Supporting Information for

Mechanochemical Ring-opening of Allylic Epoxides

Meredith H. Barbee, Junpeng Wang, Tatiana Kouznetsova, Meilin Lu, and Stephen L. Craig*

Department of Chemistry, Duke University, Durham NC, 27708

*to whom correspondence should be addressed: stephen.craig@duke.edu
## Table of Contents

General Information ........................................... S3
Small Molecule Synthesis ................................. S5
Polymer Synthesis ............................................ S7
Stability of P1 Polymers .................................. S10
Determining E/Z Ratio for P1 Polymers ............... S12
Sonication of P1 Polymers ................................ S13
Trapping Experiments ..................................... S16
Mechanochemically Induced Cross-Linking .......... S23
Control Experiments ....................................... S28
Overlap Concentration Calculations ................. S33
Single Molecule Force Spectroscopy ................. S36
Rate Constant Calculation ............................... S42
Additional NMR Spectra ................................ S43
References ................................................... S49
General Information

**Reagents**
9-Oxabicyclo[6.1.0]non-4-ene, meta-chloroperoxybenzoic acid (77%), cis,cis-1,3-cyclooctadiene, Grubbs catalyst second generation, Quadrasil MP, 2,6-Di-tert-butyl-4-methylphenol, diisobutylaluminum hydride, 1-hexene, ethyl vinyl ether, 9-phenanthrol, and HPLC grade THF were purchased from Sigma-Aldrich. CHCl₃, hexanes, methanol, and ethyl acetate were purchased from VWR. CDCl₃ was purchased from Cambridge Isotope Labs or Sigma-Aldrich. 9-Oxabicyclo[6.1.0]non-4-ene and 1-hexene were distilled prior to use. All other reagents were used as received. Silicycle SiliaFlash® F60 gel (40-63 μm particle size, 230-400 mesh) and medium pressure liquid chromatography (MPLC) was performed on a Teledyne ISCO CombiFlash Rf 200.

**Instrumentation**
¹H NMR spectra were collected on either a 400 MHz or 500 MHz Varian NMR in CDCl₃ and were referenced to CDCl₃ (δ = 7.260). ¹³C NMR was collected on a 500 MHz Varian NMR in CDCl₃ and were referenced to CDCl₃ (δ = 77.16). Gel permeation chromatography (GPC) was preformed on with 2 Agilent PLgel 10 Å, 7.5 x 300 mm, 5 μm columns (part number PL1110-6550) at room temperature at a flow rate of 1.0 mL/min. The flow rate was set using Agilent 1260 Infinity Isocratic pump, molecular weights were calculated using in line Wyatt Optilab T-rEX refractive index detector and Wyatt miniDAWN TREOS multi-angle light scattering detector, and UV absorbance was measured with an in line Agilent 1260 Infinity UV detector. The UV detector monitored 190 to 800 nm with step of 2.0 nm and slit width of 4.0 nm. The refractive index increments for the polymers were determined by using 100% mass recovery assumption calculations built into Wyatt Astra software using solutions of known concentrations. Refractive index for small molecules was determined with the RI detector off-line. UV-vis experiments were conducted on a Varian Cary 50 Conc UV-Visible spectrometer and were referenced to a blank of pure THF in quartz cuvettes. High-resolution mass spectrometry was performed on an Agilent LCMS-TOF–DART at Duke University’s Mass Spectrometry Facility.

**Sonication**
Ultrasound experiments were conducted with a Vibracell model VCZ500 at 20 kHz sonicator. 13.1 mm replaceable titanium tip probes (#630-00007) with Suslick assembly (#630-0224) and Suslick cells (#830-00005) were purchased from Sonics and Materials, Inc. All experiments were conducted at 1 mg/mL in inhibitor free THF, 30% amplitude, at an on 1 second off 1 second pattern, unless otherwise noted. Solutions were sparged with nitrogen or argon and cooled in an ice bath for 30 minutes prior to sonication. Positive pressure of inert gas and temperatures between 6-9 °C were maintained throughout each experiment. Aliquots taken from
sonication experiments were immediately ran on GPC without dilution, unless otherwise noted.

**SMFS Measurements**
The instrumentation and parameters used to collect data are similar to experiments conducted previously in the Craig group.\(^1\) Toluene was the solvent. Experiments were conducted at ambient temperature (~27 °C) using a homemade Atomic Force Microscope (AFM), which is comprised of a Digital Instruments scanning head mounted on top of a piezoelectric positioner. Cantilever probes (Sharp Microlever silicon probes (MSNL), rectangular-shaped, 205 μm, 15 μm, nominal tip radius ~ 2 nm, nominal spring constant k ~ 0.02 N/m, frequency ~ 15 kHz) were purchased from Bruker (Camarillo, CA). The spring constants were determined in air for each probe with the thermal noise method described previously.\(^2\) The tip velocity for all experiments was 300 nm s\(^{-1}\). Force curve data was collected and analyzed using Matlab (The MathWorks, Inc., Natick, MA). All data were filtered during acquisition at 500 Hz. After acquisition, the data was calibrated and plotted with software written in Matlab.
Small Molecule Synthesis

(Z)-9-oxabicyclo[6.1.0]non-2-ene (epoxyCOD) (1)

\[
\begin{array}{c}
\text{mCPBA} \\
\text{DCM}
\end{array}
\rightarrow
\begin{array}{c}
optimal
\end{array}
\]

A solution of meta-chloroperoxybenzoic acid (77%, 14.41g, 643 mmol, 1 equiv) in dichloromethane (50 mL) was added dropwise to a solution of cis,cis-1,3-cyclooctadiene (8.0 mL, 643 mmol, 1 equiv) in dichloromethane (50 mL) in an ice bath over 45 minutes. The reaction was allowed to warm to room temperature and stirred overnight. Aqueous sodium bisulfite was added to quench the reaction then the white solid was removed by filtration. The remaining solution was washed with sodium bisulfite, sodium bicarbonate, and brine, dried with sodium sulfate, then purified by silica flash chromatography (hexane to 5% ethyl acetate in hexane). The pure product was collected from vacuum distillation at 40°C to yield 1 (3.86g, 48.2% yield) as a clear colorless oil.

\begin{align*}
^1H \text{ NMR} (\text{CDCl}_3, 400 \text{ MHz}) & \delta 5.77 \text{ (dddd, } J = 11.2, 7.1, 5.6, 1.2 \text{ Hz, 1H)}, \\
& 5.59 \text{ (dq, } J = 11.2, 1.3 \text{ Hz, 1H)}, \\
& 3.45 \text{ (dt, } J = 3.9, 1.2 \text{ Hz, 1H)}, \\
& 3.11 \text{ (dtd, } J = 9.2, 3.9, 1.0 \text{ Hz, 1H)}, \\
& 2.31 \text{ (m, 1H)}, \\
& 2.18 - 1.94 \text{ (m, 2H)}, \\
& 1.86 - 1.71 \text{ (m, 1H)}, \\
& 1.71 - 1.60 \text{ (m, 2H),} \\
& 1.52 - 1.34 \text{ (m, 2H).} \\
^{13}C \text{ NMR (126 MHz, CDCl}_3\text{) } & \delta 134.49, 122.67, 58.23, 53.84, \\
& 29.18, 27.42, 25.69, 25.27.
\end{align*}

HRMS (m/z): [M+ H] \^ Calculated for C_{8}H_{12}O 125.09609, Observed 125.09579

(Z)-cyclooct-4-en-1-ol (2)

\[
\begin{array}{c}
\text{LAH} \\
\text{THF}
\end{array}
\rightarrow
\begin{array}{c}
optimal
\end{array}
\]

Monomer 2 was synthesized according to a literature procedure.\(^3\)

\begin{align*}
^1H \text{ NMR} (\text{CDCl}_3, 400 \text{ MHz}) & \delta 5.74 - 5.54 \text{ (m, 1H), 3.85 - 3.78 (m, 1H), 2.29 (ddt,} \\
& J = 18.3, 9.2, 4.0 \text{ Hz, 1H)}, \\
& 2.19 - 2.05 \text{ (m, 3H), 1.98 - 1.80 (m, 2H), 1.76 - 1.45} \\
& \text{ (m, 4H).} \\
^{13}C \text{ NMR (126 MHz, CDCl}_3\text{) } & \delta 130.28, 129.68, 72.87, 72.87, 37.86, 36.41, 25.79, \\
& 25.00, 22.91.
\end{align*}

HRMS (m/z): [M+ H] \^ Calculated for C_{8}H_{14}O 127.1117, Observed 127.1116
9-methoxyphenanthrene

The model small molecule 9-methoxyphenanthrene was synthesized according to a literature procedure with the following modifications. 4-phenanthanol (4.0 g, 1 equiv, 20.59 mmol) and potassium carbonate (4.27 g, 1.5 equiv, 30.89 mmol) were refluxed in acetone (20 mL) for 1 hour. Methyl iodide (2.56 mL, 2 equiv, 41.18 mmol) was added dropwise and refluxed overnight. The reaction progress was monitored by TLC and up to 1 additional equivalent of methyl iodide was added as necessary. After 18 hours, the reaction mixture was cooled, added to ethyl acetate, and washed with water 3 times, then brine, then dried with sodium sulfate. The mixture was then dried onto silica, then eluted from the column in pure hexane. The resulting white solid was recrystallized from boiling methanol to give 9-methoxyphenanthrene as flaky white crystals (1.98 g, 46.1%).

\[^1\text{H}\text{ NMR (CDCl}_3, 500 \text{ MHz)} \delta 8.68 (d, J = 8.1 \text{ Hz, 1H}), 8.62 (d, J = 8.0 \text{ Hz, 1H}), 8.43 (d, J = 8.0 \text{ Hz, 1H}), 7.81 (d, J = 7.7 \text{ Hz, 1H}), 7.68 (dt, J = 15.0, 7.8 \text{ Hz, 2H}), 7.56 (dt, J = 22.9, 7.2 \text{ Hz, 2H}), 7.01 (s, 1H), 4.10 (s, 3H). \]^{13}\text{C NMR (126 MHz, CDCl}_3) \delta 153.64, 133.03, 131.36, 127.42, 127.24, 126.98, 126.68, 126.58, 126.49, 124.33, 122.64, 102.03, 55.52.

HRMS (m/z): [M+ H]^+ Calculated for C_{15}H_{12}O 209.09609, Observed 209.09603
Polymer Synthesis

High Molecular Weight P1 Polymers

A stock solution of Grubbs second generation catalyst (100 µL, 0.6 mg, 0.0007 mmol, 1 equiv) in dichloromethane was charged to monomer 1 (150 mg, 1.208 mmol, 1700 equiv) in a scintillation vial. Additional DCM was added as necessary to maintain stirring. After 45 minutes, 3-4 mL of ethyl vinyl ether that had been previously purified by passing through silica was added to quench the reaction. Quadrasil (9.0 mg, 0.0134 mmol, 200 equiv) was added and the mixture was stirred overnight. Then the reaction was filtered through a celite plug and the polymer precipitated in cold methanol 3 times to yield P1 as a white solid (21.1 mg). See Figure S6 for a representative ¹H NMR and Figure S5 for the 90 degree light scattering detector trace.

Low Molecular Weight P1 Polymers

1-hexene (23.5mg, 0.280 mmol, 28 equiv) was charged to monomer 1 (2.250g, 18.1 mmol, 1700 equiv) in a scintillation vial. A stock solution of Grubbs second generation catalyst (100 µL, 9 mg, 0.010 mmol, 1 equiv) in dichloromethane was added. DCM was added as necessary to maintain stirring and the reaction was ran over night. 3-4 mL of ethyl vinyl ether that had been previously purified by passing through silica was added. After 1 hour, the polymer was precipitated into cold methanol and centrifuged 3 times to yield 176 mg of P1 as a clear oil. See Figure S25 for a representative ¹H NMR and Figure S26 for the 90 degree light scattering detector trace.
High Molecular Weight P2 Polymers

Monomer 1 (70.7 mg, 0.570 mmol, 850 equiv) was charged to a flask with monomer 2 (71.9 mg, 0.570 mmol, 850 equiv). A stock solution of Grubbs second generation catalyst (100 μL, 0.6 mg, 0.0007 mmol, 1 equiv) was added. After 10 minutes, 0.5 mL of DCM was added. The viscosity was monitored and additional DCM added as necessary to keep the solution stirring. After 15 hours, 3-4 mL of ethyl vinyl ether that had been previously purified by passing through silica was added and the reaction was stirred for 1 hour. The polymer was purified by precipitating 3 times in methanol to yield P2 as a white solid (70.7 mg). See Figure S19 for a representative ¹H NMR and Figure S20 for the 90 degree light scattering detector trace.

Low Molecular Weight P2 Polymers

Monomer 1 (1.12 g, 9.0 mmol, 850 equiv) was charged to a flask with monomer 2 (1.14 g, 9.0 mmol, 850 equiv) and 1-hexene (27.1 mg, 0.321 mmol, 28 equiv). A stock solution of Grubbs second generation catalyst (200 μL, 9.0 mg, 0.01 mmol, 1 equiv) was added. DCM was added as necessary to maintain stirring and the reaction was ran overnight. 3-4 mL of ethyl vinyl ether that had been previously purified by passing through silica was added. After 1 hour, the polymer was precipitated into cold methanol and centrifuged 3 times to give 549 mg of P2 as a clear oil. See Figure S29 for a representative ¹H NMR and Figure S28 for the 90 degree light scattering detector trace.
Monomer 1 (71 mg, 0.570 mmol, 850 equiv) was charged to a flask with monomer 2 (109 mg, 0.570 mmol, 850 equiv). A stock solution of Grubbs second generation catalyst (200 μL, 9.0 mg, 0.01 mmol, 1 equiv) was added. DCM was added as necessary to maintain stirring and the mixture was stirred overnight. 3-4 mL of ethyl vinyl ether that had been previously purified by passing through silica was added. After 1 hour, the polymer was precipitated into cold methanol 3 times to give 87.6 mg of P3 as a white solid. See Figure S36 for a representative \(^1\)H NMR and Figure S34 for the refractive index detector trace and 90 degree light scattering detector trace.
Stability of P1 Polymers

Numerous polymers were made throughout this study. Whenever possible, polymers were sonicated on the same day as they were prepared to avoid degradation and cross-linking. Occasionally polymers were stored in THF solution overnight in a flammable safe refrigerator prior to sonication. Polymers cross-linked quickly when stored dry, and initial attempts to purify polymers by precipitation alone were not as successful as those with added Quadrasil. The molecular weights of P1 polymers in particular were higher than predicted based on the ratio of catalyst to monomer, indicating that some cross-linking and branching has occurred.

To determine the stability of a P1 polymer over time, P1₁₂₅ was synthesized and left at room temperature in a THF solution for 48 hours. The retention time of the polymer did shift over this time period (Figure S1). The calculated molecular weight of the polymer does decrease between 24 and 48 hours after preparation. After this time, molecular weight determination is complicated by precipitation of the polymer (Table S1). ¹H NMR shows no indication of isomerization (Figure S2) after 48 hours. The polymers in this study were sonicated within 24 hours of preparation.

Table S1: Stability of P1₁₂₅ over 48 hours.

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Polymer</th>
<th>Mn (kDa)</th>
<th>Mw (kDa)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>P1₁₂₅</td>
<td>126</td>
<td>219</td>
<td>1.73</td>
</tr>
<tr>
<td>24</td>
<td>P1₁₂₅</td>
<td>125</td>
<td>198</td>
<td>1.58</td>
</tr>
<tr>
<td>48</td>
<td>P1₁₂₅</td>
<td>52</td>
<td>99</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Figure S1: Relative light scattering intensity for P1₁₂₅ for the 90 degree detector shortly after purification (red), after 24 hours (blue), and after 48 hours (green).
Figure S2: $^1$H NMR (400 MHz, CDCl$_3$) of P1$_{125}$ immediately after purification (pink), after 24 hours (blue), and after 48 hours (green).
Determining E/Z Ratio of P1 Polymers

Figure S3: The full $^{13}$C NMR (CDCl$_3$, 100 MHz) of P1$_{590}$.

Figure S4: A region of the $^{13}$C NMR from Figure S3. The peak assignments used to determine the E/Z ratio are shown. The E/Z ratio is the average of C2$_E$/C2$_Z$ and C1$_E$/C2$_Z$. 
Sonication of P1 Polymers

Polymer P1590 was sonicated in THF at a concentration of 1.0 mg/mL under standard conditions. After sonication, the solvent was removed by rotary evaporation to collect the sonicated polymer.

Figure S5: GPC traces (left) and calculated molecular weights (right) after every 30 minutes of sonication time for P1590. (MB_3_24)

Percent Isomerization of P1590 by ^1H NMR

% trans epoxide = \( \frac{(H_{\text{trans}})/(H_{\text{vinyl}})}{100} \times 100 = 20.8\% \)

\( H_{\text{vinyl}} = \int 5.41 - 4.93 = 1.87 \)

\( H_{\text{trans}} = \int 2.75 - 2.85 = 0.39 \)

Percent Isomerization per scission cycle

A scission cycle is defined by equation S1. Percent isomerization is defined by equation S2.

\[ (S1) \quad \text{Scission cycle} = \frac{\ln(\text{initial } M_n) - \ln(\text{final } M_n)}{\ln 2} \]

\[ (S2) \quad % \text{ Isomerization} = \frac{\% \text{ Isomerization by NMR}}{\text{scission cycle}} \]
Figure S6: $^1$H NMR (500 MHz, CDCl$_3$) of P1$_{590}$ prior to sonication.

Figure S7: $^1$H NMR (500 MHz, CDCl$_3$) of P1$_{590}$ after sonication.
Figure S8: $^1$H NMR (500 MHz, CDCl$_3$) of P1$_{590}$ before sonication (red) and after sonication (blue). The inlay shows the region with the resonance corresponding to the new trans-epoxide resonance.

Table S2: Average isomerization per scission cycle for duplicate P1 polymers

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_n$ (kDa)</th>
<th>Final $M_n$ (kDa)</th>
<th>% Isomerization per scission cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1$_{590}^a$</td>
<td>592</td>
<td>78</td>
<td>6.8</td>
</tr>
<tr>
<td>P1$_{590}^b$</td>
<td>589</td>
<td>83</td>
<td>4.0</td>
</tr>
<tr>
<td>P1$_{150}^c$</td>
<td>152</td>
<td>45</td>
<td>8.3</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td></td>
<td>6.4</td>
</tr>
<tr>
<td>std dev</td>
<td></td>
<td></td>
<td>2.2</td>
</tr>
</tbody>
</table>

a. This is the same polymer P1$_{590}$ as in Table 1.
b. This is a duplicate of P1$_{590}$
c. This polymer was sonicated for 60 minutes instead of 120 minutes.
Trapping Experiments

Polymer P1 was dissolved in a solution of 0.1M 9-phenantrol in tetrahydrofuran (THF) and sonicated under standard conditions. After sonication, the solution was concentrated and precipitated twice into cold methanol to collect the sonicated polymer.

Percent trapping by ¹H NMR

% trans epoxide = (H<sub>trans</sub>)/(H<sub>vinyl</sub>) = 17.6%
% trapping = (H<sub>aromatic/9</sub>)/(H<sub>vinyl</sub>) = 18.4%
H<sub>aromatic</sub> = ∫ 7.3-8.1 = 2.54
H<sub>vinyl</sub> = ∫ 5.41-4.93 = 1.53
H<sub>trans</sub> = ∫ 2.75-2.85 = 0.27
Figure S9: $^1$H NMR (500 MHz, CDCl$_3$) after sonication of P1$_{590}$ in the presence of 9-phenanthrol. A $^1$H NMR of P1$_{590}$ prior to sonication is shown in Figure S6.

Figure S10: Overlay of $^1$H NMR (500 MHz, CDCl$_3$) before (red) and after (blue) sonication in the presence of 9-phenanthrol.
**Figure S11**: Overlay of $^1$H NMR (500 MHz, CDCl$_3$) in the aromatic region after sonication (red) and the small molecule 9-phenanthrol, as purchased from Sigma-Aldrich (blue).
Figure S12: (A) The normalized light scattering signal for aliquots taken after different amounts of sonication time. (B) The number average and weighted average molar mass measured by SEC-MALS over increased sonication time. (C) The UV-vis absorbance signal at 254 nm for aliquots taken at different sonication times. (D) The UV detector voltage at 254 nm for the polymer before sonication (black), and the same solution was characterized again by GPC after the sonication was completed, 4.5 hours later (pink). The maximum refractive index signal occurs at a retention time of 11.85 minutes.

Room temperature control experiment

The solution of polymer and 9-phenanthrol in THF was characterized by GPC prior to sonication experiment. The same solution, which had been sitting at room temperature during the sonication experiment, was characterized by GPC again immediately after the sonication experiment was completed. Absorbance at the retention time that the polymer was eluted was the same 4 hours later as it was when the solution was made (Figure S12).
Figure S13: The UV-vis spectra collected at the retention time at the peak of the RI signal intensity for polymer P1_{590} before (black) and after (red) sonication in a solution of 9-phenanthrol.

**Calculation of percent trapping by mass from UV-vis absorbance**

The percent trapping by 9-phenanthrol was determined according to the following Equation S3:

\[
\text{wt \% trapping} = \frac{\text{mass determined by UV}}{\text{mass determined by RI}} \times 100
\]

To determine the mass by UV, the Astra software was configured to use the UV detector at 254 nm as the concentration source. The mass eluted over the entire UV peak was determined by the software based on the extinction coefficient of 9-methoxyphenanthrol. To determine the mass by RI, 100% mass recovery of the polymer was assumed. The weight percent of 9-phenanthrene is 9.1% and the molar percent of 9-methoxyphenanthrene is 5.9%.

**Calculating percent trapping by “Protein Conjugate Analysis”**

The percent trapping by 9-phenanthrol was determined using the Astra software procedure “Protein Conjugate Analysis”, which uses equations S4 and S5 to take into consideration the influence of trapping on the refractive index of the polymer in addition to the change in absorbance.

\[
\left(\frac{dn}{dc}\right)_{\text{conjugate}} = x_{\text{polymer}} \left(\frac{dn}{dc}\right)_{\text{polymer}} + (1 - x_{\text{polymer}}) \left(\frac{dn}{dc}\right)_{9\text{-methoxyphenanthracene}}
\]

\[
\varepsilon_{\text{conjugate}} = \varepsilon_{\text{polymer}} \times x_{\text{polymer}} + \varepsilon_{9\text{-methoxyphenanthracene}} (1 - x_{\text{polymer}})
\]
The extinction coefficient of the polymer at 254 nm (0 mg mL$^{-1}$ cm$^{-1}$) and the dn/dc of the polymer prior to sonication (0.0859 mL g$^{-1}$) are entered into the software as the main component. The extinction coefficient (221.0 mg mL$^{-1}$ cm$^{-1}$) and dn/dc of 9-methoxyphenanthrene (0.2580 mL g$^{-1}$) are entered as the “modifier”. The weight percent of 9-phenanthrene is 6.0%, and the molar percent of 9-phenanthrene is 3.9%.

*Determinant of extinction coefficient of 9-methoxyphenanthcene*

![Graph showing spectra and Beer's law plot](image)

*Figure S14:* Left: Spectra of various concentrations of 9-methoxyphenanthcene in THF. Right: Beer’s law plot at 254 nm, the wavelength that is used for GPC calculations. The R$^2$ value is 0.9778 and the calculated molar absorptivity is 221.0 mg mL$^{-1}$ cm$^{-1}$.

*Determinant of refractive index increment of 9-methoxyphenanthrene*

The following concentrations of 9-phenanthrol were prepared in HPLC-grade THF by weight (not as a serial dilution): 0.150 mg/mL, 0.285 mg/mL, 0.412 mg/mL, 0.656 mg/mL, 0.829 mg/mL, and 1.055 mg/mL. The THF solvent was passed through the Wyatt Optilab T-rEX RI detector with a syringe pump at a flow rate of 0.3 mL/min, followed by each of the concentrations. Each solution was pumped through until several minutes of data were collected. After the highest concentration was ran, the THF solvent was ran again to set a baseline. The Astra procedure “dn/dc from RI” was applied to the data to calculate dn/dc = 0.2580 ± 0.0047 mL/g, r$^2$ = 0.9987.
Figure S15: Left: The refractive index measured over the time of the experiment, where each plateau corresponds to a different concentration of 9-methoxyphenanthrol flowing through the detector. Right: The slope of the linear regression of the refractive index measured for each concentration gives the refractive index increment.
Mechanochemically Induced Cross-Linking

We observed that when 9-phenanthrol was present, the PDI of \( \text{P1}_{590} \) decreased during sonication. When the same polymer was sonicated without 9-phenanthrol, the PDI increased. Typically, PDI decreases with sonication time as larger polymers are broken in half. In previous work, the observation of PDI increasing with sonication time indicated cross-linking.\(^5\)

![Figure S16: The change in PDI during sonication of same polymer with (red) and without (black) 9-phenanthrol.](image)

*Sonication of \( \text{P1}_{420} \) above the overlap concentration*

In order to investigate whether the polymer could crosslink with itself, polymer \( \text{P1}_{420} \) was sonicated at a concentration of 16.8 mg/mL, above \( c^* = 5.8 \text{ mg/mL} \).
Figure S17: $M_n$ and $M_w$ both decrease with increased sonication time, but the retention time at max peak height for the light scattering trace increases from the original polymer to sonication time of 90 minutes.

The calculated molecular weight of the polymer did not increase. However, the light scattering intensity reaches its maximum at a shorter retention time after the polymer is sonicated. It appears that some cross-linking can occur between the homopolymer itself.

**Determining the monomer composition of P2\textsubscript{190}**

\[
\text{Fraction monomer 2} = \frac{H_{\text{monomer 2 vinyl}}}{H_{\text{monomer 2 vinyl}} + H_{\text{epoxy COD vinyl}}} = 0.51
\]

\[
H_{\text{vinyl monomer 2}} = \int 5.549 - 5.343 = 2.36
\]

\[
H_{\text{vinyl epoxy COD}} = \int 5.338 - 5.186 = 1.15
\]
**Figure S18:** 
$^1$H NMR (400 MHz, CDCl$_3$) of P2$_{190}$ prior to sonication showing the region integrated to determine the monomer content.

**Figure S19:** 
$^1$H NMR (400 MHz, CDCl$_3$) of P2$_{190}$ prior to sonication.
Sonication of \( P2_{190} \) at low concentration (1 mg/mL)

![Diagram of polymer P2](image)

**Figure S20:** Molecular weight degradation during sonication at 1.0 mg/mL of polymer \( P2_{230} \) in THF (left) and light scattering signals from SEC-MALS for aliquots taken at different sonication times (right).

Sonication of \( P2_{230} \) at intermediate concentration (10 mg/mL)

![Diagram of polymer P2](image)

**Figure S21:** Light scattering signals from SEC-MALS for aliquots taken at different sonication times (right) and molecular weight degradation (left) during sonication at 10 mg/mL of polymer \( P2_{230} \) in THF.
**Sonication of P2$_{230}$ at high concentration (20 mg/mL)**

**Figure S22:** Light scattering signals from SEC-MALS for aliquots taken at different sonication times (right) and molecular weight degradation (left) during sonication at 20 mg/mL of polymer P2$_{230}$ in THF.

**Figure S23:** Only slight gelation occurred, and it was not apparent until the sonication tip was cleaned. Photos taken with an iPhone 5s and unedited.
Control Experiments

Trapping and isomerization require mechanical force

Sonication of P1₈

Polymer P1₈ was dissolved in 0.1 M 9-phenanthrol at 1.5 mg/mL and sonicated under standard conditions for 120 minutes. After sonication, the solution was concentrated and precipitated 2 times into cold methanol to collect the sonicated polymer for ¹H NMR. The absorbance at 254 nm is shown in Figure 2D.

Figure S24: Normalized light scattering intensity (left) and number average and weighted average molar mass (right) for aliquots taken out at different sonication times. The control solution was left under ambient conditions for the duration of the experiment (~4.5 hours) before running on GPC.
Cross-linking requires mechanical force

Sonication of P1\textsubscript{20} above the overlap concentration

Polymer P1\textsubscript{20} was dissolved in THF at 35.1 mg/mL, above $c^* = 16.8$ mg/mL (see section on calculation of the overlap concentration), then sonicated for 120 minutes. Aliquots were taken for GPC and after sonication the solvent was removed by rotary evaporation for $^{1}$H NMR.
Figure S26: Normalized light scattering intensity (left) and number average and weighted average molar mass (right) for aliquots taken out at different sonication times. The control solution was left under ambient conditions for the duration of the experiment (~4.5 hours) before running on GPC.

Figure S27: 1H NMR (500 MHz, CDCl3) of P120 before (red) and after (blue) sonication above the overlap concentration at 35.1 mg/mL. The new peaks at 1.85 and 3.74 in the blue spectra are THF, the solvent for the sonication experiment.
Sonication of $P2_{30}$ above the overlap concentration

Polymer $P2_{30}$ was dissolved in THF at a concentration of 32.7 mg/mL, above $c^* = 16.9$ mg/mL (see section on calculation of the overlap concentration, and sonicated for 120 minutes. Aliquots were taken for GPC and after sonication the solvent was removed by rotary evaporation for $^1$H NMR.

**Figure S28:** Normalized light scattering intensity (left) and number average and weighted average molar mass (right) for aliquots taken out at different sonication times. The control solution was left under ambient conditions for the duration of the experiment (~4.5 hours) before GPC characterization.

**Figure S29:** $^1$H NMR (500 MHz, CDCl$_3$) of $P2_{30}$ before (red) and after (blue) sonication above the overlap concentration at 35.1 mg/mL.
Determining the monomer composition of $\textbf{P2}_{30}$

Fraction monomer 2 = \( \frac{\int_{5.549}^{5.343} H_{\text{monomer 2 vinyl}}}{\int_{5.549}^{5.343} H_{\text{monomer 2 vinyl}} + \int_{5.338}^{5.186} H_{\text{epoxy COD vinyl}}} \) = 0.54

$H_{\text{vinyl monomer 2}} = \int 5.549-5.343 = 1.77$

$H_{\text{vinyl epoxy COD}} = \int 5.338-5.186 = 0.75$

\[ \text{Figure S30: } ^1\text{H NMR (500 MHz, CDCl}_3\text{) of } \textbf{P2}_{30} \text{ prior to sonication showing the regions integrated to determine the monomer content.} \]
Overlap Concentration (c*) Calculations

The overlap concentration occurs when the volume of a polymer is equivalent to the volume of the system and polymers are in contact with each other. It was calculated according to a previously published method.\(^6\) Overlap concentrations are shown in Table S3.

**Table S3**: Overlap concentrations for polymers used in cross-linking experiments.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>(M_n) (kDa)</th>
<th>(M_w) (kDa)</th>
<th>PDI</th>
<th>(R_g) (nm)</th>
<th>(C^*) (mg/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1(_{420})</td>
<td>416</td>
<td>684</td>
<td>1.64</td>
<td>36.0</td>
<td>5.8</td>
</tr>
<tr>
<td>P1(_{20})</td>
<td>21</td>
<td>28</td>
<td>1.30</td>
<td>8.66*</td>
<td>16.8</td>
</tr>
<tr>
<td>P2(_{190})</td>
<td>192</td>
<td>318</td>
<td>1.66</td>
<td>32.8</td>
<td>3.6</td>
</tr>
<tr>
<td>P2(_{230})</td>
<td>231</td>
<td>442</td>
<td>1.82</td>
<td>36.7</td>
<td>3.5</td>
</tr>
<tr>
<td>P2(_{30})</td>
<td>32</td>
<td>40</td>
<td>1.27</td>
<td>9.4*</td>
<td>16.9</td>
</tr>
</tbody>
</table>

*calculated by linear regression of \(R_g\) vs. \(M^{1/2}\) for a larger polymer of the same composition.

**Determining the overlap concentration of P1\(_{420}\)**

\(M_n = 416,200, M_w = 684,200, R_g = 36.0\) nm

\[
\text{Volume of a polymer} = \frac{4}{3} \pi R_g^3
\]

\[
\text{Volume of a polymer} = \frac{4}{3} \pi (3.60 \cdot 10^{-6} \text{cm})^3 = 1.95 \cdot 10^{-16} \text{cm}^3
\]

\[
\frac{1 \text{ polymer}}{1.95 \cdot 10^{-16} \text{cm}^3} \cdot \frac{1 \text{ mol}}{6.022 \cdot 10^{23} \text{ polymers}} \cdot \frac{442,300 \text{ g}}{1 \text{ mol}} = 0.0058 \text{ g} \cdot \text{cm}^3 = 5.8 \text{ mg/mL}
\]

**Determining the overlap concentration of P1\(_{20}\)**

Since the molecular weight of polymer P1\(_{20}\) is low, the radius is less than 10 nm and cannot be determined from SEC-MALS using a Debye plot. In order to determine radius of P1\(_{20}\), the relationship between \(R_g\) and mass is determined for a larger polymer, P1\(_{420}\). The mass and radius are recorded at several retention times across the light scattering peak for a GPC chromatogram of P1\(_{420}\). The radius should scale linearly with the square root of mass for a random coil polymer, as shown in Figure S31. The calculated \(R_g\) is determined from the linear regression constrained to the origin.
Figure S31: The radius of gyration plotted as a function of the square root of the molar mass.

For \( \text{P1}_{20} \), \( M_n = 21,000 \), \( M_w = 27,500 \), and the calculated value of \( R_g = 8.66 \).

\[
\text{Volume of a polymer} = \frac{4}{3} \pi R_g^3
\]

\[
\text{Volume of a polymer} = \frac{4}{3} \pi (8.66 \cdot 10^{-7} \text{cm})^3 = 2.72 \cdot 10^{-18} \text{cm}^3
\]

\[
\frac{1 \text{ polymer}}{2.72 \cdot 10^{-18} \text{cm}^3} \cdot \frac{1 \text{ mol}}{6.022 \cdot 10^{23} \text{ polymers}} \cdot \frac{27,500 \text{ g}}{\text{mol}} = 0.0168 \frac{\text{g}}{\text{cm}^3} = 16.8 \frac{\text{mg}}{\text{mL}}
\]

**Determining the overlap concentration for \( \text{P2}_{190} \)**

\( M_n = 191,700 \), \( M_w = 318,000 \) and \( R_g = 32.8 \text{ nm} \), and \( c^* = 3.5 \text{ mg/mL} \)

\[
\text{Volume of a polymer} = \frac{4}{3} \pi R_g^3
\]

\[
\text{Volume of a polymer} = \frac{4}{3} \pi (3.28 \cdot 10^{-6} \text{cm})^3 = 1.48 \cdot 10^{-16} \text{cm}^3
\]

\[
\frac{1 \text{ polymer}}{1.48 \cdot 10^{-16} \text{cm}^3} \cdot \frac{1 \text{ mol}}{6.022 \cdot 10^{23} \text{ polymers}} \cdot \frac{318,000 \text{ g}}{\text{mol}} = 0.0036 \frac{\text{g}}{\text{cm}^3} = 3.6 \frac{\text{mg}}{\text{mL}}
\]

**Determining the overlap concentration for \( \text{P2}_{230} \)**

\( M_n = 231,500 \), \( M_w = 442,300 \) and \( R_g = 36.7 \text{ nm} \), and \( c^* = 3.5 \text{ mg/mL} \)

\[
\text{Volume of a polymer} = \frac{4}{3} \pi R_g^3
\]

\[
\text{Volume of a polymer} = \frac{4}{3} \pi (3.67 \cdot 10^{-6} \text{cm})^3 = 2.07 \cdot 10^{-16} \text{cm}^3
\]

\[
\frac{1 \text{ polymer}}{2.07 \cdot 10^{-16} \text{cm}^3} \cdot \frac{1 \text{ mol}}{6.022 \cdot 10^{23} \text{ polymers}} \cdot \frac{442,300 \text{ g}}{\text{mol}} = 0.0035 \frac{\text{g}}{\text{cm}^3} = 3.5 \frac{\text{mg}}{\text{mL}}
\]
Determining overlap concentration of P2$_{30}$

Polymer P2$_{30}$ is also smaller than 10 nm, so a linear regression is performed in the same manner as for polymer P1$_{20}$.

Figure S32: The radius of gyration plotted as a function of the square root of the molar mass.

For polymer P2$_{30}$, $M_n = 31,700$, $M_w = 40,200$, the calculated is $R_g = 9.42$ nm.

\[
Volume \ of \ a \ polymer = \frac{4}{3} \pi R_g^3
\]

\[
= \frac{4}{3} \pi (9.42 \cdot 10^{-7} \text{cm})^3 = 3.94 \cdot 10^{-18} \text{cm}^3
\]

\[
\frac{1 \text{ polymer}}{3.94 \cdot 10^{-18} \text{cm}^3} \cdot \frac{1 \text{ mol}}{6.022 \cdot 10^{23} \text{ polymers}} \cdot \frac{40,200 \text{ g}}{\text{mol}} = 0.0169 \frac{\text{g}}{\text{cm}^3} = 16.9 \frac{\text{mg}}{\text{mL}}
\]
Single Molecule Force Spectroscopy

Polymer P3_{280} was used for force spectroscopy according to previously reported methods.

![Graph](image)

**Figure S3**: GPC data for P3_{280}.

The extension curves were fit to the extended freely jointed chain model following previously published procedures. One plateau was observed in SMFS force curves for P3_{280} (Table S4). The average F* was ~1417 ± 67 pN (Figure S32), while the literature value of F* for gDCC is ~1330 pN,\(^1\) within the margin of error.

**Table S4**: SMFS data list for P3_{280}.

<table>
<thead>
<tr>
<th>gDCC content</th>
<th>F* (gDCC opening)</th>
<th>L1 (nm)</th>
<th>L2 (nm)</th>
<th>L2/L1</th>
<th>F max</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3_{280}-1</td>
<td>0.6</td>
<td>1258.42</td>
<td>256.68</td>
<td>291.59</td>
<td>1.14</td>
</tr>
<tr>
<td>P3_{280}-2</td>
<td>0.6</td>
<td>1383.89</td>
<td>218.28</td>
<td>249.43</td>
<td>1.14</td>
</tr>
<tr>
<td>P3_{280}-3</td>
<td>0.6</td>
<td>1483.16</td>
<td>426.99</td>
<td>481.67</td>
<td>1.13</td>
</tr>
<tr>
<td>P3_{280}-4</td>
<td>0.6</td>
<td>1476.53</td>
<td>487.41</td>
<td>550.95</td>
<td>1.13</td>
</tr>
<tr>
<td>P3_{280}-5</td>
<td>0.6</td>
<td>1394.61</td>
<td>407.62</td>
<td>465.26</td>
<td>1.14</td>
</tr>
<tr>
<td>P3_{280}-6</td>
<td>0.6</td>
<td>1474.52</td>
<td>621.22</td>
<td>688.17</td>
<td>1.11</td>
</tr>
<tr>
<td>P3_{280}-7</td>
<td>0.6</td>
<td>1441.44</td>
<td>525.22</td>
<td>588.11</td>
<td>1.12</td>
</tr>
<tr>
<td>P3_{280}-8</td>
<td>0.6</td>
<td>1381.84</td>
<td>197.95</td>
<td>216.74</td>
<td>1.09</td>
</tr>
<tr>
<td>P3_{280}-9</td>
<td>0.6</td>
<td>1432.42</td>
<td>487.46</td>
<td>551.56</td>
<td>1.13</td>
</tr>
<tr>
<td>P3_{280}-10</td>
<td>0.6</td>
<td>1439.11</td>
<td>392.16</td>
<td>431.11</td>
<td>1.10</td>
</tr>
<tr>
<td>Avg</td>
<td></td>
<td>1416.59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std dev</td>
<td></td>
<td>67.11</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure S34: A complete force curve for $P_{3280}$ with fits to contour length before (L1) and after (L2) the plateau corresponding to the ring-opening of gDCC. The maximum force achieved is around 2400 pN, and no additional plateau for epoxide isomerization is observed.

Figure S35: $F^*$ for gDCC ring-opening is determined by the inflection point of the force-distance curve for a representative polymer $P_{3280}$, which is found by fitting to the first and second derivative. This process is described in detail elsewhere.$^{1a}$
The experimentally measured change in contour length was also compared to the theoretical prediction for the ring opening of gDCC using Equation 6:

\[
\frac{L_f}{L_i} = \frac{(L_{2.3-dichloroalkene} \times \chi_{gDCC}) \times (L_{epoxy\ COD} \times \chi_{epoxy\ COD})}{(L_{gDCC} \times \chi_{gDCC}) + (L_{epoxy\ COD} \times \chi_{epoxy\ COD})}
\]

where \(L\) is the end to end distance determined from COGEF modeling\(^7\) and \(\chi\) is the mole fraction determined by \(^1\)H NMR. Results are summarized in Table S5.

**Table S5:** Theoretically determined extension ratios for \(\text{P3}_{280}\).

<table>
<thead>
<tr>
<th>gDCC content ((^1)H NMR)</th>
<th>(L_f/L_i) (SMFS)</th>
<th>(L_f/L_i) (COGEF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{P3}_{280})</td>
<td>0.60</td>
<td>1.12 ± 0.02</td>
</tr>
</tbody>
</table>

The mole fraction of gDCC in \(\text{P3}_{280}\) is determined by \(^1\)H NMR (Figures S34 and S35).

\[
\text{Fraction } gDCC = \frac{H_{gDCC\ vinyl}^2}{H_{gDCC\ vinyl}^2 + H_{epoxyCOD\ vinyl}^2} = 0.60
\]

\(H_{\text{vinyl\ gDCC}} = \int 5.548-5.339 = 1.93\)

\(H_{\text{vinyl\ epoxy\ COD}} = \int 5.346-5.151 = 0.65\)
Figure S36: $^1$H NMR of P3$_{280}$ (500 MHz, CDCl$_3$).

Figure S37: The region of the $^1$H NMR spectra integrated to determine gDCC content of P3$_{280}$ (500 MHz, CDCl$_3$).
Force-free contour lengths were determined with Spartan '16 modeling software using semi-empirical AM1 level of theory. Methods are detailed elsewhere, but briefly, the end-to-end distance is constrained in increments of ~ 0.2 Å and the energy is calculated for each distance. The relative energy is plotted as a function of distance and fit to a quadratic. The first derivative of the fit gives a linear relationship between force and distance. Contour length is calculated as the length at zero force. Each monomer contour length is determined three times and the average is used to calculate theoretical extension.

Figure S38: The structure modeled to determine the contour length for the cis-epoxide monomer. The constraint was between the atoms indicated with red circles.

Figure S39: A representative COGEF model of contour length for cis-epoxide monomer. Left: Quadratic fit to energy vs. distance. Right: The force-distance plot obtained from the first derivative of the quadratic fit. The average of three experiments gave a contour length of 9.52 Å, or 0.952 nm.

Figure S40: The structure modeled to determine the contour length for the cis-gDCC monomer. The constraint was between the atoms indicated with red circles.
**Figure S41:** A representative COGEF model of contour length for cis-gDCC monomer. Left: Quadratic fit to energy vs. distance. Right: The force-distance plot obtained from the first derivative of the quadratic fit. The average of three experiments gave a contour length of 9.45 Å, or 0.945 nm.

**Figure S42:** The structure modeled to determine the contour length for (Z) 2,3-dichloroalkene. The constraint was between the atoms indicated with red circles.

![Diagram](image1.png)

**Figure S43:** A representative COGEF model of contour length for (Z) 2,3-dichloroalkene product. Left: Quadratic fit to energy vs. distance. Right: The force-distance plot obtained from the first derivative of the quadratic fit. The average of three experiments gave a contour length of 11.06 Å, or 1.106 nm.
Rate Constant Calculation

The upper limit of the reaction rate was calculated from the force curve P3_{280-7}. The timestamps recorded with the force-distance data were used to determine that time interval required for the force to go from 2500 pN to 2600 pN is 0.019 s. We conservatively estimate that less than 10% of the mechanophores have reacted (or evidence of the reaction would be clearly visible in the force-distance curve), and so the force-coupled rate constant of the reaction is less than 5 s^{-1} (0.1/0.019 s) at a force of 2500 pN.

Figure S44: The time interval between F = 2500 pN and 2600 pN was determined with timestamps collected with SMFS data using software written in Matlab.
References


