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From epoxide to cyclodithiocarbonate telechelic polycyclooctene through chain-transfer ring-opening metathesis polymerization (ROMP): precursors to non-isocyanate polyurethanes (NIPUs)

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Abstract

Telechelic polycyclooctenes (PCOEs) have been successfully synthesized by ring-opening metathesis polymerization (ROMP)/cross metathesis (CM) of cyclooctene (COE) using Grubbs’ 2nd-generation catalyst (G2) in the presence of epoxide-functionalized chain-transfer agents (CTAs). The monofunctional epoxide oxiran-2-yilmethyl acrylate CTA (1) afforded the isomerized α-(glycidyl alkenoate),ω-propenyl functional (IMF) PCOEs. The use of 1,4-benzoquinone (BZQ) as additive completely inhibited the C=C isomerization process, thereby leading selectively to α-(glycidyl alkenoate),ω-vinyl telechelic (MF) PCOE. On the other hand, difunctional epoxide CTAs, bis(oxiran-2-yilmethyl) fumarate (3), bis(oxiran-2-yilmethyl) maleate (4), bis(oxiran-2-yilmethyl) (E)-hex-3-enedioate (5), and (Z)-1,4-bis(oxiran-2-ylmethoxy)but-2-ene (6), selectively afforded the corresponding α,ω-di(glycidyl alkenoate) telechelic PCOEs (DF), along with minor amounts of cyclic nonfunctional (CNF) PCOE. In presence of these difunctional symmetric CTAs, the mechanism is proposed to proceed through a tandem one-pot CM/ROMP/ring-closing metathesis (RCM) approach. CM was more effective with Z- than E-configurated CTAs (4 > 6 >> 3 >> 5), regardless of the presence of a methylene group in-between the C=C double bond and the glycidyl moiety. Subsequent dithiocarbonation of the α,ω-diepoxide telechelic PCOEs upon reaction with CS2 in the presence of LiBr quantitatively afforded the first examples of bis(cyclodithiocarbonate) end-functional PCOEs. Ensuing aminolysis of the bis(cyclodithiocarbonate) telechelic PCOEs with the polyether (triethyleneglycol) diamine JEFFAMINE EDR-148 quantitatively afforded, at room temperature without any added catalyst, the desired poly(mercaptothiourethane)s NIPUs, as evidenced from FTIR spectroscopy, TGA and DSC analyses.

Keywords: Chain-transfer agent, cyclodithiocarbonate, epoxide, NIPU, polycyclooctene, polyurethane, ring-opening metathesis polymerization (ROMP), telechelic
Introduction

Conventional polyurethanes (PUs) are widely used in many applications such as foams, paintings, adhesives, or coatings.\textsuperscript{1,2,3,4,5} Classically, PUs are synthesized from the polyaddition of a diol (or polyol) with a diisocyanate (or polyisocyanate) in the presence of a catalyst.\textsuperscript{6,7,8,9} However, isocyanates require hazardous and toxic phosgene for their manufacture, and they are considered as toxic, hence limiting their use, in particular according to REACH European regulations. Current academic and industrial research thus aims at establishing safer and “greener” alternative routes to more environmentally friendly PUs. These more sustainable approaches mainly include the use of bio-based isocyanates, the valorization of renewable vegetable oils (natural oil polyols) or CO\textsubscript{2} feedstocks, and isocyanate-free methods. Among the latter ones, the aminolysis of a bis(cyclocarbonate) compound with a di- or polyamine to form non-isocyanate PUs (NIPUs) is nowadays the most investigated and promising strategy.\textsuperscript{10,11,12,13,14,15,16,17,18}

Although six-, seven- and eight-membered cyclocarbonates react more readily with amines than five-membered cyclocarbonates (5CCs),\textsuperscript{19,20,21,22,23} the latter have been more extensively used as they can be easily prepared in high yields and stored over long periods of time due to their high stability. Polyaddition between 5CCs and amines, typically bifunctional monomers, leads to polyhydroxyurethanes (PHUs) featuring both primary and secondary alcohols at the $\beta$-carbon atom of the urethane moiety, as depicted in Scheme 1.\textsuperscript{1,4–17,24,25,26}
One first synthetic approach towards PHUs/NIPUs we have been investigating relies on the post-polymerization chemical modification of telechelic precursors such as \( \alpha, \omega \)-dihydroxy telechelic polycarbonate, polyesters or polyolefins, into their corresponding 5CC-functionalized polymers; this eventually enabled to reach high molar mass NIPU materials \( M_n, \text{SEC} \) up to 68 100 g.mol\(^{-1}\).\(^{27,28}\) Another more straightforward route we have been exploring towards the desired 5CC telechelic precursors of NIPUs relies on the direct synthesis of 5CC end-capped polymers through the ring-opening metathesis polymerization (ROMP) of a cyclic olefin using 5CC-based chain transfer agents (CTAs).\(^{29,30}\) Indeed, the metathesis pathway enables, via bifunctional symmetric alkene CTAs (methacrylate, epoxide, carboxylate, acetox, amino, carbonate, hydroxy, halide and pseudo-halide, trialkoxysilyl), to access to well-defined telechelic polyolefins; as evidenced by Grubbs\(^{31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48}\) later on by Hillmyer\(^{49,50,51,52,53,54,55,56,57}\) and recently by ourselves.\(^{58,59}\) The resulting telechelic polyolefins next mainly served as macromonomers towards the preparation of ABA triblock copolymers.

One drawback of the 5CCs is their high thermodynamic stability. Despite that several parameters can be tuned to improve the carbonate/amine reaction,\(^{12,28}\) major current issues to tackle are the low reactivity of 5CCs at room temperature, the required presence of a catalyst,
and the reaching of high molar mass polymers in relation with the ability to strictly control the functionality of the reactive telechelic precursors (both carbonate and amine).

Five-membered cyclothiocarbonates are promising, more reactive alternatives to their corresponding 5CC analogues. Endo and coworkers evidenced that the polyaddition of bis(cyclothiocarbonate)s with diamines under mild conditions (30 °C) afforded PUs featuring thiourethane groups along the polymer backbone. The poly(mercaptothiourethane)s resulting from the polyaddition of bifunctional five-membered cyclodithiocarbonates (DTC) with diamines are then exempt of hydroxyl groups. On the other hand, the pendant thiol functions of the dithiourethane moieties can be advantageously crosslinked by oxidation into disulfide linkages, thus affording polymers with improved mechanical properties (Scheme 2).

**Scheme 2.** Typical aminolysis of a five-membered bis(cyclodithiocarbonate).

In the present work, we expand our approach to NIPUs via the ROMP/cross metathesis (CM) strategy using Grubbs’ second generation catalyst and epoxide-based CTAs to prepare $\alpha,\omega$-epoxide telechelic poly(cyclooctene)s (PCOEs); these next served as precursors to the corresponding $\alpha,\omega$-DTC telechelic PCOEs. Indeed, our preliminary investigations revealed that the direct approach consisting in using DTC-based CTAs in ROMP/CM could not be implemented due to catalyst deactivation upon its reaction with the
thiol ring (Scheme S1). Whereas monofunctional epoxide-based CTAs gave linear PCOEs end-capped by epoxide and vinyl groups, the symmetric epoxide-difunctional CTAs selectively afforded the desired $\alpha,\omega$-diepoxide functionalized PCOEs, possibly with some cyclic polyolefin, through a ROMP/ring-closing metathesis (RCM)/CM approach (Schemes 3, S2–S4). These diepoxide telechelic PCOEs complement the (to our knowledge) very rare such polyolefin examples previously reported from the ROMP of cyclooctadiene (COD), from the acyclic diene metathesis of 1,9-decadiene with epoxide-containing monoolefins, or from the chemical modification of a prepolymer. Subsequent reaction of the PCOE epoxide end-functions with CS$_2$ smoothly and quantitatively afforded the five-membered bis(cyclodithiocarbonate) telechelic PCOEs, which successfully afforded poly(mercaptothiourethane) NIPUs following an ensuing aminolysis (Schemes 4–5). The polymers were thoroughly characterized by NMR, FTIR, DSC, TGA and MALDI-ToF MS.

**Experimental section**

**Materials.** All catalytic experiments were performed under inert atmosphere (argon, < 3 ppm O$_2$) using standard Schlenk line and glove box techniques. Grubbs’ 2nd-generation catalyst, ([IMesH$_2$)(Cy$_3$P)RuCl$_2$(=CHPh)], G2), acryloyl chloride, methacryloyl chloride, fumaroyl chloride, CH$_2$Cl$_2$ (stabilized with amylene), triethylamine (Et$_3$N), JEFFAMINE EDR-148 (triethyleneglycol diamine; Huntsman, primary amine content = 13.48 mequiv.g$^{-1}$), (E)-hex-3-enedioic acid, and all other reagents (Aldrich, unless otherwise mentioned), were used as received. Glycidol was distilled before use, and cyclooctene (COE, TCI Europe) was first dried over CaH$_2$ overnight, and then distilled before use. Acrylate cycldithiocarbonate (DTC-Ac)$^{70,71}$ ($^1$H and $^{13}$C{$^1$H}NMR Figures S1–S2; HRMS (ESI): C$_7$H$_8$O$_3$NaS$_2$ [M+Na]$^+$, calcd 226.9807; found 226.9806), bis(oxiran-2-ylmethyl) maleate$^{72,73}$ (4) ($^1$H and $^{13}$C{$^1$H}NMR Figures S5–S6; HRMS (ESI): C$_{10}$H$_{12}$O$_6$Na [M+Na]$^+$: calcd 251.05316; found
251.0531), and (Z)-1,4-bis(oxiran-2-ylmethoxy)but-2-ene\(^{31}\) (6) (Figures S7–S8; HRMS (ESI): C\(_{10}\)H\(_{16}\)O\(_4\)Na \([\text{M+Na}]^+\): calcd 223.0946; found 223.0945) were synthesized according to the previously reported procedure, respectively.

**Instrumentation and measurements.** \(^1\)H (500, 400 MHz) and \(^{13}\)C\{\(^1\)H\} (125, 100 MHz) NMR spectra were recorded on Bruker Avance AM 500 and AM 400 spectrometers at 25 °C in CDCl\(_3\). Chemical shifts (\(\delta\)) are reported in ppm and were referenced internally relative to tetramethylsilane (\(\delta\) 0 ppm) using the residual \(^1\)H and \(^{13}\)C solvent resonances of the deuterated solvent.

Monomer conversions were determined from \(^1\)H NMR spectra of the crude polymer sample, from the integration (Int.) ratio Int._Polymer/[Int._Polymer + Int._monomer], using the methine hydrogens (\(-\text{CH}=	ext{CH}-\): \(\delta\) 5.30 for PCOE, and 5.66 for COE).

The relative amounts of \(\alpha\)-monofunctional (MF), isomerized \(\alpha\)-monofunctional (IMF), and \(\alpha,\omega\)-difunctional (DF) polymers (neglecting linear non-functional (LNF), isomerized linear non-functional (ILNF) and cyclic non-functional (CNF) polymers – always found to be in minor amounts, *vide infra*) were determined by \(^1\)H NMR analysis of the precipitated polymer samples. The signal for the internal olefinic hydrogens adjacent to the CTA functional group (H\(^6\), \(\delta\) 7.02 Figure S9) was arbitrarily set to 1. The signal corresponding to the terminal methylene hydrogens of the vinyl group of a vinyl-end-functionalized polymer (H\(^7\), \(\delta\) 4.95, Figure S11) was used to determine the MF content as: MF (mol%) = Int.(\(\delta\) 4.95) / 2 \(\times\) 100%. The signal corresponding to the terminal methyl group adjacent to a propenyl end-functional polymer (H\(^6\), \(\delta\) 1.65, Figure S9) was used to determine the IMF content as: IMF (mol%) = Int.(\(\delta\) 1.65) / 3 \(\times\) 100%. The percentage of DF in the mixture is calculated from DF (mol%) = 100 – (MF + IMF)%.
The molar mass values of the polymers samples were determined by \textsuperscript{1}H NMR analysis in CDCl$_3$ ($M_{n,\text{NMR}}$) from the integral value ratio of the signals of end-groups’ hydrogens (typically $\delta$ ca.7.02 (H\textsuperscript{g})) to internal olefin hydrogens ($\delta$ ca. 5.36 (H\textsuperscript{1})) (Figure S9).

The average molar mass ($M_{n,\text{SEC}}$) and dispersity ($D_M = M_w/M_n$) values of the PCOE samples were determined by size exclusion chromatography (SEC) in THF at 30 °C (flow rate = 1.0 mL.min$^{-1}$) on a Polymer Laboratories PL50 apparatus equipped with a refractive index detector and a set of two ResiPore PLgel 3 µm MIXED-E 300 $\times$ 7.5 mm columns. The polymer samples were dissolved in THF (2 mg.mL$^{-1}$). All elution curves were calibrated with 12 monodisperse polystyrene standards ($M_n$ range = 580–380,000 g.mol$^{-1}$). $M_{n,\text{SEC}}$ values of polymers were uncorrected for their possible difference in hydrodynamic volume in THF vs polystyrene. The SEC traces of the polyolefins all exhibited a monomodal and symmetrical peak.

Flash chromatography was performed on a REVELERIS Prep purification system (Grace) using silica gel cartridges.

MALDI-ToF mass spectra were recorded at the CESAMO (Bordeaux, France) on a Voyager mass spectrometer (Applied Biosystems) equipped with a pulsed N$_2$ laser source (337 nm, 4 ns pulse width) and a time-delayed extracted ion source. Spectra were recorded in the positive-ion mode using the reflectron mode and with an accelerating voltage of 20 kV. A freshly prepared solution of the polymer sample in THF (HPLC grade, 10 mg.mL$^{-1}$), a saturated solution of $trans$-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidene]-malononitrile (10 mg, DCTB) in THF (1 mL, HPLC grade) were prepared. A MeOH solution of the cationizing agent (NaI or Ag(OCOCF$_3$) (AgTFA), 10 mg/mL) was also prepared. The solutions were combined in a 10:1:1 \textit{v/v} of matrix-to-sample-to-cationizing agent. The resulting solution (1–2 µL) was deposited onto the sample target and vacuum-dried.
FTIR spectra of the polymers were acquired (16 scans) with a resolution of 4 cm\(^{-1}\) on a Shimadzu IRAffinity-1 equipped with an ATR module.

Differential scanning calorimetry (DSC) analyses were performed with a Setaram DSC 131 apparatus calibrated with indium, at a rate of 10 °C.min\(^{-1}\), under a continuous flow of helium (25 mL.min\(^{-1}\)), using aluminum capsules. The thermograms were recorded according to the following cycles: −70 to 120 °C at 10 °C.min\(^{-1}\); 120 to −70 °C at 10 °C.min\(^{-1}\); −70 °C for 5 min; −70 to 120 °C at 10 °C.min\(^{-1}\); 120 to −70 °C at 10 °C.min\(^{-1}\).

Thermogravimetric analyses (TGA) were performed on a Metler Toledo TGA/DSC1 by heating polymer samples at a rate of 10 °C.min\(^{-1}\) from +25 °C to +500 °C in a dynamic nitrogen atmosphere (flow rate = 50 mL.min\(^{-1}\)) (Figure S36).

**Oxiran-2-ylmethyl acrylate (1).** To a solution of glycidol (2.00 g, 27.0 mmol) and Et\(_3\)N (5.46 g, 54.0 mmol) in CH\(_2\)Cl\(_2\) (27 mL), acryloyl chloride (2.44 g, 27.0 mmol) was added dropwise at 0 °C. The reaction mixture was stirred at room temperature for 4 h, then filtered, and concentrated under reduced pressure. Separation by flash chromatography (pentane/ethyl acetate, gradient 100:0–60:40) afforded 1 as a colorless oil (2.90 g, 85%). \(^1\)H NMR (400 MHz, CDCl\(_3\), 25 °C): \(\delta\) (ppm) 2.66 (dd, \(J = 5\) Hz, 1H, OCH\(_2\)CHCH\(_2\)OC(O)), 2.85 (t, 1H, \(J = 5\) Hz, OCH\(_2\)CHCH\(_2\)OC(O)), 3.25 (dq, \(J = 3\), 6 Hz, 1H, OCH\(_2\)CHCH\(_2\)OC(O)), 4.01 (dd, \(J = 6\), 12 Hz, 1H, OCH\(_2\)CHCH\(_2\)OC(O)), 4.49 (dd, \(J = 3\), 12 Hz, 1H, OCH\(_2\)CHCH\(_2\)OC(O)), 5.87 (dd, \(J = 3\), 10 Hz, 1H, CH\(_2\)CH(O)), 6.15 (dd, \(J = 10\), 17 Hz, 1H, CH\(_2\)CH(O)), 6.45 (dd, \(J = 3\), 17 Hz, 1H, CH\(_2\)CH(O)) (Figure S13). \(^{13}\)C\(^{\{1\}H}\)NMR (125 MHz, CDCl\(_3\), 25 °C): \(\delta\) (ppm) 44.8 (OCH\(_2\)CHCH\(_2\)OC(O)), 49.5 (OCH\(_2\)CHCH\(_2\)OC(O)), 65.1 (OCH\(_2\)CHCH\(_2\)OC(O)), 128.0 (CH\(_2\)CH(O)), 131.7 (CH\(_2\)CH(O)), 165.9 (CH\(_2\)CH(O)) (Figure S14). HRMS (ESI) (m/z): C\(_6\)H\(_8\)O\(_3\)Na [M+Na]\(^+\), calcld 151.0328; found 151.0327.

**Oxiran-2-ylmethyl methacrylate (2).** Compound 2 was synthesized following the same procedure as described for 1, using glycidol (2.00 g, 0.027 mol), Et\(_3\)N (7.29 mL, 0.054 mol),
CH₂Cl₂ (80 mL) and methacryloyl chloride (2.60 mL, 0.027 mol), and similarly purified by flash chromatography (pentane/ethyl acetate, 70:30) to give 2 as a colorless oil (1.03 g, 35%). ¹H NMR (400 MHz, CDCl₃, 25 °C) δ (ppm) 1.95 (s, 3H, CH₂C(CH₃)C(O)), 2.66 (dd, J = 3, 5 Hz, 1H, OCH₂CHCH₂OC(O)), 2.85 (t, J = 5, 1H, OCH₂CHCH₂OC(O)), 3.24 (dq, J = 3, 6 Hz, 1H, OCH₂CHCH₂OC(O)), 4.00 (dd, J = 6, 12 Hz, 1H, OCH₂CHCH₂OC(O)), 4.47 (dd, J = 5, 12 Hz, 1H, OCH₂CHCH₂OC(O)), 5.60 (s, 1H, CH₂C(CH₃)C(O)), 6.15 (s, 1H, CH₂C(CH₃)C(O)) (Figure S3). ¹³C{¹H} NMR (125 MHz, CDCl₃, 25 °C): δ (ppm) 18.2 (CH₂C(CH₃)C(O)), 44.5 (OCH₂CHCH₂OC(O)), 49.3 (OCH₂CHCH₂OC(O)), 65.1 (OCH₂CHCH₂OC(O)), 126.1 (CH₂C(CH₃)C(O)), 135.8 (CH₂C(CH₃)C(O)), 166.9 (CH₂C(CH₂)C(O)) (Figure S4). HRMS (ESI) (m/z): C₇H₁₀O₃Na [M+Na]⁺, calcd 165.0528; found 165.0527.

Bis(oxiran-2-ylmethyl) fumarate (3). Compound 3 was synthesized following the same procedure as described for 1 using glycidol (2.44 g, 33 mmol), Et₃N (8.5 mL, 33 mmol), CH₂Cl₂ (140 mL), and fumaroyl chloride (1.69 mL, 15 mmol). After 4 h of reaction at room temperature, the reaction mixture was filtered. The filtrate was washed with brine (2 x 30 mL), dried and concentrated. The recovered residue was purified by flash chromatography (pentane/ethyl acetate 100:0 to 0:100). Compound 3 was isolated as a colorless oil (0.85 g, 25%). ¹H NMR (400 MHz, CDCl₃, 25 °C): δ (ppm) 2.68 (dd, J = 3, 5 Hz, 2H, OCH₂CHCH₂OC(O)), 2.88 (t, J = 4 Hz, 2H, OCH₂CHCH₂OC(O)), 3.26 (dq, J = 3, 7 Hz, 2H, OCH₂CHCH₂OC(O)), 4.05 (dd, J = 2, 6, 12 Hz, 2H, OCH₂CHCH₂OC(O)), 4.54 (dd, J = 3, 12 Hz, 2H, OCH₂CHCH₂OC(O)), 6.90 (s, 2H, CHC(O)) (Figure S15). ¹³C{¹H} NMR (100 MHz, CDCl₃, 25 °C): δ (ppm) = 44.7 (OCH₂CHCH₂OC(O)), 49.1 (OCH₂CHCH₂OC(O)), 66.0 (OCH₂CHCH₂OC(O)), 132.1 (CHC(O)), 164.8 (OCH₂CHCH₂OC(O)) (Figure S16). HRMS (ESI) (m/z): C₁₀H₁₂O₆Na [M+Na]⁺, calcd 251.0532; found 251.0533.
Bis(oxiran-2-ylmethyl) \((E)\)-hex-3-enedioate \((5)\). A three neck flask \((100 \text{ mL})\), equipped with a condenser and a magnetic bar, was charged with \((E)\)-hex-3-enedioic acid \((2.00 \text{ g, 14 mmol})\) and SOCl\(_2\) \((4.02 \text{ mL, 56 mmol})\). The resulting suspension was heated to 75 °C and stirred over 6 h. Gasses formed during the reaction were trapped with NEt\(_3\). The resulting clear solution was cooled to room temperature and excess of SOCl\(_2\) was eliminated under vacuum. The thus recovered \((E)\)-hex-3-enedioyl chloride \((2.53 \text{ g, 14 mmol})\) was used directly in the next step for the synthesis of \(5\), following the same procedure as described for \(3\) using distilled glycidol \((2.60 \text{ g, 35 mmol})\), Et\(_3\)N \((7.6 \text{ mL, 56 mmol})\) and CH\(_2\)Cl\(_2\) \((130 \text{ mL})\). The recovered residue was purified by flash chromatography (pentane/ethyl acetate 90:10 to 0:100) to give \(5\) as a colorless oil \((0.60 \text{ g, 17%})\). \(^1\)H NMR \((400 \text{ MHz, CDCl}_3, 25 ^\circ \text{C})\): \(\delta\) (ppm) 2.64 (dd, \(J = 2, 5 \text{ Hz, 2H, OCH}_2\text{CHCH}_2\text{OC(O)}\)), 2.84 (t, \(J = 5 \text{ Hz, 2H, OCH}_2\text{CHCH}_2\text{OC(O)}\)), 3.14 (m, 4H, CH\(_2\)\(\text{C(O)}\)), 3.20 (ddd, \(J = 3, 4, 7 \text{ Hz, 2H, OCH}_2\text{CHCH}_2\text{OC(O)}\)), 3.92 (ddd, \(J = 2, 6, 12 \text{ Hz, 2H, OCH}_2\text{CHCH}_2\text{OC(O)}\)), 4.42 (ddd, \(J = 5, 12 \text{ Hz, 2H, OCH}_2\text{CHCH}_2\text{OC(O)}\)), 5.71 (tt, \(J = 2, 4 \text{ Hz, 2H, CH}_2\text{C(O)}\)) (Figure S17). \(^{13}\)C\{\(^1\)H\} NMR \((100 \text{ MHz, CDCl}_3, 25 ^\circ \text{C})\): \(\delta\) (ppm) 37.6 (CH\(_2\)\(\text{C(O)}\)), 44.7 (OCH\(_2\)\text{CHCH}_2\text{OC(O)}), 49.3 (OCH\(_2\)\text{CHCH}_2\text{OC(O)}), 65.3 (OCH\(_2\)\text{CHCH}_2\text{OC(O)}), 125.9 (CH\(_2\)\text{C(O)}), 171.2 (CH\(_2\)\text{C(O)}\)) (Figure S18). HRMS (ESI) \((m/z)\): C\(_{12}\)H\(_{16}\)O\(_6\)Na [M+Na]\(^+\), calcd 279.0845; found 279.0841.

CTAs \(1, 2, 3, \) and \(5\) were stable in air at room temperature over at least 24 months.

**General procedure for ROMP/CM of COE.** All polymerizations were performed according to the following typical procedure (Table 2, entry 3). The only differences lie in the nature of the solvent, CTA and its initial concentration \([\text{CTA}_0]\), and in the presence of an additive in some cases. Under argon atmosphere, a Schlenk flask equipped with a magnetic stir bar, was charged sequentially with CH\(_2\)Cl\(_2\) \((5.0 \text{ mL})\), COE \((1.53 \text{ mL, 1.29 g, 11.7 mmol})\) and CTA \(3\) \((27 \text{ mg, 0.12 mmol})\). The concentration of starting reagents (COE + CTA) was maintained at
1.8 mol.L⁻¹. The resulting solution was placed at 40 °C and the polymerization was started upon addition of a fresh CH₂Cl₂ solution (2.0 mL) of G2 (5.0 mg, 5.9 μmol). The reaction mixture turned highly viscous within 2 min. The viscosity then slowly decreased over the following 10 min. After the desired reaction time (typically 24 h), volatiles (solvent and ethylene) were removed under vacuum. The polymer was recovered upon precipitation in methanol (50 mL) (thereby allowing removal of the catalyst), filtration and drying at 25 °C under vacuum. All polymers were recovered as white powders, readily soluble in chloroform and THF, and insoluble in methanol (Tables 1–2). The isolated polymers were characterized by ¹H, ¹³C{¹H} NMR, SEC, MALDI-ToF mass spectrometry and DSC analyses (Figures S9–S12, 1–3, S34).

**General procedure for the chemical modification of PCOE epoxide chain-end groups into cyclodithiocarbonate ones.** The reaction was carried out according to a modified literature procedure, upon optimization of the initial stoichiometry, i.e. using PCOE-GA₂ (1 equiv.; GA = glycidyl alkenoate), LiBr (2 equiv.) and CS₂ (2.2 equiv.) (refer to the Supporting Information, Figures S30–34).

**Synthesis of NIPUs from bis(cyclodithiocarbonate) telechelic PCOE.** All syntheses of NIPUs were performed according to the following typical procedure. A Schlenk flask equipped with a magnetic stir bar was charged sequentially with CH₂Cl₂ (1.0 mL), PCOE-DTC₂ (0.130 g, 0.87 mmol (DTC).g⁻¹, 0.113 mmol DTC, as determined by ¹H NMR spectroscopy using benzene as internal standard), and a polyether diamine (JEFFAMINE EDR-148) (8 mg, 13.0 mmol (NH₂).g⁻¹; taking into account the primary amine content (mmol.g⁻¹), 0.104 mmol NH₂), and hydroxyethyl acrylate (13 mg, 8.6 mmol (C=Ç).g⁻¹). The resulting solution was stirred at 23 °C. The solution progressively turned slightly off white and precipitation of an off white solid was gradually observed over the reaction course. After the desired reaction time (typically 24 h; not optimized), the polymer was recovered upon
complete precipitation in methanol (50 mL), filtration and drying at 25 °C under vacuum. All polymers were isolated as off white powders. The polymers, insoluble in common organic solvents (CHCl₃, THF, CH₂Cl₂, DMF), were characterized by FTIR, TGA and DSC analyses (Figures 6, S35).
Results and Discussion

The ROMP/CM of cyclooctene (COE) catalyzed by Grubbs’ second generation catalyst (G2), in the presence of several epoxide- and DTC-based CTAs, including both monofunctional (five-membered cyclo(dithiocarbonate) acrylate (DTC-Ac), oxiran-2-ylmethyl acrylate (1), oxiran-2-ylmethyl methacrylate (2)), or difunctional (bis(oxiran-2-ylmethyl) fumarate (3), bis(oxiran-2-ylmethyl) maleate (4), bis(oxiran-2-ylmethyl) (E)-hex-3-enedioate (5), and (Z)-1,4-bis(oxiran-2-ylmethoxy)but-2-ene (6)) CTAs, has been investigated towards the synthesis of α,ω-diepoxide and -bis(cyclo(dithiocarbonate) telechelic PCOEs (Schemes 3, S1–S4), the latter ultimately serving as precursors towards NIPUs (Schemes 4–5).

Synthesis of CTAs 1, 2, 3, 5. CTAs 1, 2, 3, and 5 were synthesized from the reaction of glycidol and acryloyl chloride, methacryloyl chloride, fumaroyl chloride or (E)-hex-3-enedioyl chloride, respectively, in the presence of triethylamine in CH2Cl2 (ca. 17–85% yield, Figures S3–S4, S13–S18).

Attempted direct synthesis of cyclo(dithiocarbonate) difunctionalized PCOE. The ROMP/CM of COE mediated by G2 in the presence of cyclo(dithiocarbonate) acrylate (DTC-Ac) was attempted in THF and CH2Cl2 at 40 °C for 2 h with [COE]0/[DTC-Ac]0/[G2]0 = 1000:10:1 or 2000:20 or 80:1 (Scheme S1). However, whereas all COE was consumed, the PCOEs recovered did not feature any detectable alkenoate dithiocarbonate end-group; only linear non-functional PCOE (LNF) and possibly CNF was recovered, as evidenced by NMR (Figure S19). The same polymerization, carried out in the presence of an additional CTA known to be efficient in the ROMP of COE under similar conditions, namely the corresponding five-membered cyclocarbonate acrylate (5CC-Ac),29,30 proceeded with full monomer consumption and gave the mono-(5CC-Ac) functional PCOE (Table S1, entry 2). The absence of DTC end-groups likely indicates partial deactivation of the ruthenium catalyst (most likely by C=S moieties)67 after the fast ROMP stage, and the inability to perform the
CM step with DTC-Ac (*vide infra*),\textsuperscript{58} while it could proceed to some extent with 5CC-AC. Given the difficulties in using a DTC-based CTA in the direct ROMP/CM of COE to prepare the corresponding bisDTC telechelic PCOE (PCOE-DTC\textsubscript{2}) and subsequently the corresponding NIPU, we then undertook the synthesis of first diepoxide end-capped PCOEs, prior to their post-polymerization dithiocarbonatation.

**Epoxide functionalized PCOEs.**

*Mechanistic considerations.* Depending on the functionality of the epoxide-based CTAs, a range of various epoxide or vinyl end-functionalized PCOEs may thus be prepared (Schemes 3, S2–S4). Indeed, asymmetric CTAs are well-known to give a statistical distribution of end-capped polymers during ROMP, including linear (isomerized) and/or cyclic non-functional (LNF, ILNF CNF), (isomerized) α-monofunctional (IMF, MF) and/or α,ω-difunctional (DF) PCOEs (Schemes S2–S3).\textsuperscript{58,59} On the other hand, symmetrical alkene CTAs such as bis-epoxide CTAS 3–6 enable the selective formation of α,ω-difunctional (DF) PCOE possibly along with cyclic polymers (CNF; Schemes 3, S4). The functionality of PCOEs is thus essentially imparted by the nature of the CTA as well as by operating conditions.
Scheme 3. Tandem ROMP/CM/RCM of COE catalyzed by Grubbs’ second generation catalyst G2 in the presence of a difunctional epoxide alkene CTA 3, 4, 5, or 6, showing the possible polymers (FG: glycidyl functional group; DF: α,ω-difunctional, CNF: cyclic non-functional).

**Monoepoxide functionalized PCOEs: synthesis and characterization.** The polymerization of COE mediated by G2 in the presence of glycidyl acrylate 1 and glycidyl methacrylate 2 as CTAs (Scheme S2) was performed to assess any possible selectivity difference in the functionality of the formed PCOEs (Table 1). In our previous related works, NMR and MALDI-ToF MS analyses showed that the non-functionalized polymers (CNF, LNF and ILNF) were always formed in minor amounts (< 15%), if any, as compared to the functionalized polymers (MF, IMF, and DF). Therefore, only MF, IMF and DF were considered to be formed in significant amounts in the present process.
Table 1. ROMP/CM of COE catalyzed by G2 using CTA 1 or 2, and BZQ in CH$_2$Cl$_2$ and THF at 40 °C for 24 h.$^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>CTA</th>
<th>Solvent</th>
<th>[COE]$_0$/[I]$_0$/[G2]$_0$</th>
<th>[BZQ]$_0$</th>
<th>MF$^b$ (mol%)</th>
<th>IMF$^b$ (mol%)</th>
<th>DF$^b$ (mol%)</th>
<th>$M_{n,	ext{theo}}$ $^c$ (g.mol$^{-1}$)</th>
<th>$M_{n,	ext{NMR}}$ $^d$ (g.mol$^{-1}$)</th>
<th>$M_{n,SEC}^e$ (g.mol$^{-1}$)</th>
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<td>220 000$^f$</td>
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$^a$ General conditions: Catalyst = 5.9 µmol, [COE + CTA]$_0$ = 1.8 mol L$^{-1}$; COE and CTA conversion observed by $^1$H NMR analysis = 100% for 100% and 0% for 2, respectively.$^b$ Relative molar ratio as determined by $^1$H NMR analysis of MF = α-functionalized PCOE; IMF = α-functionalized PCOE; DF = α,ω-di-functional PCOE (Scheme S2).$^c$ Theoretical molar mass value calculated from $M_{n,	ext{theo}}$ = (DF% × [COE][CTA]$_0$) / ([COE]$_0$ + [CTA]$_0$) + (MF% × [COE]$_0$) / ([COE]$_0$ + [CTA]$_0$) + (IMF% × [COE]$_0$) / ([COE]$_0$ + [CTA]$_0$).$^d$ Theoretical molar mass value determined by $^1$H NMR analysis (refer to the Experimental Section).$^e$ Number-average molar mass ($M_{n,SEC}$) and dispersity ($D_M = M_w/M_n$) values determined by SEC vs polystyrene standards (uncorrected $M_n$ values).$^f$ SEC analysis of the polymer samples gave molar mass values ($M_{n,SEC}$) in fair agreement with both the expected molar mass values ($M_{n,\text{theo}}$) and the experimental ones as determined by NMR ($M_{n,NMR}$), while displaying a single symmetrical
peak ($D_m = \text{ca. } 1.5$; Figure S22). The $^1$H and $^{13}$C($^1$H) NMR spectra of an IMF PCOE prepared from [COE]$_0$/[1]$_0$/[G2]$_0 = 1000:20:1$ in THF (Table 1, entry 1) are illustrated in Figures S9 and S10, respectively. The $^1$H NMR spectrum evidenced, along with the signals of the hydrogens of the repeating unit (H$^1$, H$^2$, H$^3$; in red), the presence of the isomerized C=C terminal bond (H$^{4,5}$, H$^6$; in green), and glycidyl $\alpha,\beta$-unsaturated carboxylate chain-end (H$^g$, H$^f$, H$^e$, H$^d$, H$^b$, H$^a$, H$^g$; in black) (Figure S9). Correspondingly, the $^{13}$C($^1$H) NMR spectrum confirmed the presence of glycidyl $\alpha,\beta$-unsaturated carboxylate end-group in IMF (H$^d$, H$^f$, H$^e$, H$^b$, H$^a$, H$^{g,h}$; in black) (Figure S10). Also, the distinctive $^{13}$C($^1$H) NMR signals of the terminal methyl group (C$^{6\text{trans}}$, C$^{6\text{cis}}$; in green; always displaying the same integration ratio (ca. 2:1), consistent with a set of trans/cis isomers), and its adjacent methylene hydrogens (C$^4$, C$^5$; in green) characteristic of the propenyl-end-functionalized polymers IMF, were observed (Figure S10). Remarkably, upon addition of 1,4-benzoquinone (BZQ), a hydrogen acceptor known to successfully impede undesirable isomerization process in various olefin metathesis reactions,$^{58,59,74,75,76}$ $\alpha$-glycidyl,$\omega$-vinyl telechelic (MF) PCOE could be isolated selectively (Table 1, entry 6). Indeed, the characteristic signal of IMF (H$^6$) is no longer observed, while the typical signal of $\alpha$-glycidyl acrylate,$\omega$-vinyl PCOE, namely (besides H$^a$–H$^b$) the methine H$^g$, H$^f$, and H$^e$, and methylene H$^7$ hydrogens, then display the relative integration values 1:1:1:2, respectively, supporting the monofunctionalization of PCOE. Correspondingly, the $^{13}$C signals of the C$^6$ cis/trans isomers disappeared, whereas the characteristic resonance of the terminal methylene carbon atom C$^7$ showed up at $\delta$ 110.1 ppm (Figures S11–S12).

On the other hand, when using glycidyl methacrylate (CTA 2) in CH$_2$Cl$_2$, $^1$H NMR analysis of the recovered sample showed the presence of only non-functional PCOEs, as the characteristic methylene hydrogen signals of an $\alpha,\beta$-unsaturated carboxylate chain-end ($\delta$ 7.1, 5.8 ppm CH$_2$CH=CHCOO) were not observed (Figure S23) (Table 1, entries 7–8). This
indicates that CM did not take place during this polymerization. Control experiments carried out using a 1:1 mixture of 1 and 2 as CTAs gave a full COE conversion and consumption of 1, whereas 2 remained unreacted (Table S2). The PCOEs thus formed only displayed a glycidyl α,β-unsaturated carboxylate and a vinyl chain-ends. Since CTA 2 did not inhibit these latter polymerizations, this suggests that the observed inactivity of the G2/2 catalytic system did not arise from possible residual impurities which could deactivate G2, but rather from the intrinsic inefficiency of 2 in promoting the ROMP/CM of COE (Table 1, entries 7–8). 39

Diepoxide functionalized PCOEs: synthesis and characterization. The polymerization of COE mediated by G2 was investigated in the presence of a difunctional glycidyl CTA (3–6), at 40 °C for 24 h in CH2Cl2 (Scheme 3). All polymerizations proceeded with full monomer consumption and selectively afforded DF and possibly CNF PCOEs. The most significant results are gathered in Table 2.

Table 2. ROMP/CM of COE catalyzed by G2 using CTAs 3–6 in CH2Cl2 at 40 °C for 24 h.

<table>
<thead>
<tr>
<th>Entry</th>
<th>CTA</th>
<th>[COE]/[CTA]/[G2]</th>
<th>CTA Conv. (%)</th>
<th>( M_{\text{N,NMR}} ) (g.mol(^{-1}))</th>
<th>( M_{\text{N,NMR}} ) (g.mol(^{-1}))</th>
<th>( D_{\text{M}} )</th>
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</table>
While the polymerization of COE using the fumarate CTA 3 afforded only DF and possibly CNF PCOEs as evidenced from NMR analyses (Figures S24–S25), the consumption of 3 remained low (< ca. 40%), regardless of the [COE]₀/[3]₀ feed ratio (Table 2, entries 1–6). Assuming that the analogous CTA featuring a Z configuration may facilitate its interaction with G2, as a result of the better accessibility of the C=C bond,77 the ROMP/CM of COE was then comparatively investigated using the maleate CTA 4 (Table 2, entries 7–16). Monitoring the molar mass of the crude polymer sample as determined by NMR analysis, for a reaction carried out with CTA 4 and [COE]₀/[CTA]₀/[G2]₀ = 2000:50:1, first revealed the sharp increase of \( M_{n,NMR} \) within the first 10 min, in line with the visual increase of the viscosity of the reaction medium (Figure 1). The consecutive \( M_{n,NMR} \) decrease, larger in the case of 4 vs 3, is correlated to the CTA conversion (up to 80% with 4, vs 34% with 3), and thus to the better efficiency of the CM with 4. Also, the molar mass of the polymers as determined by NMR \( (M_{n,NMR}) \) fairly matched the calculated value \( (M_{n,\text{theo}}) \) and decreased proportionally to the increasing amount of initial CTA loading, thus evidencing an efficient chain-transfer process (Table 2). The SEC traces showed only one symmetrical peak \( (D_M = \text{ca} 1.65 \text{ Figure S26}) \), suggesting that DF, and CNF if any, had a similar molar mass.
Figure 1. Monitoring of the molar mass determined by NMR over time of a polymer sample prepared by the ROMP/CM of COE in the presence of G2/CTA 3 or 4, with [COE]₀/[CTA]₀/[G2]₀ = 2000:50:1, in CH₂Cl₂ at room temperature (Table 2, entries 4, 10).

¹H and ¹³C{¹H} NMR analyses of a PCOE prepared from G2/CTA 4 evidenced the sole formation of DF and possibly CNF (Figures 2, S27). Indeed, the main chain olefinic hydrogens (H₁–H₃, C₁–C₃) were clearly observed along with the signals typical of the glycidyl α,β-unsaturated carboxylate (Hₐ–Hᵢ, Cₐ–Cₗ) end-groups (vide supra). The characteristic signals of LNF, MF (allyl methylene terminus, δCH₂ 5.15, 4.90 ppm) and their isomerized analogues ILNF and IMF (methyl group of the propenyl end-moiety, δ 1.64 ppm) were not observed. MALDI-ToF MS analyses were performed using a DCTB matrix and a silver salt as cationizing agent so as to assess the presence of both DF and CNF PCOEs (Figure 3). The mass spectra showed a major population of PCOE with a repeating unit of 110 g.mol⁻¹ end-capped with two glycidyl α,β-unsaturated carboxylate moieties, i.e. DF PCOE,
with e.g. $m/z_{\text{experimental}} = 1988.2 \text{ g.mol}^{-1}$ vs $m/z_{\text{simulated}} = 1988.6 \text{ g.mol}^{-1}$ for $n = 15$. This was unequivocally supported by the close match of the simulated isotopic distribution of the DF PCOE with e.g. $m/z_{\text{simulated}} = 1988.6 \text{ g.mol}^{-1}$ for $n = 15$. A second minor population was attributed to the CNF PCOE with e.g. $m/z_{\text{experimental}} = 1981.4 \text{ g.mol}^{-1}$ for $m = 17$ vs $m/z_{\text{simulated}} = 1980.8 \text{ g.mol}^{-1}$. The typical isomerization pattern previously observed with sets of signals separated by $m/z = 14 \text{ g.mol}^{-1}$ around each peak of DF corresponding to a given degree of polymerization (i.e. each $n$ value), was clearly not observed in the spectra of the present polymers, thereby evidencing the absence of isomerized COE units.

**Figure 2.** $^1\text{H NMR}$ spectrum (500 MHz, CDCl$_3$, 25 °C) of the polymer sample prepared by ROMP/CM of COE in the presence of G2/CTA 4 showing DF and possibly CNF PCOEs (Table 2, entry 15) (* stands for residual solvent (acetone δ 2.10 ppm), water (δ 1.55 ppm)).
Figure 3. MALDI-ToF mass spectrum (DCTB matrix, AgTFA ionizing salt) of a polymer sample prepared by ROMP/CM of COE in the presence of \(G_2 / CTA_4\) (Table 2, entry 15) showing a mixture of DF and CNF PCOEs; see top zoomed region and the corresponding middle and bottom simulations for \(n = 15\) and \(m = 17\), respectively.

Given the difference in the efficiency of CTAs 3–4 in the ROMP/CM of PCOE resulting from the \(E\) vs \(Z\) configuration, respectively, with the less sterically encumbered double bond of the alkene CTA 4 providing more efficient chain-transfer, we next evaluated CTAs 5–6, structurally related to 3–4. The effect of the distance between the double bond and the functional group within a CTA, studied for hydroxy, carboxylic, ester, ether, nitrile and halide functions, revealed no general trend in literature reports. Experimentally, in our case, the CM efficiency based on the CTA conversion was in the order \(4 > 6 >> 3 >> 5\), with CTAs with a \(Z\) configuration being more effective than those with an \(E\) configuration (similarly to 4 vs 3, vide supra), regardless of the presence of methylene group in-between the \(C=\)C double bond and the glycidyl \(\alpha,\beta\)-unsaturated carboxylate/ether moiety, as previously reported (Table 2). The polymerization of COE mediated by \(G_2\) in the presence of CTA 5 or 6 similarly afforded the corresponding DF and possibly CNF PCOEs end-capped by the
CTA’s functional group, as evidenced by $^1$H and $^{13}$C/$^1$H NMR analyses (Figures S28–29).

Note that the ROMP of cyclooctadiene (COD) mediated by the catalyst $[(\text{PCy}_3)_2\text{Cl}_2\text{Ru=CHPh})]/\text{CTA}$ 5 with $[^\text{COD}]_0/[^5]_0/[^\text{catalyst}]_0 = 4000:50–267:1$, at 45 °C in 48 h, similarly afforded the diepoxide telechelic polybutylene.

**Chemical modification of diepoxide telechelic PCOE into bis(cyclodithiocarbonate) telechelic PCOE.** Since the PCOE-DTC$_2$ could not be directly synthesized by the polymerization of COE in the presence of DTA-Ac (*vide supra*), the post-polymerization chemical modification of the diepoxide PCOE (PCOE-GA$_2$) into PCOE-DTC$_2$ was then performed. The reaction with CS$_2$ proceeded at 40 °C for 17 h in quantitative yield upon optimizing the quantity of LiBr to a stoichiometric amount (an excess led to the formation of unidentified side-products) and lowering the CS$_2$ excess to 1.1 equiv. (instead of the original 1.8 equiv.; Scheme 4, Table S3). This is, to our knowledge, the first example of cyclo(di)thiocarbonate end-functionalized PCOE. The reaction proceeded without alteration of the molar mass ($M_{\text{n,NMR}}$, Table 3).

![Scheme 4](image)

**Scheme 4.** Chemical modification of diepoxide telechelic PCOE (PCOE-GA$_2$) into bis(cyclodithiocarbonate) telechelic PCOE (PCOE-DTC$_2$).
Table 3. Macromolecular characteristics of PCOE-GA$_2$, PCOE-DTC$_2$ synthesized upon
dithiocarbonatation reaction of PCOE-GA$_2$, and of the resulting poly(mercaptothiourethane)
NIPU synthesized upon aminolysis of PCOE-DTC$_2$ with JEFFAMINE EDR-148.

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</table>

$^a$ Experimental molar mass value determined by $^1$H NMR analysis (refer to the Experimental Section). $^b$ Number-average molar mass ($M_{n,SEC}$) and dispersity ($D_M = M_w/M_n$) values determined by SEC vs polystyrene standards (uncorrected $M_n$ values) in THF at 30 °C. $^c$ Thermal transition temperatures measured by DSC (second heating scan). n.o. not observed.

$^1$H NMR monitoring of the dithiocarbonatation reaction showed, besides the main chain olefinic hydrogens (H$^1$, H$^2$, H$^3$; in red), the disappearance of the GA end-groups (vide supra with 1) concomitantly to the appearance of the characteristic DTC signals (H$^a$– H$^i$; in black) (Figure S30), up to the quantitative formation of the $\alpha$,$\omega$-bisDTC telechelic PCOE (Figure 4). Correspondingly, $^{13}$C{$^1$H} NMR spectroscopy confirmed the presence of the DTC termini on the PCOE backbone (C$^a$–C$^h$; in black) (Figure S31). FTIR analysis of the PCOE-DTC$_2$ sample showed the DTC characteristic $\nu_{C=S}$ (1192 cm$^{-1}$), $\nu_{C=O}$ (1726 cm$^{-1}$) (Figure S32). Furthermore, MALDI-ToF MS analyses performed using a DCTB matrix and a sodium or silver salt as cationizing agent, evidenced the presence of DF PCOE-DTC$_2$ and CNF PCOE, respectively (Figure 5a and b). The mass spectra showed two major populations of PCOE with a repeating unit of 110 g.mol$^{-1}$ corresponding to COE. As unequivocally supported by the close match of the simulated isotopic distributions, one population is end-capped with two DTC moieties, i.e. DF PCOE, with e.g. $m/z_{,experimental} = 1283.8$ g.mol$^{-1}$ vs $m/z_{,simulated} = 1283.8$ g.mol$^{-1}$ for $n = 8$ (Figure 5a), and the other one corresponds to the CNF PCOE with e.g. $m/z_{,experimental} = 1210.2$ g.mol$^{-1}$ for $m = 10$ vs $m/z_{,simulated} = 1210.0$ g.mol$^{-1}$, and
with e.g. \( m/z_{\text{experimental}} = 1337.8 \ \text{g.mol}^{-1} \) for \( p = 11 \) vs \( m/z_{\text{simulated}} = 1338.1 \ \text{g.mol}^{-1} \) (Figure 5b).

Finally, DSC analyses of PCOE-DTC\(_2\) samples revealed a thermal behavior similar to that of PCOE-GA\(_2\) precursors, with a melting and a crystallization temperatures at \( T_m = +56 \ ^\circ\text{C} \) and \( T_c = +45 \ ^\circ\text{C} \), respectively (Table 3) (Figures S33–S34).

**Figure 4.** \(^1\)H NMR spectrum (500 MHz, CDCl\(_3\), 25 \(^\circ\text{C}\)) of a PCOE-DTC\(_2\) sample prepared by reaction of PCOE-GA\(_2\) with CS\(_2\) in the presence of LiBr (Table S3, entry 5).
Figure 5. MALDI-ToF mass spectrum (DCTB matrix, sodium (top) AgTFA (bottom) ionizing salt) of a PCOE-DTC$_2$ sample prepared by reaction of PCOE-GA with CS$_2$ in the presence of LiBr (Table S3, entry 5), showing DF (top) and CNF (bottom) PCOE-DTC$_2$; a) see top zoomed region and the corresponding bottom simulation for $n = 8$; b) see top zoomed region and the corresponding middle and bottom simulations for $m = 10$ and $p = 11$, respectively.

**Aminolysis of bis(cyclodithiocarbonate) telechelic PCOE into NIPU.** The stoichiometric aminolysis of PCOE-DTC$_2$ with a polyether diamine (JEFFAMINE EDR-148) was investigated towards the formation of poly(mercaptothiourethane)s as NIPUs. Ethyl acrylate, known to favor the thiol/acylate Michael reaction, was used as an additive to prevent the formation of disulfide bridges, so as to provide a priori linear polymer samples (Scheme 5). The ring-opening of PCOE DTC chain-ends was quantitative at room temperature over 24 h, as evidenced by the decreasing intensity of the $\nu_{C=S(DTC)}$ concomitant with the increasing intensity of $\nu_{C-N(NIPU)}$. The formed NIPU materials were unexpectedly recovered as insoluble...
solids, thus precluding NMR and SEC analyses (and the subsequent evaluation of the molar mass values). Considering the implemented stoichiometric polyaddition towards the formation of the NIPU, a linear polymer was anticipated (Scheme 5). However, the insolubility of the produced polymers most likely hints crosslinked, final structures. Several origins may be envisioned for such crosslinking: i) possible presence of small amounts of triamines or higher functionality polyamines in the commercial grade of JEFFAMINE EDR-148 used; ii) formation of small amounts of disulfide bridges despite the use of thiol-acceptors; iii) possible crosslinking via thiol-ene reaction involving C=C bonds of the polyene backbone. A control click reaction of a linear PCOE-DTC$_2$ with an excess of 2-mercaptoethanol, performed under the same conditions as those used for the NIPUs synthesis (CH$_2$Cl$_2$, 23 °C, 24 h), showed the stability of the polyolefin backbone, thus ruling out this latter scenario. The latter NIPUs were thus characterized by FTIR spectroscopy, DSC and TGA analyses (Figures 6, S35, S36; Table 3). FTIR analyses showed the absence of the $\nu_{\text{C=S(DTC)}}$ (1193 cm$^{-1}$), along with the apparition of the distinctive $\nu_{\text{N-H}}$ (3385 cm$^{-1}$) and $\nu_{\text{C-N}}$ (1539 cm$^{-1}$) (Figure 6).$^{19,20,21}$ These results thus support the complete conversion of PCOEs-DTC$_2$ into the corresponding NIPUs. DSC analyses showed the semi-crystallinity of the poly(mercaptopthiourethane)s NIPUs, alike PCOE-DTC$_2$ and PCOE-GA$_2$ (Table 3, Figure S35). The NIPU materials did not display a $T_g$ while both their $T_m = ca. 51$ °C and $T_c = ca. 32$ °C were significantly lower than those of PCOE-GA$_2$ and PCOE-DTC$_2$ ($T_m > 56$ °C, $T_c = 30–46$ °C). TGA analyses revealed that PCOE-NIPU remained stable up to ca. 400 °C while the onset of the degradation temperature of PCOE-DTC$_2$ was observed at ca. 310 °C. A lower degradation temperature of the PCOE-DTC$_2$ ($T_d^{50} =$ temperature at which 50% of mass loss occurs = 437 °C) precursor was observed as compared to that of the resulting NIPU which displayed a slightly better temperature stability ($T_d^{50} = 451$ °C) (Figure S36). Both copolymers were fully degraded (96–98%) at ca. 480–487 °C. Polythioureas reported in
literature are very scarce and feature different soft segments, making the comparison of thermal characteristics delicate.\textsuperscript{65,82,84,85} Thermal properties of known polythioureas generally revealed $T_g$ values ($-29^\circ\text{C} - 57^\circ\text{C}$) without any melting or crystallization temperatures being mentioned. The reported thermal stability of these materials was also lower ($T_d^{50} < \text{ca.} 370^\circ\text{C}$) than that of the PCOE-NIPU reported in the present work. The thermal behavior of the PCOE-NIPU thus revealed these materials promising for industrial applications.\textsuperscript{88}

\begin{center}
\textbf{Scheme 5.} Aminolysis of bis(cyclodithiocarbonate) telechelic PCOE (PCOE-DTC$_2$) into the corresponding poly(mercaptothiourethane) NIPU.
\end{center}
Figure 6. FTIR spectrum of a polymer sample (black trace) prepared by reaction of PCOE-DTC$_2$ (green trace) with JEFFAMINE EDR-148 in the presence of ethyl acrylate at 23 °C for 24 h in CH$_2$Cl$_2$ (Table 3, entry 3).
Conclusion

Telechelic PCOEs have been successfully synthesized by tandem ROMP/CM of COE using Grubbs’ 2nd-generation catalyst in the presence of various epoxide functionalized CTAs. The monofunctional epoxide CTA 1 selectively gave the isomerized $\alpha$-epoxy-$\omega$,propenyl monofunctionalized PCOE (IMF), but the use of 1,4-benzoquinone as additive allowed inhibiting completely the isomerization process, thus selectively affording $\alpha$-glycidyl alkenoate,$\omega$-vinyl telechelic PCOE (MF). The methacrylate CTA 2 related to 1 only afforded non-functionalized PCOE. As anticipated, the difunctional epoxide CTAs 3–6 selectively afforded the corresponding $\alpha$,$\omega$-diepoxide telechelic PCOEs (DF), and possibly CNF, through a proposed tandem one-pot CM/ROMP/RCM mechanism. Z-configurated CTAs were more effective than the $E$ analogues ($4 > 6 >> 3 >> 5$). Subsequent cyclodithiocarbonatation of the $\alpha$,$\omega$-diepoxide telechelic PCOE (PCOE-GA$_2$) from CS$_2$/LiBr quantitatively provided the first example of cyclo(di)thiocarbonate end-functionalized PCOE, PCOE-DTC$_2$. Although, CS$_2$ is a rather toxic compound, it is yet used herein as an intermediate reagent (fully consumed under stoichiometric conditions) in the preparation of safe cyclodithiocyclocarbonate end-capped NIPU pre-polymers. CS$_2$ has also otherwise been used as a resource towards functional polymers.$^{86}$

Finally, aminolysis of the PCOE-DTC$_2$ with JEFFAMINE EDR-148 quantitatively afforded the desired poly(mercaptothiourethane)s as NIPUs. To our knowledge, NIPUs were thus prepared in high yield, for the first time from the room temperature reaction of a dithiocarbonate $\alpha$,$\omega$-end-capped prepolymer with a diamine and without any added catalyst. Being able to prepare NIPUs from a room temperature reaction is a significant achievement in comparison to the prior approach through the opening of the five-membered carbonates which required heating at typically 50–80 °C.$^{8,12,27,28}$ Also noteworthy, the aminolysis was, in the present work, carried out without any catalyst, another major improvement. Indeed, to our
knowledge, a five-membered carbonate ring was reported to be successfully ring-opened at room temperature, yet in the presence of triazabicyclodecene guanidine (TBD) or LiOTf as catalyst/additive.\textsuperscript{87} These solid NIPUs and their forthcoming liquid congeners to be published in due time, are envisaged as valuable synthons for adhesive, mastic or surface coating industrial applications.\textsuperscript{88}

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**Electronic supplementary information (ESI) available:** Complementary synthetic procedures and macromolecular data, $^1$H and $^{13}$C{$^1$H} NMR and FTIR spectra, DSC traces of CTAs and polymers. (PDF)

**Notes**

The authors declare no competing financial interest.

**Graphical Abstract**

![Graphical Abstract](image-url)
References


78 The Z-configurated CTA 5 analogue featuring an additional methylene group on both sides of the C=C double bond was not synthesized, given the non-commercial availability of (Z)-hex-3-enedioic acid and the poor reactivity of E-configurated CTA 5.


Note that reaction of the acrylate with the amine may also be envisioned. However, under very similar conditions to those used in the present study, acrylates have been reported to preferentially react with thiol rather than with amine functions. Also, FTIR analyses support the absence of such an acrylate/amine reaction since the $\nu_{C-N} = 1220 \text{ cm}^{-1}$ absorption (characteristic of the formation of the resulting secondary amine) was not observed (Figure 6).


