Synthesis and Characterization of Well-Defined Block Copolymers by Combing Controlled Radical and Cationic Polymerization

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Summary: A facile synthetic strategy for well-defined poly(ethyleneimine)-polystyrene (PEI-PS) block copolymers utilizing controlled radical polymerization through the macroinitiator approach is presented. Poly(2-methyl-2-oxazoline) containing an alkoxyamine initiating unit at the chain end was prepared by ring opening cationic polymerization of 2-methyl-2-oxazoline through a nitroxide containing initiator. Polymerization of styrene with the poly(2-methyl-2-oxazoline) macroinitiator was carried out under nitroxide-mediated radical polymerization (NMRP) conditions. GPC and NMR revealed that the polymerization was accurately controlled and well-defined polystyrene chains were attached to the chain end of the macroinitiator to give the poly(2-methyl-2-oxazoline-b-styrene) block copolymers. Hydrolysis of the poly(2-methyl-2-oxazoline) block resulted effectively in poly(ethyleneimine-*b*-styrene) block copolymers.

Keywords: block copolymers; controlled radical polymerization; macroinitiator; ring opening cationic polymerization

Introduction

The ability to synthesize polymers with complex and controlled architectures has become an important aspect of polymer science.[1–3] Traditional methods for controlling polymeric structure, such as anionic[4] and cationic[5,6] procedures, have suffered from the rigorous synthetic conditions, incompatibility with a wide range of monomers, and thus, the inability to form a broad variety of functional copolymers. Conventional free-radical polymerizations techniques can be adapted well for the polymerization of monomers with various functional groups under synthetically robust condition. However, they do not permit the synthesis of block copolymers because of the predominance of termination reactions. Today, a variety of methods have been developed to obtain block copolymers also by free-radical polymerization, including the use of multifunctional macroinitiators[7–10] and living/controlled radical polymerisations.[11–13] Especially controlled radical polymerization procedures, such as nitroxide-mediated radical polymerization (NMRP),[14–18] atom transfer radical polymerization (ATRP),[19,20] and reversible addition fragmentation chain transfer (RAFT),[21–23] have witnessed explosive growth because these techniques permit the polymerization of a wide variety of monomer families, which are either difficult or not at all polymerizable via other polymerization processes, with high degree of structural control under synthetically robust condition.

Conventional free-radical polymerization using functional macroinitiators which contain free-radical polymerization initiating units such as azo, peroxy, disulfide, and so on, in the main or side chain have been applied for the preparation of block and graft copolymers,[7–10] however, without molecular weight control of the resulting

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products. Recently, novel synthetic strategies for the preparation of well-defined polymers through controlled radical polymerization using macroinitiators of various functionality have been proposed.[24–28,32,33] However, only a few examples are known for combining different controlled polymerization mechanisms for the preparation of block copolymers through a macroinitiator approach which further expands the structural variety in block copolymers.[34,35] In this report, we describe a synthetic strategy for block copolymers composed of poly(2-methyl-2-oxazoline) and polystyrene (PS) using a macroinitiator for the controlled radical polymerization which was prepared by cationic polymerization. The structural control was verified.

Experimental Parts

Chemicals

2-Methyl-2-oxazoline (99%, Arcos), benzyl chloride (99%, Arcos) and styrene (99%, Aldrich) were distilled under vacuum over CaH_2 immediately prior to use. Piperazine and (R, R)-N,N-bis(3,5-di-tert.-butylsalicylidene)-1,2-cyclohexanediaminomangan (III) chloride (Mn(salen), Aldrich) were used as received. N-(1-(4-(chloromethyl)phenyl)-ethoxy)-N-tert-butyl-2-methyl-1-phenylpropane-1-amine (CM-AAI) was prepared according to a developed procedure by Hawker et al.[29].

Measurements

^{1}H (500 MHz) and ^{13}C (125 MHz) NMR measurements were performed with a Bruker DRX 500 using tetramethylsilane (TMS) as an internal standard in chloroform-*d* ($CDCl_3$). Monomer conversion was determined by ^{1}H NMR measurement of the crude reaction mixtures (calculated from integration ratio between vinyl protons of styrene and aromatic protons at 6.3–7.2 ppm of polystyrene). Composition of the copolymers was calculated by ^{1}H NMR spectrum from the integration ratio between the signal for the aliphatic protons of PS units at 6.3–7.2 ppm and the signal for the methylene group of poly(2-methyl-2-oxazoline) repeating units at 3.41 ppm. Number average molecular weight (M_n) and polydispersity (M_w/M_n) were determined by gel permeation chromatographic (GPC) analysis. For the block copolymers GPC was carried out on a 1100 Series - high performance liquid chromatography system - (pump and RI - detector) of the company Agilent Technologies equipped with a guard column (PL OligoPore - rectifying column of polymer Laboratories) using polystyrene standards (Polyscience) for calibration and chloroform ($CHCl_3$) as an eluent. Alternatively, for the polyoxazoline macroinitiators, 1100 Series (pump and RI - detector) of the company Agilent Technologies equipped with PL MIXED-B - rectifying column (10μm) of Polymer Laboratories using PVP standards for calibration and dimethylacetamide (DMAc) as an eluent were used with a 1.0 ml/min flow rate.

Synthesis of Polymers

Poly(2-methyl-2-oxazoline) macroinitiator (A)

A 25 ml Schlenk tube, which was heated to 120 °C with three cycles of vacuum- argon flashing, was filled with 2-methyl-2-oxazoline (508 mg, 5.97 mmol) dissolved in 2 ml of acetonitrile. Alkoxyamine initiator (CM-AAI) (or benzyl chloride for the model experiment) with [M]/[I] = 80 was added and the mixture was stirred and heated at 80 °C for 25 hrs. Piperazine was used as a terminating agent (four equivalents with respect to initiator) and was added to the reaction medium dissolved in 1.0 ml acetonitrile. The mixture was further kept under stirring for 2 hrs. The resulting poly(2-methyl-2-oxazoline) macroinitiator was precipitated in cold diethyl ether two times and dried under vacuum for 24 hours. It gives a yellow powder (401 mg, 79% yield). $M_n = 6{,}800$, $M_w/M_n = 2.13$.

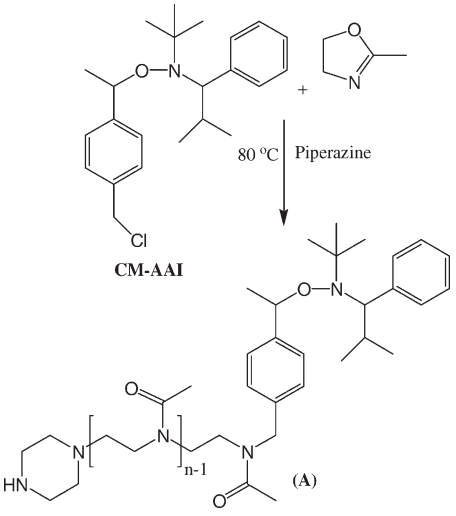
Poly(2-methyl-2-oxazoline-b-styrene) Block Copolymer (B)

As a specific example, a mixture of poly(2-methyl-2-oxazoline) macroinitiator (A) (231 mg/ 33.9 μmol) ($M_n = 6{,}800$, M_w/

$M_n = 2.13$), styrene (2.83 g, 271 mmol) and acetic anhydride (20 mg/ 19.6 μmol) was degassed by three freeze/thaw cycles and heated under argon at 125 °C for 8 h. The viscous reaction mixture was then dissolved in chloroform and precipitated into methanol. The precipitate was collected by vacuum filtration and dried in vacuum to give the purified block copolymer (B) as a white powder with $[M]/[I] = 800$ (2.44 g, 80% yield). $M_n = 51{,}500$, $M_w/M_n = 1.46$.

Alkaline Hydrolysis of Poly(styrene-block-methyl-2-oxazoline)

A mixture of poly(St-b-MeOx) (0.043 mmol) and NaOH or KOH (50 mmol) as hydrolysis reagent was refluxed in water /1,4-dioxane: 1/1 (v/v) for 40 h with stirring. The product was purified several times by precipitation. The isolated polymer was dried in vacuo.



Scheme 1.
Preparation of the alkoxyamine functionalized poly(2-methyl-2-oxazoline) macroinitiator.

Results and Discussion

It has been shown previously, that N-(1-(4-(chloromethyl)phenyl)ethoxy)-N-tert-butyl-2-methyl-1-phenylpropan-1-amine (CM-AAI) is an efficient NMRP adduct for the controlled radical polymerisation of styrene.[28,29] We used now the benzyl chloride unit of CM-AAI as initiator for the synthesis of the nitroxide functionalized poly(2-methyl-2-oxazoline) (PMeOx) macroinitiator (A) according to ring opening polymerization of 2-methyl-2-oxazoline (Scheme 1).

For a deeper understanding of the process, firstly the ability of the benzyl chloride modified alkoxyamine to initiate ring-opening polymerization of methyl-2-oxazoline was evaluated in detail. For that, the polymerization of methyl-2-oxazoline initiated by an ordinary benzyl chloride was investigated in comparison with a modified alkoxyamine initiator, as shown in Figure 1. It could be shown that the polymerization rate using both initiators was very similar. Products of molecular weights of 5.200 and 6.800 g/mol were achieved under similar conditions with relatively broad polydispersities above 2. Even though the cationic polymerization of 2-oxazolines shows some characteristics of a living-type polymerization, like active chain end and the possibility to prepare effectively block copolymers through second monomer addition, the initiation system used for our system is relatively slow and not highly effective so that macromolecules of broad polydispersity were achieved.

However, the ring opening polymerisation of 2-methyl-2-oxazoline using CM-AAI proceeded well at 80 °C to afford the corresponding alkoxyamine functionalized poly(2-methyl-2-oxazoline). Piperidine was

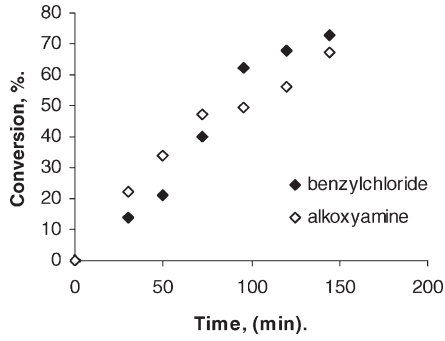


Figure 1.
2-Methyl-2-oxazoline conversion in the presence of benzyl chloride and the alkoxyamine initiator CM-AAI vs. time at 80 °C.

used to effectively stop the living-type polymerisation.[36] The structure of the synthesized polymer (A) was confirmed by ^{1}H (Figure 5) and ^{13}C NMR measurements. The resonances assigned to the methylene protons of 2-methyl-2-oxazoline appeared at about 3.4 ppm. The methyl group in the repeating unit was assigned to the signal at 2.05 ppm. It was also confirmed that the polymerization proceeded without dissociation or decomposition of the alkoxyamine units. In the ^{1}H NMR spectrum, the signals assigned to the alkoxyamine unit were observed at 0.5–2.5 and 4.0–5.2 ppm as shown in Figure 5.

Figure 2 shows a first order kinetics plot for the NMRP styrene polymerization using the alkoxyamine initiator CM-AA1 indicating a constant radical concentration throughout the polymerization. This might not be expected for the NMRP polymerization but it points to no unwanted termination and a relative fast initiation. In addition, the high control achieved with this functionalized initiator is demonstrated by a linear increase of molar mass of the resulting polystyrene with conversion as shown in Figure 3.

As CM-AAI was effectively applied in the NMRP of styrene, it was expected that also the nitroxide functionalized poly(2-methyl-2-oxazoline) macroinitiator (A) will be able to start the controlled polymerization of styrene. Thus, (A) was used to prepare poly(2-methyl-2-oxazoline-*b*-styrene) block copolymers (B) of different block ratios under typical NMRP conditions at 120 °C as shown in Scheme 2 and Table 1.

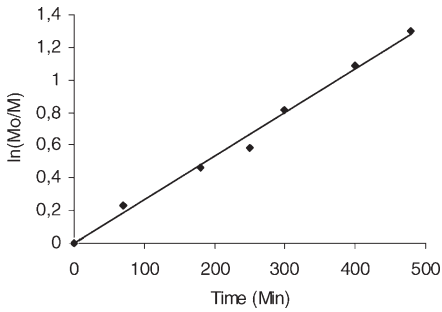


Figure 2.
First order kinetics plot of ln(M/Mo) versus time for the polymerization of styrene initiated by CM-AAI at 120 °C.

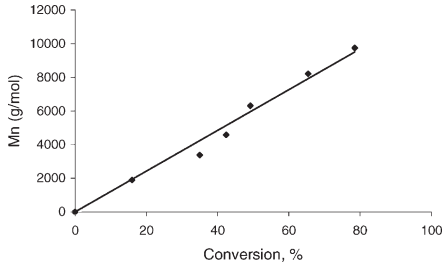


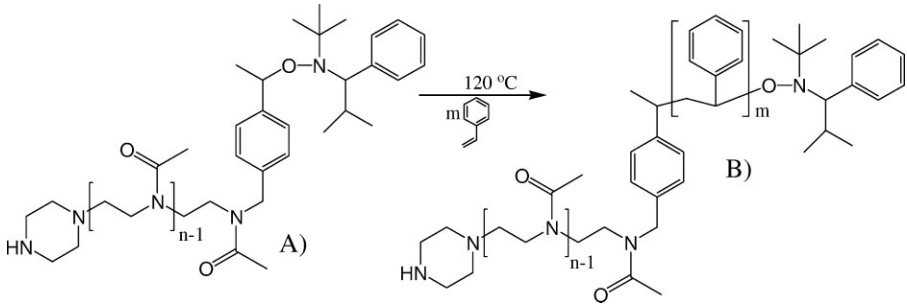
Figure 3.
Mn versus conversion for the polymerization of styrene initiated by CM-AAI at 120 °C.

As shown in Figure 4, a clear shift in molar mass was observed after the polymerization of styrene from (A). The M_n shifts from 6.800 to 51.500 g/mol with a polydispersity of the product of 1.47. The narrowing of the polydispersity compared to the macroinitiator indicates a rather high control in the NMRP polymerization but is also a result of the rather high molecular weight of the second block masking the broad polydispersity of the first block.

In Figure 4 the block copolymer raw product without any work up is shown which still exhibits a shoulder in the molar mass range of the macroinitiator indicative for an initiator efficiency below 100%. However, unreacted macroinitiator could be removed by selective precipitation. Table 1 summarizes some of the prepared block copolymers with varying block.

Figure 4 and 5 compare the ^{1}H NMR spectra of the macroinitiator and the resulting block copolymer ($M_n = 51{,}500$). Clearly, the signals of the styrene units dominate the block copolymer spectrum but the poly(2-methy-2-oxazoline) block is easily identified by the signals at 2.05 and 3.4 ppm.

The block copolymer formation has been evaluated kinetically. Figure 7 compares the conversion vs. time results obtained for the styrene polymerization initiated by CM-AAI and by the poly(2-



Scheme 2.
Polymerization of styrene by the use of alkoxyamine macroinitiator (A).

Table 1.
Results of the ring opening polymerization for the macroinitiator and the NMRP for the block copolymer preparation.

Initiator	T (°C)	M/I	t (h)	Yield %	$M_{n,\ GPC}$ (g/mol)	PD (M_w/M_n)	Block ratio*	Block ratio**
Benzyl chloride	80	80	25	76	5200	2.51	–	–
CM-AAI	80	80	25	79	6800	2.13	–	–
Macroinitiator (A)	125	200	8	80	21200	1.82	1:2.1	1:3.9
Macroinitiator (A)	125	500	8	79	37600	1.52	1:4.5	1:7
Macroinitiator (A)	125	580	8	76	42100	1.57	1:5	1:9.6
Macroinitiator (A)	125	710	8	80	51500	1.46	1:6.5	1:10.3
Macroinitiator (A)	125	740	8	81	53500	1.48	1:6.9	1:11.1

*calculation of block ratio according to molar mass.
**calculation of block ratio according to NMR molar ratio.

methyl-2-oxazoline) macroinitiator (A). No significant lowering of the activity for the macroinitiator compared to the low molar mass NMRP adduct could be observed. Figure 8 demonstrates that again a constant radical concentration can be assumed in the styrene polymerization initiated by the macroinitiator (A) demonstrated by a first order kinetics plot. The products isolated at different polymerization times showed, as expected, a gradual molecular weight increase with reaction time.

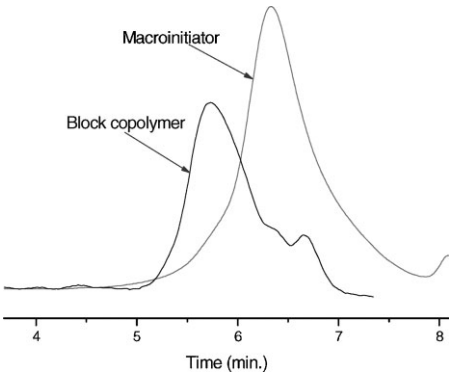


Figure 4.
GPC traces of PMeOx macroinitiator and PMeOx-b-PS.

Thus, it was possible to effectively prepare poly(2-methyl-2-oxazoline-b-styrene) block copolymers through combining cationic ring-opening polymerization (ROP) and nitroxide-mediated radical polymerization (NMRP).

The resulting block copolymers are highly interesting, since poly(2-methyl-2-oxazoline) can be considered as a precursor polymer for linear polyethyleneimine (PEI) giving the chance for the synthesis of so far unknown PEI-PS block copolymers (C). For that, the PMeOx block in the copolymer B was hydrolyzed in alkaline medium overnight as shown in Scheme 3. NMR proved the effective hydrolysis.

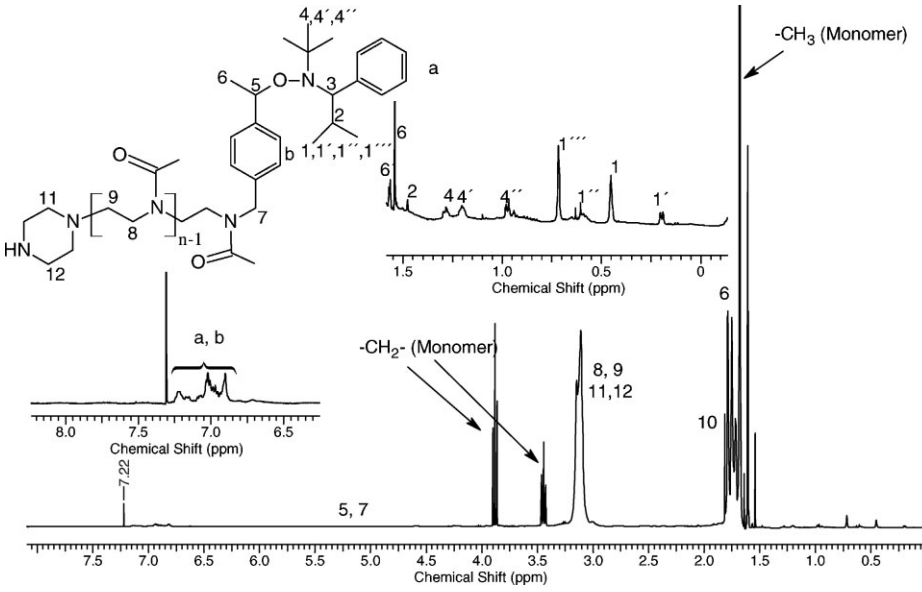


Figure 5.
^{1}H NMR spectrum of the alkoxyamine macroinitiator poly(2-methyl-2-oxazoline) (A) before workup (contains unreacted monomer).

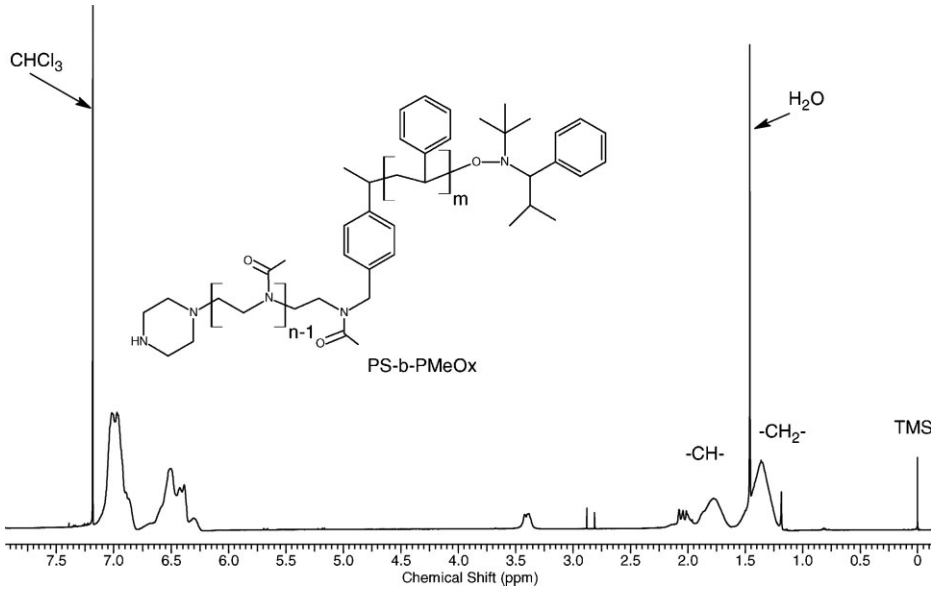


Figure 6.
^{1}H NMR spectrum of poly(2-methyl-2-oxazoline-*b*-styrene) ($M_n = 51{,}500$ g/mol).

Presently, the block ratio is further varied and the phase and self-assembly behaviour of these interesting block copolymers is under investigation.

Conclusion

An alkoxyamine macroinitiator based on poly(2-methyl-2-oxazoline) (PMeOx)

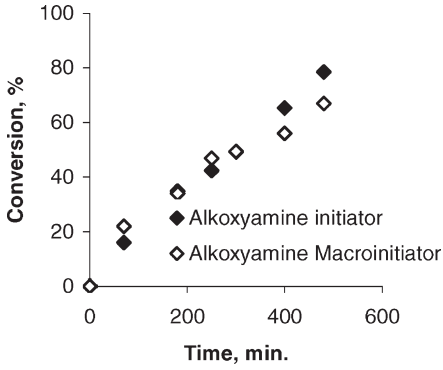


Figure 7.
Styrene conversion in the present of alkoxyamine initiator CM-AAI and the alkoxyamine macroinitiator (A) vs. time at 120 °C with (M/I) = 500.

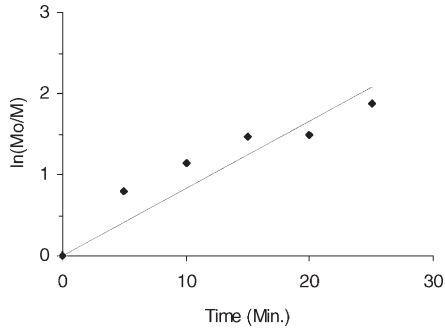
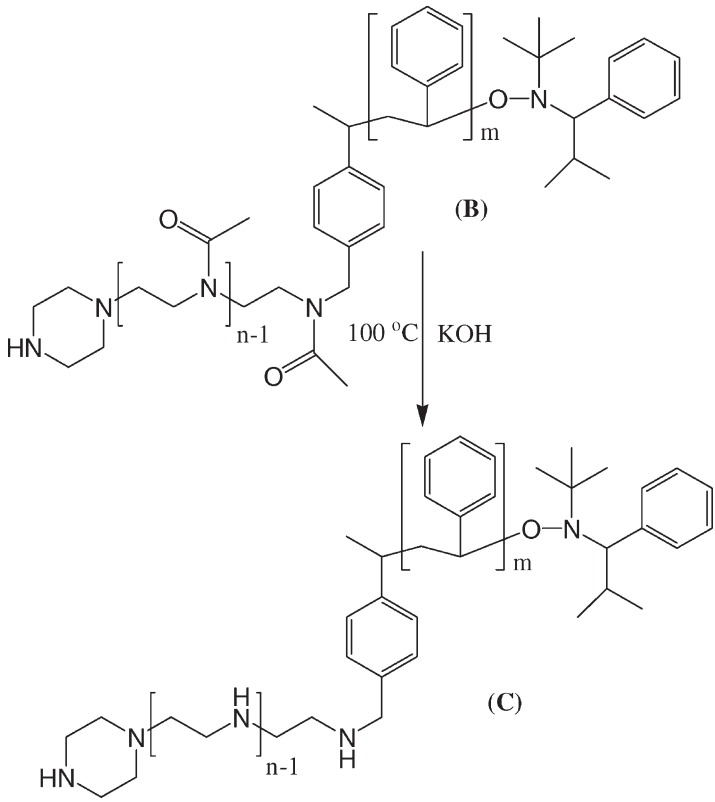


Figure 8.
First order kinetics plot of ln(M/Mo) versus time for the polymerization of styrene initiated by the alkoxyamine macroinitiator (A) at 120°C with M/I = 500.

could be successfully synthesized through a benzyl chloride modified alkoxyamine using cationic ring opening polymerization. This functionalized PMeOx can be used effectively as a macroinitiator for the NMRP of styrene leading to polystyrene blocks of well-defined molecular weight. Through hydrolysis of the PMeOx segment



Scheme 3.
Hydrolysis of PMeOx-PS block copolymer (B) to PEI-PS (C).

it was possible to prepare by this combination of two different living-.type polymerization techniques new poly(ethyleneimine)-polystyrene block copolymers. The strategy described here is available for the preparation of a wide variety of well-defined block copolymer libraries to be readily prepared in the minimum number of steps under synthetically robust conditions, and is expected to be a powerful systematic screening tool for the preparation of interesting phase separated functional polymeric materials with specific metal binding ability.

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