Cyclobutenyl Inimers as Versatile Initiators for Macromonomers Synthesis by Atom Transfer Radical Polymerization

Sandie Piogé, Gaëlle Morandi, Stéphanie Legoupy, Véronique Montembault, Sagrario Pascual, and Laurent Fontaine*

LCOM-Chimie des Polymères, UCO2M, UMR CNRS 6011, Université du Maine, Avenue O. Messiaen, 72085 Le Mans Cedex 09, France

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ABSTRACT: Novel α-cyclobutenyl-containing inimers were used successfully for atom transfer radical polymerization (ATRP) of *tert*-butyl acrylate and styrene leading to narrow molecular weight α-cyclobutenyl-terminated macromonomers ($\overline{M}_{n,SEC}$= 1600−11 500; PDI = 1.06−1.24). The ATRP processes followed first-order kinetics with respect to the monomer concentration. ^{1}H NMR studies showed that the cyclobutenyl moiety in the initiator is stable during ATRP processes. The bromine chain end of resulting macromonomers has been used successfully for the syntheses of block copolymer-based α-cyclobutenyl macromonomers by ATRP. In particular, a range of well-defined polystyrene-*b*-poly(*tert*-butyl acrylate) macromonomers with various terminal α-cyclobutenyl groups were synthesized through this methodology.

Introduction

Controlled/living polymerization processes allow the synthesis of complex and well-defined polymer architectures. Among these architectures, graft copolymers (e.g., cylindrical polymer brushes) offer the unique possibility of tailoring materials properties through modification of their structural parameters such as nature of the polymer backbone and composition and density of the grafts.[1−3] Through changes of these segments, properties such as morphology, order−disorder transitions, and phase behavior can be tuned.[4−6] Graft copolymers are therefore a valuable class of materials used for a variety of applications,[1−3] and many potential applications are expected.[3−9] Among the main synthetic approaches that have been developed, a common route to well-defined graft copolymers relies on macromonomer polymerization ("grafting through" strategy).[10−14] This strategy has proven to be one of the most convenient methods for preparing well-defined graft copolymers, as it allows better control of grafts, backbone length, as well as grafting density.

In our group, we are investigating the combination of atom transfer radical polymerization (ATRP) and ring-opening metathesis polymerization (ROMP) in order to synthesize well-defined grafted copolymers based on a strictly linear 1,4-polybutadiene (PBu) backbone bearing a high density of pendant functionalities via the macromonomer route.[15] Because of their unique properties, PBu graft copolymers could be used for a variety of applications, such as nanomaterials, thermoplastic elastomers, impact-resistant plastics, compatibilizers, polymeric emulsifiers, and nanoparticles for drug delivery.[16−19] In our work, the "grafting through" strategy combining ROMP and ATRP was chosen. This technique affords an exclusively linear polybutadiene with a strictly 1,4-type microstructure and an exact control over the placement of the grafts. The strategy requires the preparation of well-defined macromonomers (i.e., well-defined polymeric chains functionalized at one end by a polymerizable unit for ROMP). The 3,4-disubstituted cyclobutene functionality was selected as the "ROMP-able" entity of the macromonomers. The polymerizability of 3,4-disubstituted cyclobutenes was previously highlighted,[20−23] and we have demonstrated that ROMP of such monomers is a living process affording well-defined (co)polymers.[24] ATRP was chosen to design well-defined polar grafts in order to gain control over composition, end functionalities, molecular weights, polydispersities, and thus the polymer properties.

Table 1. Thermal Ring-Opening of Inimers 2 and 5 into Diene at 100°C Determined by ^{1}H NMR[a]

entry	inimer[a]	reaction time (h)	diene ratio (%)
1	**2**	0.4	not detected
2	**2**	2	4
3	**2**	5	10
4	**5**	0.4	not detected
5	**5**	1	1
6	**5**	5	7

[a] Inimer structures: see Figure 1.

In the literature, various (oxa)norbornenyl inimers (initiator-monomers) bearing an initiating (or transfer) functionality usable for controlled/living processes have been reported for the synthesis of α-functionalized macromonomers.[25−37] Living anionic[25−30] and ring-opening polymerization,[31−33] as well as ATRP[34−36] and reversible addition-fragmentation transfer (RAFT)[37] processes have been used for the preparation of those α-functionalized macromonomers. One-pot and tandem methods, combining a controlled radical process (ATRP, RAFT, or nitroxide mediated polymerization) and ROMP have also been reported for the synthesis of graft copolymers.[7,38−42] Only norbornenyl and oxanorbornenyl inimers have been reported up to now in the literature. In contrast, our strategy requires the synthesis of cyclobutenyl inimers and the use of those precursors as initiators for ATRP to prepare α-cyclobutenyl-terminated macromonomers.[15] Herein, we report the synthesis of new cyclobutenyl inimers (Figure 1) and their use as initiators for the ATRP of styrene and *tert*-butyl acrylate in order to prepare α-cyclobutenyl-terminated macromonomers. These po-

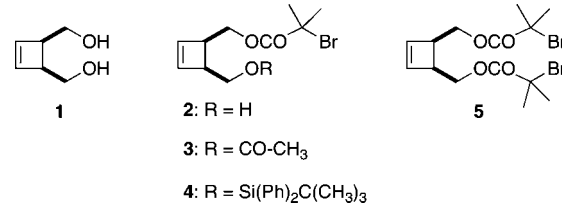

Figure 1. Inimers and precursor used in this work.

* To whom correspondence should be addressed. Phone: +33 (0)2 43 83 33 30; Fax: +33 (0)2 43 83 37 54; E-mail: laurent.fontaine@univ-lemans.fr.

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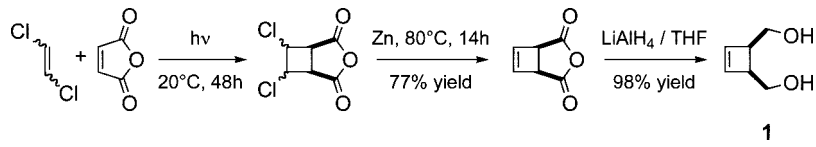
Scheme 1. Synthesis of *cis*-3,4-Bis(hydroxymethyl)cyclobutene (1)[a]



[a] THF: tetrahydrofuran.

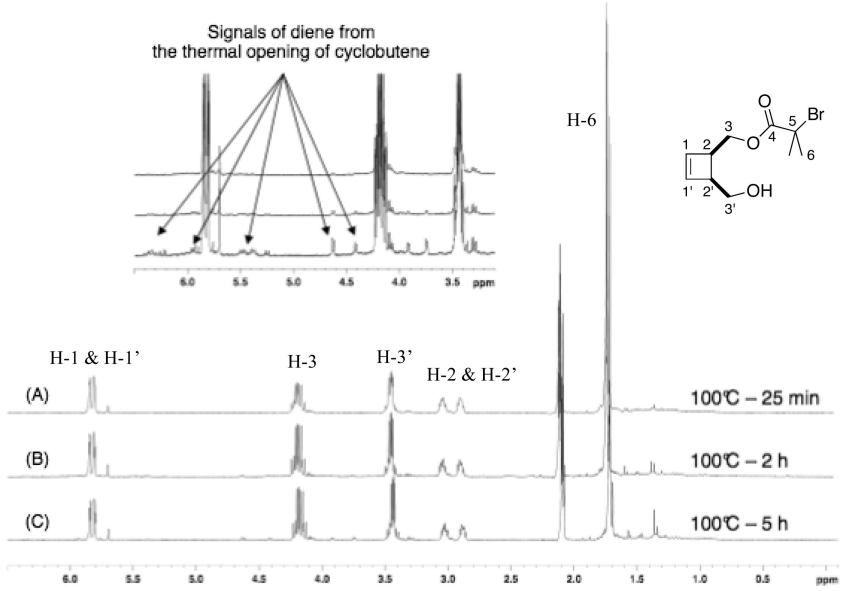
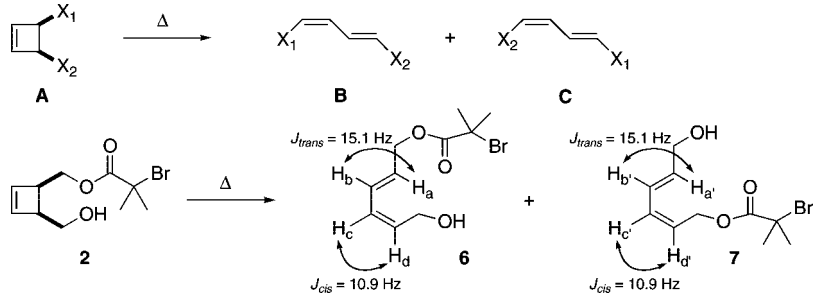


Figure 2. ^{1}H NMR spectra of *cis*-(4-(hydroxymethyl)cyclobut-2-enyl)methyl 2-bromo-2-methylpropanoate (inimer **2**) heated at 100 °C in toluene-d_7; reaction time: 25 min (A), 2 h (B), and 5 h (C).

Scheme 2. Thermal Ring-Opening of Cyclobutene Derivatives



lymerizations produced macromonomers (homopolymers and block copolymers) with controlled molecular weights and narrow molecular weight distributions.

Experimental Section

General Characterization. NMR spectra were recorded on a Bruker Avance 400 spectrometer for ^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz). Chemical shifts are reported in parts per million relative to the deuterated solvent resonances. Molecular weights and molecular weight distributions were measured using size exclusion chromatography (SEC) on a system equipped with a SpectraSYSTEM AS 1000 autosampler, with a Guard column (Polymer Laboratories, PL gel 5 μm Guard column, 50 mm × 7.5 mm) followed by two columns (Polymer Laboratories, 2 PL gel 5 μm MIXED-D columns, 2 × 300 mm × 7.5 mm) and with a SpectraSYSTEM RI-150 detector. The eluent used was tetrahydrofuran (THF) at a flow rate of 1 mL·min^{-1} at 35 °C. Polystyrene standards (580−4.83 × 10^5) were used to calibrate the SEC. High resolution mass spectra were recorded on Waters-Micromass GCT premier spectrometers. Elemental analysis was performed by the Service Central d'Analyses du Centre National de Recherche Scientifique, Gif-sur-Yvette (France).

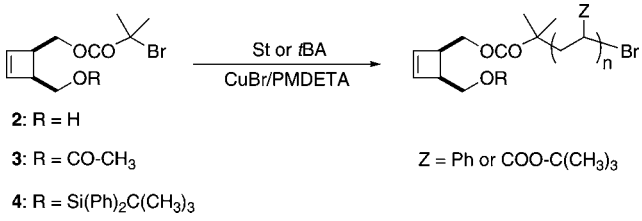
Materials. All chemicals were purchased from Acros unless otherwise noted. Acetic anhydride (99%, Aldrich), 2-bromoisobutyryl bromide (98%), CaH_2 (93%), CuBr (99.999%, Aldrich), cyclohexane (99%), diethyl ether, *N*,*N*-dimethylformamide (DMF, 99%), ethyl acetate (99%), hydrochloric acid (37%), imidazole (99%), anhydrous magnesium sulfate, methanol (99%), neutral alumina, *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine (PMDETA, 99+%), pyridine (99%), sodium chloride, sodium hydrogenocarbonate, silica gel 60 (SiO_2, 0.063−0.200 mm, Merck), *tert*-butyldiphenylchlorosilane (98%, Aldrich), and toluene (99%) were used as received. Anisole (99%), styrene (St, 99%), and *tert*-butyl acrylate (*t*BA, 99%) were distilled under vacuum and were stored at −15 °C after purification. Dichloromethane (CH_2Cl_2, 99%+) and triethylamine (99%) were distilled over CaH_2 and were stored at −4 °C after purification. *cis*-3,4-Bis(hydroxymethyl)cyclobutene (**1**) was prepared according to a procedure reported in literature.[43] cyclobut-3-ene-1,2-diylbis(methylene)bis(2-bromo-2-methylpropanoate (**5**) was synthesized as described in earlier publication.[15]

Table 2. Synthesis of Homopolymer-Based *cis*-Cyclobutenyl Macromonomers by Atom Transfer Radical Polymerization (ATRP) of Styrene (St) and *tert*-Butyl Acrylate (*t*BA) Initiated by Inimers 2, 3, and 4[a] using CuBr/PMDETA[c] as Catalytic System

sample	I[a]	M[b]	$[M]_0/[I]_0/[CuBr]_0/[L]_0$[c]	*T* (°C)	time (h)	conv[d] (%)	$\overline{M}_{n,calcd}$[e]	$\overline{M}_{n,SEC}$[f]	PDI[g]
m-1	2	St	100/1/0.5/0.5	100	1	13	1615	1600	1.10
m-2	2	St	100/1/0.5/0.5	100	1	10	1303	2500	1.08
m-3	2	St	100/1/0.5/0.5	100	48	37	4111	5600	1.09
m-4	2	St	100/1/1/1	100	3.5	28	3175	5300	1.06
m-5	2	St	100/1/1/1	100	9.5	66	7127	11500	1.10[h]
m-6	2	*t*BA	100/1/0.5/0.5	60	6.5	46	6308	7700	1.24
m-7	3	St	100/1/0.5/0.5	100	1	15	1865	2900	1.10
m-8	3	St	100/1/0.5/0.5	100	1	20	2385	3300	1.13
m-9	3	St	100/1/0.5/0.5	100	8	41	4569	6300	1.09
m-10	3	St	100/1/0.5/0.5	100	8.5	55	6140	10600	1.11[h]
m-11	3	*t*BA	100/1/0.5/0.5	60	8.5	47	6436	7600	1.24
m-12	4	St	100/1/0.5/0.5	100	1	19	2478	2500	1.11

[a] I: inimer structures: see Figure 1. [b] M: monomer = styrene (St), *tert*-butyl acrylate (*t*BA). [c] L: ligand = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine (PMDETA); all polymerizations were performed in 50% v/v toluene solution. [d] Monomer conversion determined using ^{1}H NMR spectroscopy. [e] Number-average molecular weight calculated using: $M_{n,calcd}$ = (conversion (%) × $[M]_0/[I]_0$ × M_M) + M_I where M_M and M_I are the molecular weights of monomer and inimer, respectively. [f] Number-average molecular weight measured by size exclusion chromatography (SEC) calibrated with polystyrene standards. [g] Polydispersity index measured by SEC. [h] Bimodal molecular weight distribution.

Scheme 3. Atom Transfer Radical Polymerization (ATRP) of Styrene (St) and *tert*-Butyl Acrylate (*t*BA) Initiated by Inimers 2, 3, and 4[a]



[a] PMDETA = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine.

Inimers Synthesis. *cis-(4-(Hydroxymethyl)cyclobut-2-enyl)methyl 2-Bromo-2-methylpropanoate (**2**).* *cis*-3,4-Bis(hydroxymethyl)cyclobutene (**1**) (1.095 g, 9.5 mmol) and triethylamine (1.50 mL) were dissolved in anhydrous CH_2Cl_2 (140 mL) under a nitrogen atmosphere. The solution was cooled in an ice−water bath, and 2-bromoisobutyryl bromide (1.30 mL, 10.5 mmol) was added dropwise under stirring. The mixture was stirred overnight at room temperature. The resulting CH_2Cl_2 solution was washed successively with 22 mL of hydrochloric acid aqueous solution (10%), 22 mL of sodium hydrogenocarbonate aqueous solution (10%), and 22 mL of saturated sodium chloride aqueous solution. The organic layer was dried over anhydrous magnesium sulfate. After filtering off the drying agent, the solvent was removed by rotary evaporator. The crude product was purified by chromatography on SiO_2 using 5/1 cyclohexane/ethyl acetate, and **2** was obtained as a colorless liquid. Yield: 76%. ^{1}H NMR ($CDCl_3$): δ (ppm): 6.16 (dd, 1H, =C*H*−CH−CH_2−OCO), 6.13 (dd, 1H, =C*H*−CH−CH_2−OH), 4.47 (dd, 1H, C*H*−OCO), 4.28 (dd, 1H, C*H*−OCO), 3.82 (m, 2H, CH_2−OH), 3.31 (m, 1H, =CH−C*H*−CH_2−OCO), 3.23 (m, 1H =CH−C*H*−CH_2−OH), 1.94 (s, 6H, 2 CH_3). ^{13}C NMR ($CDCl_3$): δ (ppm) 171.5 (O−*C*=O), 138.4 and 137.6 (=*C*H−), 65.7 (CH_2−OCO), 62.2 (CH_2−OH), 55.8 (−$C(CH_3)_2$−Br), 48.0 (*C*H−CH_2−OCO), 44.2 (*C*H−CH_2−OH), 30.8 (CH_3). HRMS (CI−NH_3). Calcd for $C_{10}H_{15}BrO_3$ + NH_4: 280.0548. Found: 280.0548.

*cis-(4-(Acetoxymethyl)cyclobut-2-enyl)methyl 2-Bromo-2-methylpropanoate (**3**).* *cis*-(4-(Hydroxymethyl)cyclobut-2-enyl)methyl 2-bromo-2-methylpropanoate (**2**) (0.134 g, 0.51 mmol) was mixed with anhydrous pyridine (1 mL) under nitrogen atmosphere. The mixture was cooled in an ice−water bath, and acetic anhydride (0.48 mL, 5.1 mmol) was added dropwise under stirring. The mixture was stirred for 16 h at room temperature, thereafter cooled in an ice−water bath, and methanol (2 mL) was added. The reaction mixture was evaporated under vacuum, and **3** was obtained as a colorless liquid. Yield: 94%. ^{1}H NMR ($CDCl_3$): δ (ppm) 6.14 (m, 2H, =C*H*−), 4.33 (d, 2H, CH_2−OCO−$C(CH_3)_2$Br), 4.26 (d, 2H, CH_2−OCO−CH_3), 3.30 (m, 2H, =CH−C*H*−), 2.10 (s, 3H, OCO−CH_3), 1.94 (s, 6H, $C(CH_3)_2$). ^{13}C NMR ($CDCl_3$): δ (ppm) 171.6 and 170.9 (O−*C*=O), 138.1 and 137.5 (=*C*H−), 65.5 and 63.9 (CH_2−OCO), 55.7 (−$C(CH_3)_2$Br), 44.1 and 44.4 (=CH−*C*H−), 30.7 (−$(CH_3)_2$C−Br), 21.9 (CH_3). HRMS (CI−NH_3). Calcd for $C_{12}H_{17}BrO_4$ + NH_4: 322.0658. Found: 322.0654.

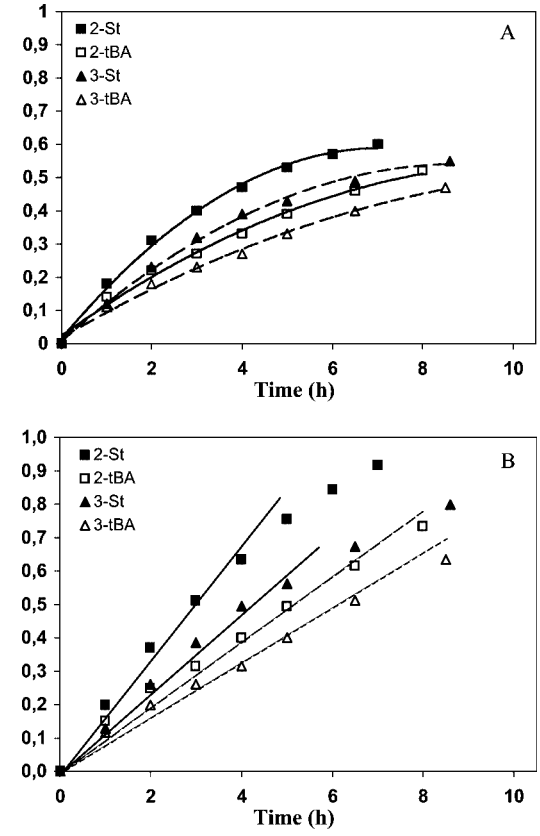


Figure 3. Monomer conversion (A) and ln($[M]_0/[M]$) (B) vs time for the atom transfer radical polymerization (ATRP) of styrene (St) and *tert*-butyl acrylate (*t*BA) using **2** and **3** as initiators ([initiator] = 5.4 10^{-4} mol·L^{-1}) and CuBr/PMDETA as the catalytic system in 50% v/v toluene (PMDETA = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine): (■) $[St]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0$ = 100/1/1/1 at 100 °C; (▲) $[St]_0/[\mathbf{3}]_0/[CuBr]_0/[PMDETA]_0$ = 100/1/0.5/0.5 at 100 °C; (□) $[t\text{BA}]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0$ = 100/1/0.5/0.5 at 60 °C; (Δ) $[t\text{BA}]_0/[\mathbf{3}]_0/[CuBr]_0/[PMDETA]_0$ = 100/1/0.5/0.5 at 60 °C.

*cis-(4-(tert-Butyldiphenylsilyl)cyclobut-2-enyl)methyl 2-Bromo-2-methylpropanoate (**4**).* Imidazole (0.137 g, 2 mmol) and *tert*-butyldiphenylchlorosilane (0.52 mL, 2 mmol) were added to a

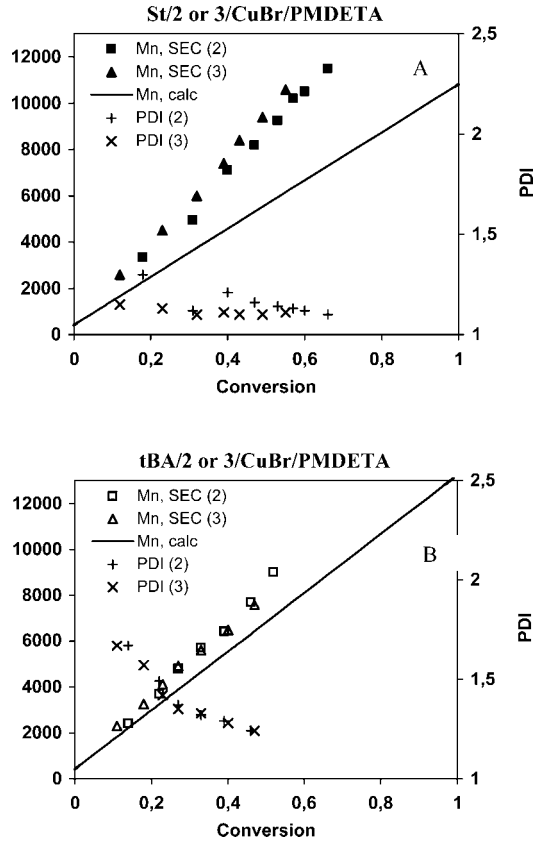
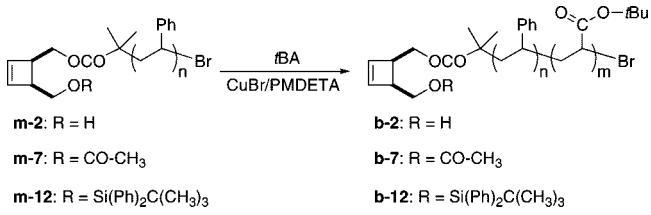


Figure 4. $\overline{M_n}$ and PDI of macromonomers vs monomer conversion for the atom transfer radical polymerization (ATRP) of styrene (St) and *tert*-butyl acrylate (*t*BA) initiated by **2** or **3** using CuBr/PMDETA as the catalytic system in 50% v/v toluene (PMDETA = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine): (A) ATRP of St at 100 °C with (■) $[St]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/1/1$; (▲) $[St]_0/[\mathbf{3}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$; (B) ATRP of *t*BA at 60 °C with (□) $[t\text{BA}]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$; (Δ) $[t\text{BA}]_0/[\mathbf{3}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$.

Scheme 4. Synthesis of Block Copolymer-Based Macromonomers[a]



[a] 60°C, toluene solvent; *t*BA = *tert*-butyl acrylate; PMDETA = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine.

solution of *cis*-(4-(hydroxymethyl)cyclobut-2-enyl)methyl 2-bromo-2-methylpropanoate (**2**) (0.442 g, 1.7 mmol) in anhydrous DMF (1.4 mL) under nitrogen atmosphere. The mixture was stirred for 16 h at room temperature. Water (2 mL) was added, and the resulting mixture was extracted with diethyl ether (4 × 2 mL). The total diethyl ether solution was then dried over anhydrous magnesium sulfate. After filtering off the drying agent, the solvent was removed by rotary evaporator. The crude product was purified by chromatography on SiO_2 using 20/1 cyclohexane/ethyl acetate, and **4** was obtained as a colorless liquid. Yield: 69%. ^{1}H NMR ($CDCl_3$): δ (ppm) 7.66 (m, 4H, *H-ortho*), 7.40 (m, 6H, *H-meta* and *H-para*), 6.14 (m, 2H, =C*H*—), 4.39 (m, 2H, CH_2—OCO), 3.82 (m, 2H, CH_2—O—Si), 3.23 (m, 2H, =CH—C*H*—), 1.87 and 1.86 (s, 6H, C(CH_3)$_2$Br), 1.05 (s, 9H, Si—C(CH_3)$_3$). ^{13}C NMR ($CDCl_3$): δ (ppm) 171.5 (O—*C*=O), 139.0 and 137.2 (=*C*H—), 135.6 (*C-ortho* Si), 129.6 (*C-para* Si), 127.6 (*C-meta* Si), 66.2 and 63.8 (*C*H_2—O), 55.8 (*C*—Br), 47.6 and 44.1 (=CH—*C*H—), 30.8 (—(*C*H_3)$_2$C—Br), 26.9 (Si—C(*C*H_3)$_3$), 19.2 (Si—*C*). Anal. Calcd for $C_{26}H_{33}BrO_3Si$: C, 62.27; H, 6.63. Found: C, 62.13; H, 6.85.

ATRP Polymerizations. A typical procedure is given below for the polymerization of styrene (St) using *cis*-(4-(hydroxymethyl)-cyclobut-2-enyl)methyl 2-bromo-2-methylpropanoate (**2**) as the initiator ($[St]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$). A solution of 3.60 mL (0.03 mol) of styrene, 81.6 mg (0.30 mmol) of **2**, 3.60 mL (50% v/v) of toluene, and 0.40 mL (5% v/v) of anisole previously degassed by three freeze−pump−thaw cycles was transferred under argon into a Schlenk tube containing 22 mg (0.155 mmol) of CuBr using a cannula. The reaction mixture was degassed by three freeze−pump−thaw cycles and back-filled with argon. It was then placed in an oil bath thermostated at 100 °C. Once the reaction temperature was reached, 32 μL (0.155 mmol) of degassed PMDETA was added under argon ($t = 0$). After certain intervals, samples were withdrawn from the reaction mixture via a degassed syringe for conversion monitoring (^{1}H NMR) and molecular weight analysis (SEC). Each sample was dissolved in dichloromethane and passed through a neutral alumina column to remove the catalyst. The polymer solution was concentrated under vacuum, and then, the polymer was precipitated in a large excess of methanol and dried under vacuum until constant weight. The sample was further analyzed by SEC (see Table 2). A similar procedure was followed for polymerization of *tert*-butyl acrylate (*t*BA) and for the preparation of block copolymers using the appropriate inimer or macroinimer and the following conditions:

α-*Cyclobutenyl* (**2**) polystyrene: $[St]_0/[\mathbf{2}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/1/1$; 100 °C.

α-*Cyclobutenyl* (**2**) and (**3**) poly(*t*BA): $[t\text{BA}]_0/[\mathbf{2}]_0$ or $[\mathbf{3}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$; 60 °C.

α-*Cyclobutenyl* (**3**) and (**4**) polystyrene: $[St]_0/[\mathbf{3}]_0$ or $[\mathbf{4}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$; 100 °C.

α-*Cyclobutenyl* (**2**), (**3**) and (**4**) poly(St)-*b*-poly(tBA): $[t\text{BA}]_0/[\mathbf{2b}]_0$ or $[\mathbf{3a}]_0$ or $[\mathbf{4a}]_0/[CuBr]_0/[PMDETA]_0 = 100/1/0.5/0.5$; 60 °C.

Results and Discussion

Synthesis of Cyclobutenyl-Functionalized ATRP Inimers. Many functionalized cyclobutenes can be conveniently synthesized using the *cis*-cyclobut-3-ene-1,2-dicarboxylic anhydride precursor (Scheme 1) that is available by photochemical [2 + 2] cycloaddition between maleic anhydride and acetylene. Although this reaction involves inexpensive reagents, it is cumbersome and not totally safe. This hazardous character of the monomers synthesis may explain the limited number of studies dedicated so far to the ROMP of cyclobutene derivatives compared to their norbornene counterparts.[20−23,44−49] In our laboratory, a new safe and original synthetic route was developed using (*Z* + *E*)- or (*E*)-dichloroethene as acetylene equivalents.[43] The photochemical step is safer and less cumbersome. The subsequent elimination in the presence of activated zinc followed by reduction (Scheme 1) provides *cis*-3,4-bis(hydroxymethyl)cyclobutene (**1**) in very good yield. ROMP is known to be highly sensitive to the stereochemistry of the monomer around the double bond.[50−53] The *cis* stereochemistry was preferred to the *trans* as previous studies have highlighted the higher reactivity of *cis*-3,4-disubstituted cyclobutenes compared to their *trans* analogues in ROMP.[24]

A series of original cyclobutenyl-functionalized ATRP initiators were synthesized from compound **1** that contains a ring-opening metathesis polymerizable cyclobutene moiety and two hydroxymethyl groups that allowed 2-fold and unsymmetrical functionalization. Inimer **2** (Figure 1) was prepared from **1** and 2-bromoisobutyryl bromide by a simple nucleophilic substitution reaction using triethylamine/CH_2Cl_2. Pure **2** was obtained in 76% yield after column chromatography by using a slight excess (1.1 equiv) of 2-bromoisobutyryl bromide in dilute solution ([**1**] = 0.068 mol·L^{-1} in CH_2Cl_2 solution). The OH functionality

Table 3. Atom Transfer Radical Polymerization (ATRP) of *tert*-Butyl Acrylate (*t*BA) using α-Cyclobutenyl Polystyrene as Macroinitiator and CuBr/PMDETA as Catalyst at 60°C[a]

sample	MI[b]	$[tBA]_0/[MI]_0/[CuBr]_0/[PMDETA]_0$	time (h)	conv[c] (%)	$\overline{M}_{n,calcd}$[d]	$\overline{M}_{n,SEC}$[e]	PDI[f]
b-2	**m-2**	100/1/0.5/0.5	7.5	18	4804	7000	1.18
b-7	**m-7**	100/1/0.5/0.5	8	27	6356	6800	1.42
b-12	**m-12**	100/1.0.5/0.5	24	18	4732	3100	1.16

[a] Solvent = toluene, 50% v/v; PMDETA = *N*,*N*,*N*′,*N*′,*N*″-pentamethyldiethylenetriamine. [b] MI: α-cyclobutenyl polystyrene macroinitiator (see Table 2). [c] Monomer (*t*BA) conversion determined using ^{1}H NMR spectroscopy. [d] Number-average molecular weight calculated using: $M_{n,calcd}$ = (conversion (%) × $[M]_0/[MI]_0 \times M_M$) + M_{MI} where M_M and M_{MI} are the molecular weights of monomer and macroinitiator, respectively. [e] Number-average molecular weight measured by size exclusion chromatography (SEC) calibrated with polystyrene standards. [f] Polydispersity index measured by SEC.

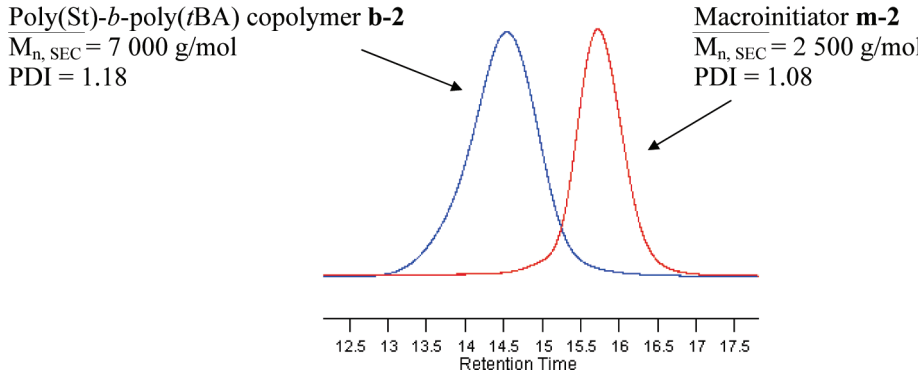


Figure 5. Size exclusion chromatography (SEC) traces of polystyrene macroinitiator (**m-2**) and poly(St)-*b*-poly(*t*BA) block copolymer (Table 3, sample **b-2**) prepared from *cis*-(4-(hydroxymethyl)cyclobut-2-enyl)methyl 2-bromo-2-methylpropanoate (inimer **2**).

of **2** was also modified into an acetyl moiety according to a procedure already reported in the literature[54] in 94% yield. Finally, the reaction of **2** with 1.2 equiv of *tert*-butyldiphenylchlorosilane in the presence of imidazole in anhydrous DMF stirred for 16 h afforded **4** in 69% yield, after chromatographic purification. Such an inimer was selected as it provides a complete orthogonality between the silyl group and the ester group allowing a selective regeneration of the hydroxyl functionality from the silyl moiety.[55] Unsymmetrical inimers can thus be prepared, containing two initiation functions that can initiate different polymerization mechanisms selectively and independently, giving rise to orthogonal or dual initiators. This concept of dual initiator has been successfully applied to the combination of numerous polymerization techniques.[56]

Thermal Stability of the Inimers. The formation of dienes by thermal opening of cyclobutenes is a long established route.[57] Indeed, the *cis*-3,4-disubstituted cyclobutenes **A** usually produce mixtures of both (*Z*, *E*)-dienes **B** and **C** (Scheme 2), though the ratio strongly depends on the electronic effects of the allylic substituents.[58−60] The π-donors mainly or exclusively lead to outward rotation and π-acceptors, to inward rotation.[57] In addition, when both substituents have complementary preferences in the conrotatory mode[61] as the unsymmetric inimer **2**, the thermal ring opening is facilitated and can occur at low temperature. The thermal stability of the inimer **2** was thus investigated under typical ATRP conditions. Toluene is widely used as a solvent for the ATRP of conventional monomers such as acrylates and styrene.[62−64] Therefore, inimers dissolved in toluene were heated to evaluate the survival of the cyclobutenyl ring during the ATRP process. Figure 2 illustrates the monitoring by ^{1}H NMR of the evolution of inimer **2** heated at 100 °C in toluene-d_7 during 25 min, 2 h, and 5 h, respectively. The appearance of the double bond resonances of the two isomeric (*Z*, *E*)-dienes **6** and **7** was observed at 4.4−4.65 ppm (Figure 2B and C). The coupling constants for **6** and **7** are consistent with the expected (*Z*, *E*) structures (Scheme 2, (*Z*, *E*)-dienes **6** and **7**).[65]

Table 1 summarizes the ring-opening ratio at various time intervals for the thermal ring-opening of **2**. The results show that the experimental conditions are compatible with the ATRP process as **2** is stable up to 100 °C for a duration of 2 h. The thermal stability of **2** is similar to that observed for the symmetric inimer **5** (Scheme 1 and Table 1, entries 4−6).

Synthesis of Cyclobutenyl Macromonomers by ATRP. We have previously shown that the ATRP of styrene (St) and *tert*-butyl acrylate (*t*BA) initiated by inimer **5** enables the synthesis of well-defined macromonomers with controlled molecular weight and composition as well as narrow molecular weight distribution.[15] Herein, we investigated the ATRP of St and *t*BA initiated by inimers **2**, **3**, and **4** at 100 and 60 °C, respectively, in toluene (50% v/v) using CuBr/PMDETA[66] as the catalytic system and different initiator/catalytic system ratios (Scheme 3 and Table 2).

The polymerizations were carried out at temperatures ranging from 60 to 100 °C as the cyclobutenyl group has shown a limited chemical stability under elevated temperatures (Table 1). To confirm the stability of the cyclobutenyl moiety in the inimer during the ATRP process, a α-cyclobutenyl (**2**) poly(St) of $\overline{M}_{n,SEC}$ = 5300 (Table 2, sample **m-4**) was subjected to analysis by ^{1}H NMR spectroscopy. The peaks corresponding to the cyclobutenyl ring end-group were clearly visible in the spectrum. In particular, peaks corresponding to the hydrogens of the double bond at 5.95 and 6.06 ppm were observed, providing good evidence that this moiety did not thermally open during the polymerization. Moreover, the molecular weight distribution of the macromonomer was narrow (Table 2, PDI = 1.06) clearly indicating that the cyclobutenyl group in the initiator was not involved in the ATRP process. Aliquots removed periodically during polymerizations were analyzed by both ^{1}H NMR spectroscopy (to monitor the monomer conversion) and by SEC to determine the number-average molecular weight and polydispersity index of the final polymers (Figures 3 and 4). During the ATRP of styrene, the $\ln[M]_0/[M]$ vs time plots clearly show a decrease of the concentration of propagating radicals from 45% and 35% styrene conversions with **2** and **3**, respectively (Figure 3B). The SEC traces of α-cyclobutenyl (**2**) and (**3**) polystyrenes obtained at high conversions show a bimodal molecular weight distribution with the presence of a shoulder (Table 2, samples **m-5** and **m-10**). Moreover, the evolution of the number-average molecular weights of the resulting poly(St)s

using either **2** or **3** as initiators shows that the experimental $\overline{M}_{n,SEC}$ are higher than the calculated ones for high conversions (Figure 4A). This confirms the presence of irreversible terminations between polystyryl propagating radicals and/or radicals arising from side reactions involving the cyclobutenyl moiety. These side reactions are favored by long reaction times at an elevated temperature (100 °C). In contrast, the $\ln([M]_0/[M])$ versus time plots for the ATRP of *t*BA are linear with both **2** and **3** initiators (Figure 3B). This first-order kinetic is compatible with a constant concentration of propagating radicals throughout the polymerization. Moreover, the SEC analysis shows that the number-average molecular weight of poly(*t*BA) increased linearly with increasing the *t*BA conversion (Figure 4B). The polydispersities remained narrow and decreased with *t*BA conversion (Figure 4B). The ATRP of *t*BA is well-controlled using both initiators **2** and **3**; this is compatible with a good efficiency of such initiators.

To further investigate the living characteristics of polymers prepared from **2**, **3**, and **4**, block copolymers were prepared via sequential addition (Scheme 4), and the results are summarized in Table 3. Well-defined α-cyclobutenyl polystyrenes were preliminary synthesized. Polymerizations of styrene were performed in solution at 100 °C using CuBr as the catalyst, PMDETA as the ligand, and toluene as the solvent. In each case, the isolated and purified α-cyclobutenyl polystyrenes obtained at low conversion (Table 2, samples **m-2**, **m-7**, and **m-12**) were subsequently used as macroinitiators for the polymerization of *t*BA at 60 °C using CuBr/PMDETA as the catalytic system.

Resulting α-cyclobutenyl poly(St)-*b*-poly(*t*BA) macromonomers **b-2** and **b-12** showed relatively low PDI values (1.16−1.18). The SEC trace of the diblock copolymer **b-2** showed a monomodal curve with no detectable quantities of unreacted macroinitiator indicating that the polymerization of the second block was initiated quantitatively (Figure 5).

Conclusion

Unsymmetric α-cyclobutenyl initiators were demonstrated to provide a good efficiency for the initiation and controlled polymerization of styrene and *t*BA using a commercially available ligand (PMDETA) to afford well-defined polymers with relatively narrow polydispersities (PDI = 1.06−1.24). The stability of the terminal cyclobutenyl group during the macromonomer preparation was confirmed by ^{1}H NMR spectroscopy. In contrast to previous work reporting the competitive reactivity of the norbornenyl functionality during ATRP of acrylates,[34] our results show that the cyclobutenyl unsaturation survives intact the polymerization process. The resulting α-cyclobutenyl polystyrene-based macromonomers have been used as ATRP macroinitiators to further prepare α-cyclobutenyl poly(St)-*b*-poly(*t*BA)-based block copolymers. Such macromonomers with a second functionality on the α-cyclobutenyl ring can serve as an initiator for another polymerization, giving access to Janus-type polymer brushes with two polymeric chains of different nature that show promising applications (e.g., within the field of new drug delivery systems).[67] We have previously shown that amphiphilic water-soluble α-cyclobutenyl poly(styrene)-*b*-poly(acrylic acid)-based block copolymers prepared by acidolysis[15] can be used as stabilizers in emulsion polymerization of styrene.[68] Study of the ROMP of these α-cyclobutenyl macromonomers in aqueous dispersed media is currently under investigation in our group and will be reported in due course.

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