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Mechanochemical strengthening of a synthetic polymer in response to typically destructive shear forces

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Abstract

High shear stresses are known to trigger destructive bond-scission reactions in polymers. Recent work has shown that the same shear forces can be used to accelerate non-destructive reactions in mechanophores along polymer backbones, and it is demonstrated here that such mechanochemical reactions can be used to strengthen a polymer subjected to otherwise destructive shear forces. Polybutadiene was functionalized with dibromocyclopropane mechanophores, whose mechanical activation generates allylic bromides that are crosslinked *in situ* by nucleophilic substitution reactions with carboxylates. The crosslinking is activated efficiently by shear forces both in solvated systems and in bulk materials, and the resulting covalent polymer networks possess moduli that are orders-of-magnitude greater than those of the unactivated polymers. These molecular-level responses and their impact on polymer properties have implications for the design of materials that, like biological materials, actively remodel locally as a function of their physical environment.

Materials typically break down in response to repeated cycles of mechanical load and stress that they experience during use. In polymer solutions, for example, shear-induced bond breaking reduces molecular weight and leads to a loss in viscosity[1], a problem that plagues oils and lubricants in high-performance engines[2]. In solid-state applications, stress-induced bond scission or chain slippage triggers the formation of microcracks that propagate and eventually lead to material failure[3]. Many biological materials, however, remodel and become stronger in direct response to the mechanical forces that otherwise might cause them to fail. Bone and muscle, for example, build mass and strength when subjected to load, and

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Author contributions

A.L.B.R. and S.L.C. conceived and designed the experiments. A.L.B.R. and Z.S.K. performed the synthesis, J.A.O. contributed extrusion equipment and analysed that data with A.L.B.R. A.L.B.R. and S.M.E. performed the shear experiments. W.E.K. contributed the nanoindentation tools and M.C. performed the nanoindentation experiments and analysed that data. A.L.B.R., Z.S.K. and S.L C. analysed the data and co-wrote the paper.

Additional information

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Competing financial interests

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wood[4] and hair[5] respond to force-induced bond breaking at the molecular level by forming new bonds in the strained conformation, which results in a net increase in strength. Here, we report a family of synthetic polymers in which the same forces responsible for the destructive processes of bond scission and chain disentanglement are channelled into constructive, bond-forming reactions. The response, to which we refer for convenience as activated remodelling via mechanochemistry (ARM), requires no additional external stimulus or energy input beyond the imposed shear, and functions in both solution and bulk, to form molecularly remodelled polymer gels and crosslinked monoliths in which the number of bonds formed exceeds the number of bonds broken under typically destructive mechanical conditions. The molecular-level modifications result in orders-of-magnitude increases in bulk moduli.

The ARM concept is shown in Fig. 1. The enabling chemistry is that of a mechanophore, a polymer-embedded mechanically reactive moiety. Much recent work has focused on using mechanophores and mechanochemistry[6,7] to produce new chemistry[8,9], force accelerated and selective transformations[10–21], and stress-responsive material properties[22–24]. The ARM polymers described within this paper incorporate large numbers of mechanophores in the covalent structure of the polymer, so that the destructive forces responsible for bond scission also activate widespread latent reactivity in the mechanophores. We chose *gem*-dibromocyclopropanes (*g*DBCs, $\mathbf{1_{closed}}$) for the mechanophores embedded within a poly(butadiene) (PB) backbone (Fig. 1a) because the mechanically triggered ring opening leads to a 2,3-dibromoalkene product ($\mathbf{1_{open}}$) that is susceptible to nucleophilic substitution[14], which provides the basis for remodelling and potential self-strengthening or self-repair through covalent crosslinking, as proposed, but not demonstrated, elsewhere[25] (Fig. 1). The PB scaffold is attractive both synthetically and practically because of the ease of incorporating many mechanophores along a single polymer chain and its commercial utility. The parent *g*DBC mechanophore is inert towards nucleophilic substitutions, so the repair reaction only occurs when and where sufficient forces are experienced within the polymer to cause the non-scissile, ring-opening reactions.

We tested the ARM response to the shear forces of twin-screw extrusion, a common technique for bulk polymer processing. The conditions employed were destructive on a molecular level; extrusion of $\mathbf{1_{closed}}$ alone for 30 minutes at 40 °C and 50 revolutions per minute (r.p.m.) generated bulk shear stresses in the range 0.15–0.25 MPa (see Supplementary Information) that resulted in bond scission and a reduction in molecular weight from 780 to 560 kDa. At the same time, the shear forces responsible for chain scission mechanically activated the conversion of 7% of the *g*DBCs into their open form. Several pieces of evidence support a mechanical, rather than thermal, activation mechanism. Most compelling is to decouple the mechanophore from shear-generated tension along the polymer main chain by adding the *g*DBC to the pendant side-chain alkene of 1,2-PB. When 8 kDa, 66% 1,2-*g*DBC-PB polymer is co-extruded with 110 kDa *cis*-1,4-PB (40 minutes, 40 °C, 100 r.p.m.), the shear forces are large enough to degrade the molecular weight of the *cis*-1,4-PB to 68 kDa. No activation was observed, however, in the 1,2-*g*DBC control sample, which supports a mechanical, rather than thermal, activation pathway (see Supplementary Information). Additional support is found in the increased activation previously reported to occur at lower extrusion temperatures[14], and in the absence in the extruded sample of HBr elimination products from the ring-opened product that accompany the thermally activated reaction.

Reasoning that a divalent nucleophile might allow for polymer crosslinking, we extruded the **ARM-1** system, $\mathbf{1_{closed}}$, with the ditetrabutylammonium salt of sebacic acid (TBA SA; Fig. 2). We chose carboxylates as the nucleophiles because they are easily accessible and common functional groups in polymer chemistry, they show sufficient reactivity for

nucleophilic substitution of the allyl bromide and, because of their weak basicity, they are not as prone to triggering elimination as other nucleophiles that we tested (for example, amines and alkoxides). The same shear conditions led to a solid polymer that, unlike extrusion of **1** alone, was insoluble in each of five different solvents and solvent combinations, consistent with the desired crosslinking. Interestingly, the mechanically triggered crosslinking appears to outcompete the destructive shear forces during the extrusion process, as the dynamic viscosity reading coupled to the extruder initially decreases, consistent with chain alignment and scission, but after ~13 minutes of extrusion, the required torque begins to increase slightly in a manner not observed in control polymers, which suggests an increase in molecular weight from crosslinking. Support for this crosslinking is provided by infrared spectroscopy, which reveals the disappearance of the TBA SA carboxylate stretch at 1,571 cm^{-1} and the appearance of a new carbonyl stretch at 1,721 cm^{-1} (Fig. 2), in excellent agreement with characteristic frequencies of esters and the value obtained in a model compound (see Supplementary Information).

This molecular-scale remodelling has a dramatic and positive impact on bulk mechanical properties. We characterized the properties of the samples using nanoindentation, which has emerged as a sophisticated and reliable technique for measuring the hardness and elastic modulus of materials at the submicron scale[26]. Extruding $\mathbf{1_{closed}}$ led to insignificant changes in elastic modulus (8±5 MPa for $\mathbf{1_{closed}}$, 8±3 MPa for $\mathbf{1_{open}}$), as determined by sampling each substrate at three different locations with four different loads, ranging from 30 to 60 μN. When the TBA SA salt was mixed with $\mathbf{1_{closed}}$ to form the **ARM-1** system, the modulus of the nascent sample reduced considerably (2±0.5 MPa). When the **ARM-1** system was extruded, the remodelled sample that emerged was noticeably stiffer not only than in its unextruded form, but also than any of the other samples. Nanoindentation confirmed that the material became significantly stronger in response to typically destructive mechanical forces, with an increase of nearly two orders of magnitude in the elastic modulus to a value of 150±85 MPa (see Supplementary Information). This increase is attributed primarily to the molecular-scale crosslinking that occurs in response to the mechanochemical trigger. Tetrabutylammonium bromide was formed by the crosslinking reaction, but its contribution to bulk material properties is assumed to be small and softening, comparable to the changes observed from the addition of TBA SA to $\mathbf{1_{closed}}$. In line with the interpretation of molecular-level self-strengthening, the modulus continues to increase in the resting, extruded sample as additional crosslinking reactions occur at the sites of mechanophore activation; by one week post-extrusion there was an increase in the infrared absorbance at 1,721 cm^{-1} (ester) and a concomitant decrease in absorbance at 1,560 cm^{-1} (free carboxylate). In that same time, the modulus nearly doubled to 280±61 MPa. In comparison, $\mathbf{1_{closed}}$ and $\mathbf{1_{open}}$ registered modest or even negligible changes in modulus after a week (to 2±1 MPa and 17±9 MPa, respectively; see Supplementary Information).

We next tested the ARM concept in the context of shear-responsive polymer solutions. In solution, the mechanical triggers were elongational flow forces that accompany the collapse of cavitating bubbles during pulsed ultrasound[27,28]. The resulting forces of tension along the backbone of polymer solutes of sufficient molecular weight (typically >40 kDa)[29] are quite large (nano-Newton range) and, as in the extrusion experiments, these forces are destructive and lead to chain scission and a decrease in polymer molecular weight. Larger molecular-weight polymers are more likely to experience forces necessary for scission, which makes them degrade faster[30], so we wondered whether the pace of bond making could match or exceed that of bond breaking.

We first explored the response of the **ARM-1** two-component mixture used in the bulk studies. Monitoring the molecular weight of $\mathbf{1_{closed}}$ by gel permeation chromatography (GPC) as a function of sonication time in THF in the presence of TBA SA revealed the

competition between the bond-breaking events that reduce molecular weight and the bond-forming events that increase molecular weight. As seen in Fig. 2, the GPC traces initially shift to longer retention times with increasing sonication, which indicates a decrease in polymer molecular weight and confirms that the high-shear environment is, indeed, destructive. At longer sonication times, however, a high molecular-weight front begins to grow into the chromatogram, indicative of early stages of gelation[31], and sonication times in excess of 30 minutes result, first in the formation of insoluble precipitates and eventually in a free-standing film that can be peeled from the side of the Suslick vessel. As with the extrusion studies, these precipitates are insoluble in a wide variety of solvents.

To simplify the system, we engineered a single-component system (**ARM-2**) in which the crosslinking nucleophile is present on the same backbone as the mechanophore (Fig. 3). The activity of the mechanophore was demonstrated by subjecting precursor **2**, in which the carboxylic acid remains protonated and therefore unreactive to crosslinking, to pulsed ultrasound in the same manner as for $\mathbf{1_{closed}}$, which again produced the desired 2,3-dibromoalkene. No precipitation or other evidence for intermolecular reactivity was observed as a consequence of sonicating **2**. When the carboxylic acid was activated to the nucleophilic carboxylate salt in **ARM-2**, however, sonication led to an even more prominent precipitate formation than was observed in the two-component system. A newly formed infrared absorption peak at 1,724 cm^{-1} again verified the formation of the desired ester crosslinks. The ARM response is efficient enough that bond making can outpace bond breaking during the pulsed ultrasound experiment, but an even more dramatic response ensues once the intermittent shear is stopped: the polymer solution gels to form an integrated, macroscopic crosslinked network. As in the bulk, mechanical-property measurements confirm the qualitative observations. The storage moduli of the various nascent polymer solutions, including unsonicated **ARM-2**, were at or below the limit of detection of our rheometer, whereas the stress-responsive gelation resulted in a modulus increase of greater than two orders of magnitude (see Supplementary Information). No increase in modulus was observed in sonicated polymer **2**, sonicated polymer $\mathbf{2_{open}}$ or unsonicated **ARM-2** (Fig. 3). Fourier transform infrared spectroscopy (FTIR) again verified the formation of ester crosslinks, but at a greater relative population in the sample than in the two-component ARM system. As in previous cases, crosslinking was further confirmed by the insolubility of the dried gel in a wide variety of organic solvents.

The absence of gelation in nucleophilically inactive **2** provides good evidence that gelation does, indeed, require intermolecular crosslinking of the type proposed (the inactivity of the carboxylic acid in **2** is confirmed by an unchanged infrared absorbance at 1,700 cm^{-1}, which corresponds to the carboxylic acid rather than an ester), and this conclusion is further supported by additional observations (see Supplementary Information). First, if **ARM-2** is sonicated at concentrations below its critical overlap concentration (at which the average volume of a single polymer chain overlaps with the volume of another polymer chain, which favours intermolecular rather than intramolecular ester formation)[32], no precipitates are formed during sonication and there is only a minimal increase in viscosity after the shear is stopped. Second, we showed previously that the *gem*-dichlorocyclopropane (*g*DCC) mechanophores are activated to the corresponding allyl chloride products to the same extent as the gDBCs under pulsed ultrasound, but small-molecule model systems demonstrate that, unlike the allylic bromide, the allylic chloride is not susceptible to nucleophilic displacement by a carboxylate. Consistent with expectations, sonication of the dichlorocyclopropanated polymer (**ARM-inactive**, see Supplementary Information) did not lead to precipitation, gelation or changes in the carbonyl region of the infrared spectrum. The same result was obtained with a polymer that contains only the carboxylate and no mechanophore. Third, sonication is necessary; allowing the **ARM-2** system to sit overnight without sonication results in no gelation. Fourth, the mechanical nature of the activation was confirmed by

sonicating a low molecular-weight (9 kDa) **ARM-2** polymer, which experienced the same temperatures and pressures as the active **ARM-2** systems, but is below the limiting molecular weight for mechanical activation, and no ring opening or gelation was observed.

In the systems reported here, the consequences of molecular remodelling are global, in that the remodelling occurs throughout the material and they are observed in conjunction with irreversible deformation of the material (a characteristic of all reported bulk mechanochemical activations of which we are aware). These results, however, also raise the intriguing possibility of localized mechanochemical self-strengthening to 'at-risk' regions within a load-bearing material, as occurs in biological systems. Localized remodelling should, therefore, be possible because the activation and subsequent crosslinking only occur at the discrete molecular sites that experience high forces of tension, and such molecular-scale forces are distributed to different extents in different classes of materials and loading environments, including crosslinked solids[22]. Whether local or global, orders-of-magnitude autonomous self-strengthening is shown here to be possible, and the magnitude of the response should be tunable through the nature of the mechanophore, its abundance within the material and the reactivity and concentration of the reacting partner. Underlying the response is a new principle for materials design, in which chemomechanical coupling is used to capture otherwise destructive mechanical energy and funnel it into constructive processes that, as in biological systems, actively remodel a synthetic material in response to its physical environment. The direct coupling of mechanical force to covalent chemistry differs from previously reported gelations triggered by sonication or shear[33,34], both in the mechanism of activation and in the controlled and potentially localized nature of the response. The same is true relative to conventional polymeric strain hardening caused by mesoscale morphological changes, such as polymer-chain alignment and/or crystallization[35]. Finally, the use of polymer mechanochemistry makes available a rich palette of chemical responses, many of which are inaccessible via thermal and/or photochemical stimuli, and so not only the mechanical but, ultimately, also the chemical, electronic or other functional properties of a material might be combined with the physical remodelling.

Methods

Preparation of ARM polymers

The synthesis, purification and characterization of all ARM polymers are described in detail in the Supplementary Information, including NMR, infrared and GPC data, mechanical characterization, control experiments and additional details.

Extrusion

Extrusion was performed on a Haake minilab microcompounder, comprising a clamshell barrel with two conical screws and a recirculation pathway to allow for extended processing intervals. The experiments were conducted using a recirculation pathway, which required about 7 ml of volume to allow for proper flow of the processed material. The polymer was introduced into the preheated barrel using a mechanical plunger, and the samples were processed at the indicated rate of screw rotation. Samples were stored under vacuum until ready to be processed. The compounder is equipped with two pressure transducers integrated in the backflow channel, which allows the measurement of sample dynamic viscosity. Pre- and post-extrusion moduli were characterized by nanoindentation, as described in the Supplementary Information.

Sonication

Ultrasound experiments (unless otherwise noted) were performed in BH-free THF (BHT = 3,5-di-*tert*-butyl-4-hydroxytoluene)) on a Vibracell Model VCX500 operated at 20 kHz with

a 12.8 mm replaceable tip titanium probe from Sonics and Materials. Three-necked glass Suslick cells were obtained from Sonics and Materials and were oven dried before use. The sonications were carried out on 16 ml of the indicated solutions in THF in a room-temperature water bath. Solutions were degassed with bubbling N_2 for 30 minutes prior to sonication and a positive headspace of N_2 was kept during the experiment. Pulsed ultrasound was carried out at 8.7 W cm^{-2} of power at one second on, six seconds off. Pre- and post-sonication moduli were characterized by rheometry, as described in the Supplementary Information.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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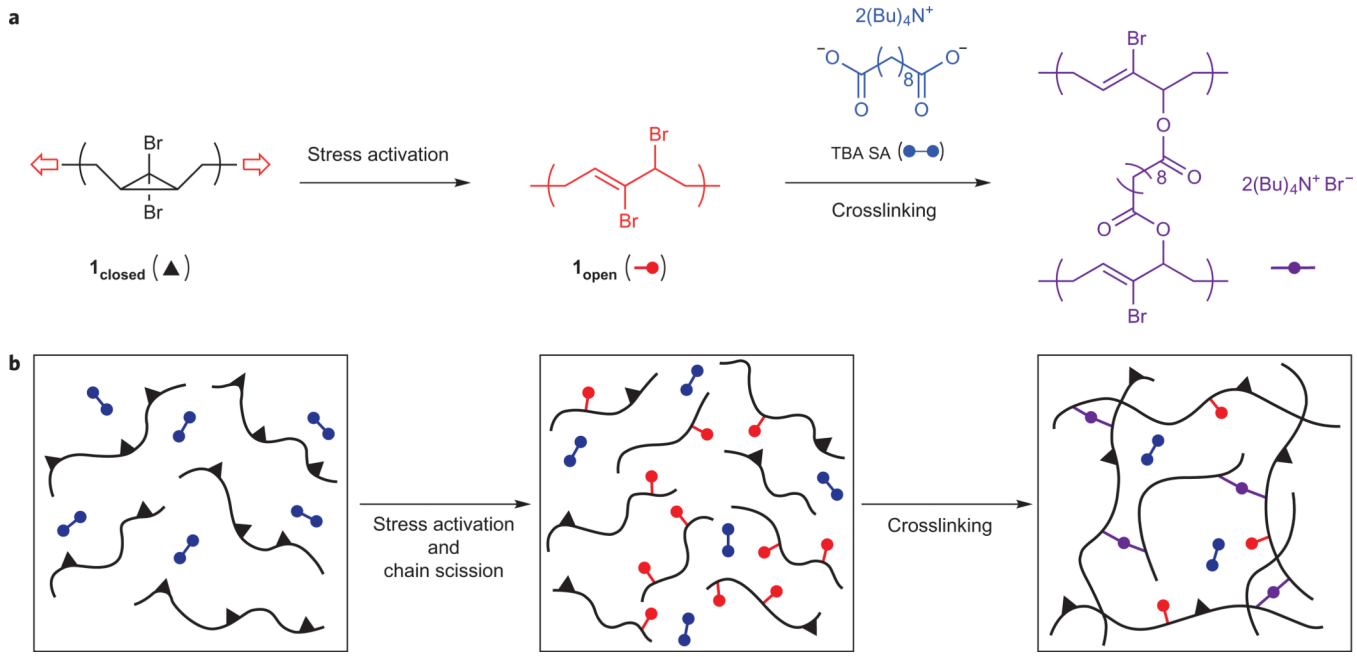

Figure 1. The mechanochemical self-strengthening concept

a, A *g*DBC mechanophore within a polymer chain under tension undergoes a ring-opening reaction from $\mathbf{1}_{\mathbf{closed}}$ to $\mathbf{1}_{\mathbf{open}}$. This increases the contour length and provides an allylic bromide that is capable of self-strengthening through nucleophilic displacement reactions. **b**, System-wide force causes chain scission, but also activates the mechanophore (black triangle to red dot), which subsequently reacts with a crosslinker (blue) to form an active crosslink (purple) that overcomes the damage.

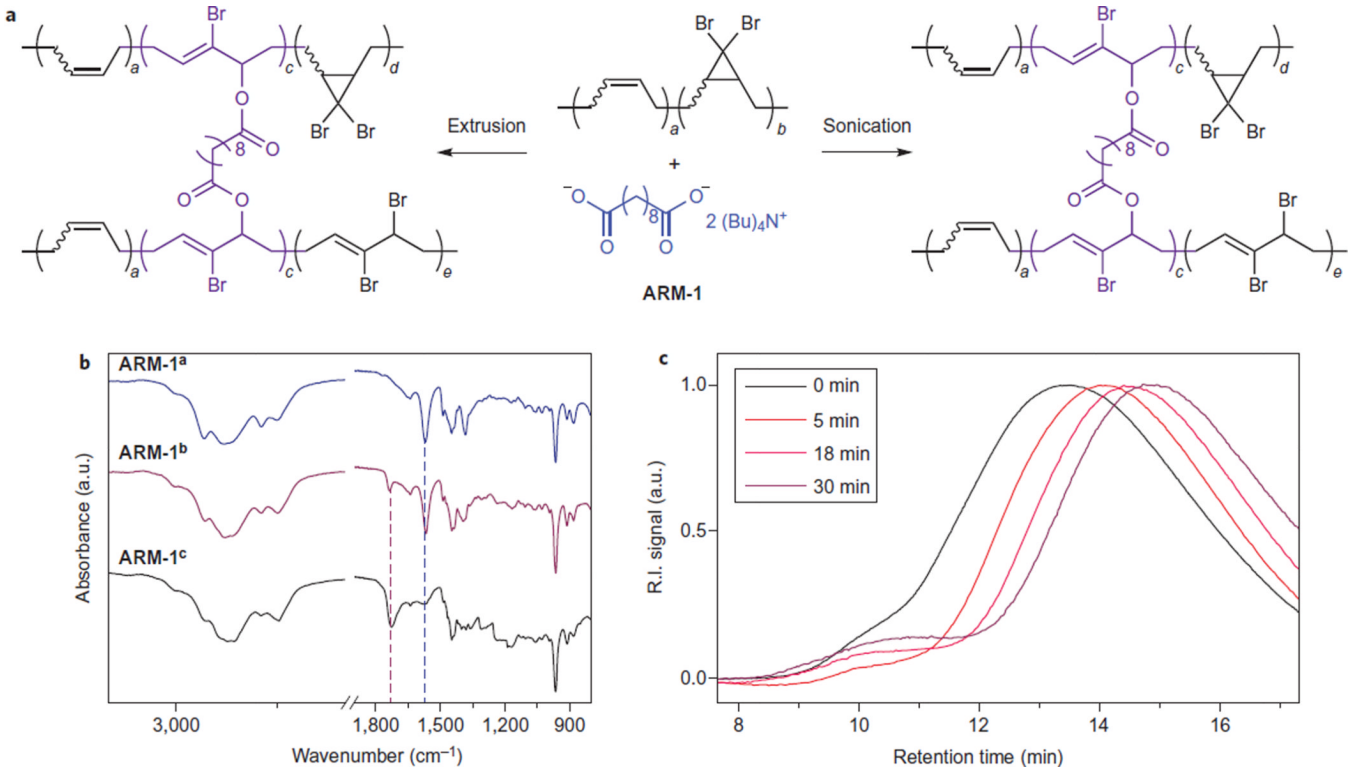

Figure 2. Shear-induced mechanochemical crosslinking in solution and the bulk

a, The **ARM-1** system responds to extrusion in the bulk (left) and sonochemical shearing in solution (right) by forming covalent crosslinks in the regions of high force along the polymer backbone. Polymer chain scission also occurs, but is not shown for clarity. The fraction of PB monomer (subscript *a* in the chemical formulae) remained constant throughout either experiment, and the fraction of *g*DBC mechanophore (*b*) decreases to (*d*) because of activation to the 2,3-dibromoalkene (*e*). A portion of the activated mechanophores reacts to form crosslinks (*c*). **b**, FTIR spectra overlay of the initial **ARM-1** polymer (**ARM-1^{a}**, blue), the **ARM-1** polymer extruded (**ARM-1^{b}**, purple) and the same **ARM-1** polymer one week post-extrusion (**ARM-1^{c}**, black). The dotted lines designate the precursor carboxylate absorbance peak at 1,571 cm^{-1} (blue) and the product ester absorbance peak at 1,721 cm^{-1} (purple). **c**, Sonication of **ARM-1** leads to fronting in the GPC trace, indicative of the early stages of network formation. a.u., arbitrary units.

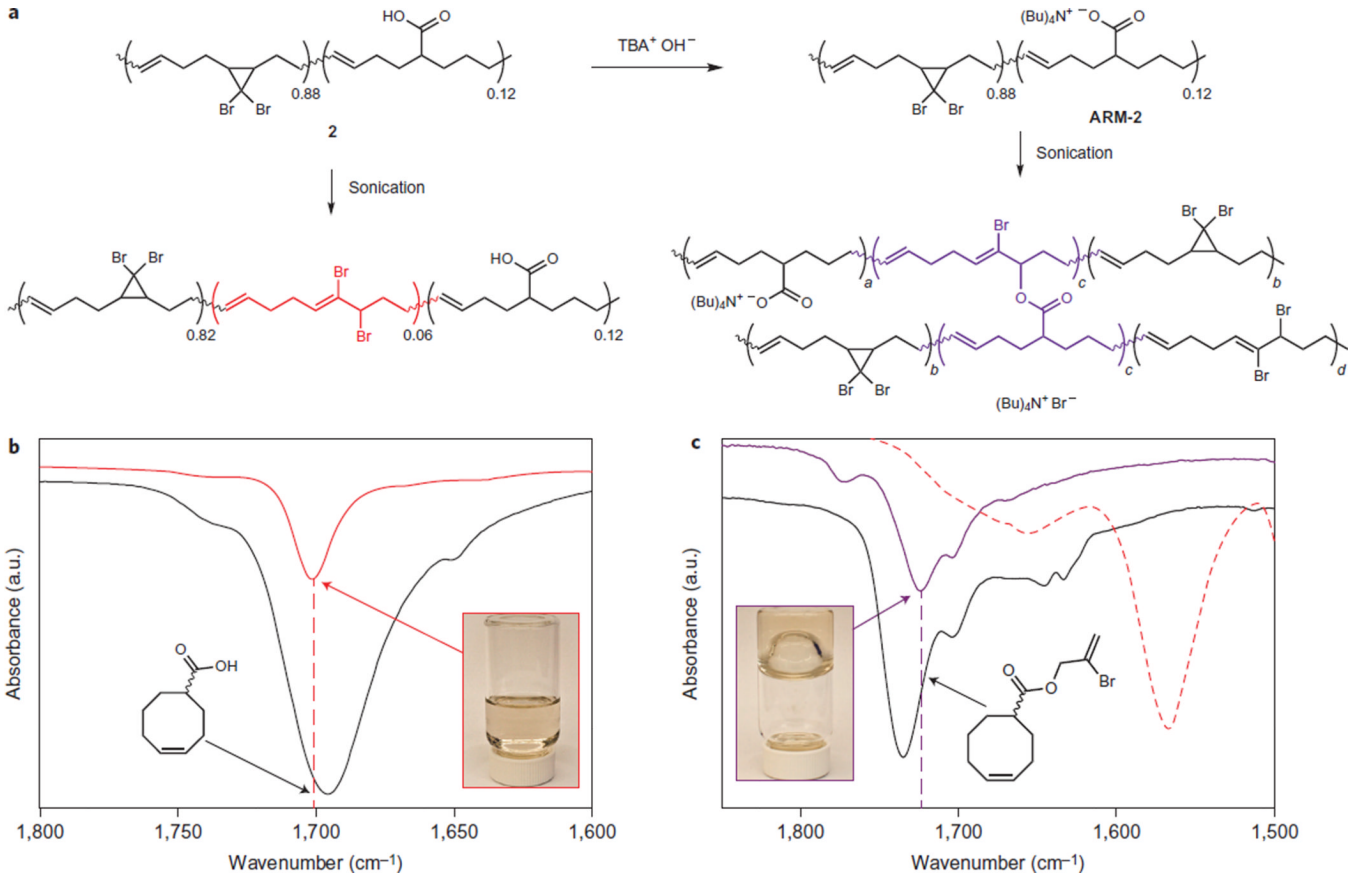

Figure 3. Chemistry and response of a single-component ARM system

a, Treatment of **2** with $TBA^+ OH^-$ leads to the **ARM-2** system. Sonication of **2** leads to mechanochemical ring-opening of the mechanophore, but does not cause the carbonyl absorbance to shift from 1,701 cm^{-1} in FTIR (**b**, red), which matches the model compound absorbance (**b**, black). Sonication of **ARM-2**, however, leads to covalent crosslinking and gelation through ester formation as indicated by the carbonyl absorbance at 1,724 cm^{-1} (**c**, purple), in agreement with a small molecule model compound (**c**, black). Shown for contrast in **c** is the infrared spectrum of the TBA carboxylate of the model compound (dashed red line). Polymer main-chain scission also occurs in both cases, but is not shown for clarity.