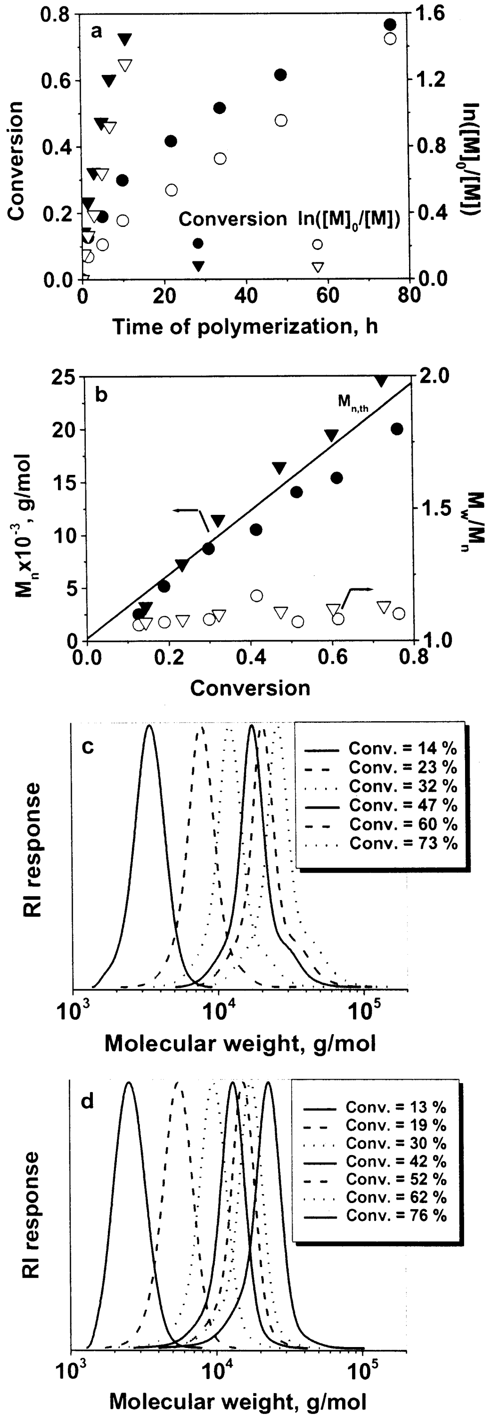
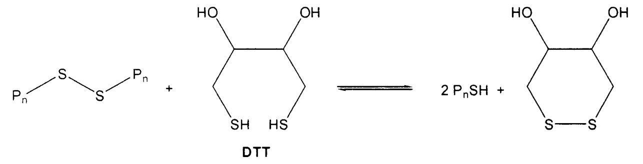


Figure 1. (a) Kinetics, (b) evolution of molecular weights and polydispersity indices, and (c, d) evolution of SEC traces of the polymers for the ATRP of Sty initiated by $BHEDS(BP)_2$ at 90 °C using different catalyst concentrations: [Sty]/[PMDETA]/[CuBr]/[$BHEDS(BP)_2$] = 300:1:1:1 (▼, ▽, c) and [Sty]/[PMDETA]/[CuBr]/[$BHEDS(BP)_2$] = 300:0.2:0.2:1 (●, ○, d).

Sty was polymerized in diphenyl ether at 90 °C using CuBr/PMDETA as the catalyst. The kinetics of the ATRP and the evolution of the polymer molecular weight distributions with conversion for reaction systems using two different concentrations of catalyst (ratio of the catalyst to initiator 1:1 and 0.2:1) are presented in Figure 1a,b. The semilogarithmic kinetic plots (Figure

Scheme 1. Reduction of Disulfides by DTT; P_n Denotes Either a Polymer Chain or a Low-Molecular-Weight Group



1a) are close to linear for both studied systems, indicating a constant number of active propagating species throughout the polymerization—one of the criteria used to ascertain the living nature of a polymerization process.

The molecular weights increase with conversion in a linear fashion (Figure 1b), remaining close to the values predicted from the ratio of monomer to initiator ($M_{\mathrm{n,th}}$ = conversion × M(Sty) × [Sty]/[BHEDS(BP)$_2$]). In addition, the polydispersities of the polymers remain low (below 1.2 in all cases). This indicates that transfer to the disulfide function originating from the initiator is negligible at conversions up to ca. 70−75%. Analysis of the shape of the SEC traces of polymers, obtained at different conversions (Figure 1c,d), reveals more details about the significance of side reactions such as radical−radical coupling and transfer. When the catalyst was present at high concentration (ratio of catalyst to initiator 1:1), the polymerization was fast due to high radical concentration, which in turn led to the occurrence of coupling reactions. (Note the appearance of a small second peak in the SEC traces of polymers, obtained at conversions above ca. 40%, at a molecular weight double this of the main peak (Figure 1c). The products of this coupling reaction retain the ability to initiate polymerization, since the α,ω-bromine atoms are preserved.) As the amount of catalyst was decreased (ratio 0.2:1 to the initiator), the coupling reactions were significantly suppressed, and the SEC traces (Figure 1d) of the produced polymers show narrower and more symmetrical molecular weight distributions.

The product of the ATRP of Sty initiated by BHEDS(BP)$_2$ contains an internal disulfide bond, which can be easily cleaved in the presence of reducing agents, leading to polymers with a thiol end group. A variety of reagents for this type of reduction have been described in the literature, due to its applications in protein chemistry and biochemistry.[44,45] Dithiothreitol (2,3-dihydroxy-1,4-butanethiol, DTT) was selected for the purposes of this study for several reasons. First, disulfide reductions by DTT are rather efficient, due to its low redox potential, which has been explained by the stability of the six-membered cyclic disulfide formed after the oxidation of this dithiol (Scheme 1).[37,44,46] In addition, DTT is very soluble in a range of solvents including those that dissolve pSty such as THF and DMF.

Reduction of the pSty-SS-pSty molecules was performed in both solvents. The degree of reduction can be conveniently followed by SEC. Figure 2 shows the change of the SEC traces with time for two reactions performed in DMF and THF. The reaction was faster in the more polar solvent, DMF (Figure 2a), with about 75% of cleaved disulfide bonds after 48 h. Approximately 60% of the bonds reacted during the same time in THF (Figure 2b). Thus, DMF was the solvent of choice for further reactions. Using longer reaction times and higher concentrations of the reducing agent, the conversion of pSty-SS-pSty to pSty-SH could be driven to completion, as shown in Figure 3.

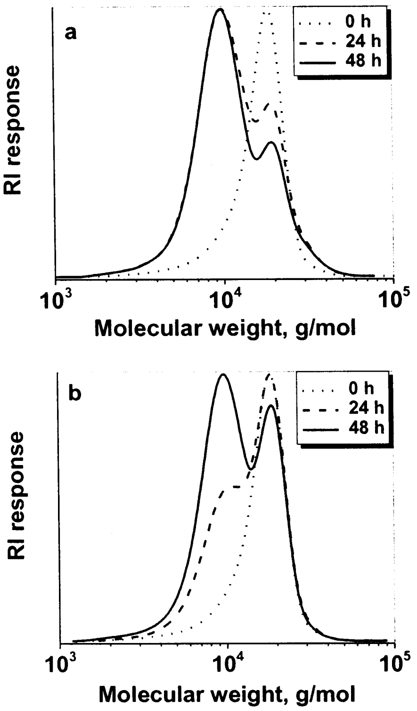


Figure 2. Evolution of polymer SEC traces with time for the reduction of pSty-SS-pSty by DTT at 60 °C in (a) DMF and (b) THF. Concentrations: 2×10^{-5} mol of polymer and 1×10^{-3} mol of DTT in 6 mL of solvent.

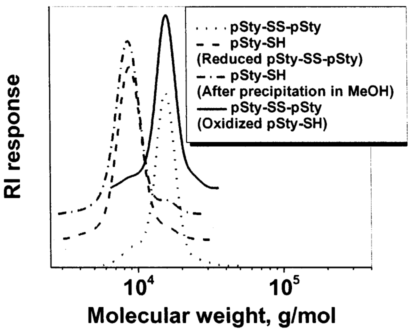
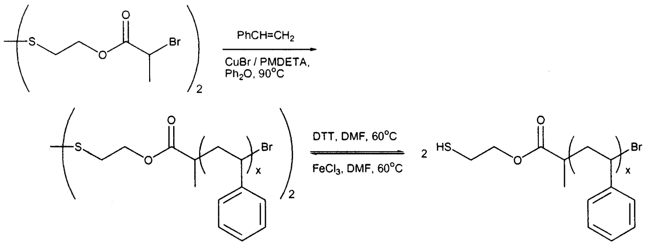


Figure 3. SEC traces of polymer with internal disulfide bond, the product of its reduction (1.3×10^{-5} mol of pSty-SS-pSty and 1×10^{-3} mol of DTT in 6 mL of DMF, 60 °C, 50 h) before and after precipitation in methanol, and the product of the oxidation of the latter polymer by FeCl$_3$.

Polymers with a terminal mercapto group can be easily oxidized under mild conditions back to the original polymers with a disulfide link.[19] Reagents such as iodine, FeCl$_3$, and oxygen from air, to mention few, can be used.[39] Metal salts are typically required as catalysts for the air oxidation. Strong oxidizing agents should generally be avoided because they can oxidize the thiol group to sulfinate or sulfonate groups, thus preventing the possibility of coupling. During the purification of pSty-SH (precipitation in methanol), some coupling had already occurred presumably, due to oxidation by air. Figure 3 shows the appearance in the SEC trace of a small peak corresponding to a molecular weight twice that of the thiol pSty-SH. However, since oxidation by air was slow and incomplete (even after bubbling air through a solution of the mercapto-terminated polymer in DMF for several days), FeCl$_3$ was used as the oxidative coupling agent for pSty-SH in the

Scheme 2. Preparation of PSty-SS-pSty by ATRP and Its Reversible Reduction to PSty-SH



present study. Oxidation by $FeCl_3$ was fast in DMF solution at 60 °C, and after 24 h practically no unreacted thiol remained in the reaction mixture, as seen from Figure 3.

The experiments described herein clearly indicate the reversibility of the reduction−oxidation reaction of the disulfide group in pSty-SS-pSty. The chemical transformations described so far are schematically presented in Scheme 2.

Another approach to thiol- or disulfide-functionalized polymers, employing ATRP, is the nucleophilic substitution of the halide end groups by a sulfur-based precursor of the mentioned groups, such as disulfide or (hydrogen) sulfide salts,[29] thiourea,[29] thiodimethylformamide (TDMF),[31,32] etc. Some of these reactions suffer from serious limitations. In the case of disulfide or sulfide salts, they are related to the basicity of the reagents, which can lead to elimination of hydrogen halide from the polymer. Thiourea is a widely used thiol precursor,[29,30,47] but because of its relatively low solubility in solvents suitable for polymers (DMF or especially THF), the reactions with halide-terminated polymers synthesized by ATRP should be slow and inefficient. Side products are also possible since the reagent possesses two nucleophilic centers: the thione sulfur atom and the two nitrogen atoms. In the current paper, the preparation of mercapto-terminated polymers was achieved by the reaction of bromo-terminated pSty with TDMF. This reagent has already been applied to the preparation of sulfhydryl-terminated polymers.[31,32] It is a liquid, which readily dissolves various organic compounds, including polymers, and it can be used as the reaction medium, thus avoiding the need for other solvents and therefore dilution of the thiol-yielding reagent. For the purposes of the current study, the dibromo-terminated polystyrene was dissolved in TDMF (bubbled with nitrogen prior to use in order to avoid any oxidative coupling of the eventually obtained thiols), and the reaction mixture was heated to 80 °C for 24 h under nitrogen. The product of the reaction was subjected to methanolysis, and the dithiol-terminated polymer (HS-pSty-SH) was isolated and analyzed by SEC (Figure 4).

The SEC curve shows formation of only insignificant amount of a dimer during the synthesis and isolation of the polymer. Being a difunctional mercaptan, the produced polymer can be further used for the preparation of higher molecular weight polystyrene with internal disulfide bonds ((−S-pSty-S−)$_n$). This was achieved by oxidation with $FeCl_3$. The SEC trace of the product is shown in Figure 4. The oxidation was efficient, leaving only relatively small amount (ca. 10%) of the "monomer" (HS-pSty-SH) after 22 h at 60 °C. The preparation of polystyrene α,ω-dimercaptan and its oxidation are shown in Scheme 3.

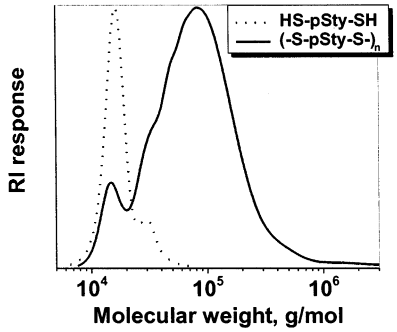
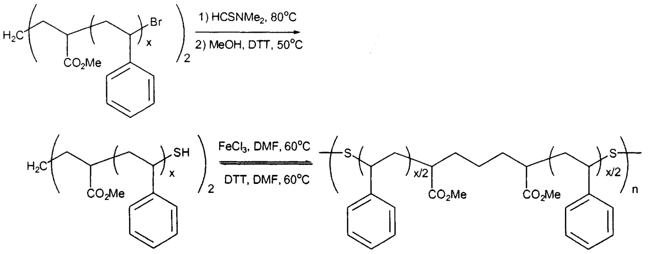


Figure 4. SEC traces of dimercapto-terminated pSty synthesized by the reaction of the corresponding dibromo-terminated polymer with TDMF followed by methanolysis and the product of its oxidative coupling ($FeCl_3$).

Scheme 3. Transformations of Br-pSty-Br to HS-pSty-SH and to the Disulfide-Containing Polymer with pSty Segments (−S-pSty-S−)$_n$



Conclusions

The diester of bis(2-hydroxyethyl) disulfide with 2-bromopropionic acid was successfully used as initiator for the ATRP of styrene, leading to well-defined polymers with an internal disulfide bond. The catalyst employed was the CuBr complex of *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine. Radical coupling reactions were insignificant, especially when low catalyst concentration was used (0.2:1 vs the initiator). The reversible reductive cleavage of the disulfide bond in the presence of dithiothreitol lead to polymers with a thiol end group. When the latter polymers were reacted with $FeCl_3$, oxidative coupling of the thiol groups occurred, regenerating the original polymer with an internal disulfide bridge. Both the reduction and oxidation reactions were efficient, and practically no unreacted starting polymer remained in the reaction mixtures.

A dibromo-terminated polystyrene was prepared by ATRP using the same catalytic system with dimethyl 2,6-dibromoheptanedioate as a difunctional initiator. The bromine end groups were successfully converted to thiol functionalities by a reaction with thiodimethylformamide, and the synthesized dimercapto-terminated polymer was oxidatively coupled to a high-molecular-weight polymer with internal disulfide bonds using $FeCl_3$ as the oxidant.

Acknowledgment. The authors thank the members of the ATRP/CRP consortia at Carnegie Mellon University and NSF (Grant DMR 0090409) for funding.

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MA021061F