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Cooperative reduction of various RAFT polymer terminals using hydrosilane and thiol via polarity reversal catalysis

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Cooperative reduction of thiocarbonylthio terminal of polymers obtained by RAFT polymerization was investigated using a catalytic amount of thiol as a polarity reversal catalyst in conjunction with hydrosilane as a reducing agent. A combination of C₁₂H₂₅SH and Ph₃SiH enabled the complete removal of xanthate, dithiobenzoate, and trithiocarbonate groups from poly(vinyl acetate), polystyrene, and poly(methyl acrylate) in the radical conditions.

Although a radical species is neutral, a radical reaction is affected by the polarity of the radical and substrate. Namely, a nucleophilic radical tends to react with an electron-deficient substrate, and vice versa. Therefore, catalysts that can switch or reverse the polarity of components are referred to as polarity reversal catalysts and efficiently work to facilitate a radical reaction. Thiol is a representative that is employed for efficient hydrogenation or reduction of a haloalkane as the substrate with a hydrosilane as the apparent reducing agent.^{1–3} In this reaction, the polarity of a hydrogen atom is changed from the electron-rich state on silicon to the electron-deficient state on sulfur via a delivery process induced by the catalysis between thiol and thiyl radical. Thiol can thus catalytically provide an electron-deficient hydrogen to the nucleophilic alkyl radical to catalyze the reduction of haloalkane with hydrosilane. However, this switchable catalysis has not been employed in polymer chemistry despite its effectiveness in various organic radical reactions.

Among various living/controlled radical polymerizations, which are effective for preparation of an extensive range of functional polymer materials, reversible addition-fragmentation chain transfer (RAFT) polymerization using a thiocarbonylthio compound (R–SC(S)Z) as the degenerative chain-transfer agent is most versatile for almost all radically polymerizable monomers, including styrenes, (meth)acrylates, acrylamides,

acrylonitrile, vinyl esters, and vinyl amides.⁴ Irrespective of various advantages of the thiocarbonylthio-mediated RAFT process, i.e., no metal catalysts, high tolerance to polar functional group, and versatility of monomers, the remaining thiocarbonylthio moiety at the chain end of the resulting polymers often causes problems, such as color, odor, and thermal instability of the products. Therefore, removal of the thiocarbonylthio moiety from the resulting polymer chain end is one of the most important targets in the RAFT process regarding its application.^{5–9} Although various transformation reactions of the thiocarbonylthio groups are possible, the reduction of ~C–SC(S)Z to ~C–H is often desirable due to its high stability.

Reduction of the terminal thiocarbonylthio group (~C–SC(S)Z) to hydrogen (~C–H) has been investigated using various reducing agents (X–H) in the presence of a radical source primarily for polyacrylates, polymethacrylates, polyacrylamides, and polystyrene (PSt), which are derived from conjugated monomers.^{10–15} Among the reducing agents, tributyltin hydride or tributylstannane (*n*-Bu₃SnH) is the most effective, whereas its toxicity and the complex byproducts are often problematic. While *N*-ethylpiperidine hypophosphite (EPHP) is the second best, its large 5–20-fold excess over the thiocarbonylthio moiety is required for complete removal.¹⁰ For poly(vinyl acetate) (PVAc), only one short result was obtained using *n*-Bu₃SnH.¹⁵ Recently, UV and visible lights were utilized in the presence or absence of photocatalysts to activate the terminal C–SC(S)Z bond of polymers of mostly conjugated monomers for more efficient reduction using appropriate reducing agents in mild conditions.^{16–18}

In this study, we examined the availability of polarity reversal or switching catalysis for reduction of the thiocarbonylthio polymer terminal with a hydrosilane as the apparent reducing agent in conjunction with a thiol as the polarity reversal catalyst using a radical initiator or light as the radical generator. Specifically, not only PSt and poly(methyl acrylate) (PMA) but also PVAc with thiocarbonylthio terminal were prepared using appropriate RAFT agents (dithiobenzoate, trithiocarbonate, and xanthate) and then reacted with

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Table 1 Cooperative reduction of RAFT terminal of poly(vinyl acetate), polystyrene, and poly(methyl acrylate)

entry	polymer-RAFT group	radical source	$[C_{12}H_{25}SH]_0/[RAFT\ group]_0$	time (h)	hydride terminal or removal of RAFT group (%) ^a	$M_n(SEC)^b$	M_w/M_n^b
1	PVAc-xanthate ^c	AIBN ^d	0.50	12	96	4500	1.14
2	PVAc-xanthate ^c	AIBN ^d	0	130	6	4600	1.14
3	PVAc-xanthate ^c	AIBN ^d	2.0	130	6	4700	1.14
4	PVAc-xanthate ^c	TPO/blue LED ^e	0.50	4	>99	4900	1.13
5	PVAc-xanthate ^c	UV LED ^f	0.50	160	>99	4500	1.15
6	PSt-dithiobenzoate ^g	AIBN ^d	0.50	140	43	5400	1.08
7	PSt-dithiobenzoate ^g	TPO/blue LED ^e	0.50	30	>99	5800	1.17
8	PSt-dithiobenzoate ^g	UV LED ^f	0.50	120	>99	5600	1.11
9	PMA-trithiocarbonatete ^h	AIBN ^d	0.50	120	68	3000	1.08
10	PMA-trithiocarbonatete ^h	TPO/blue LED ^e	0.50	170	98	3100	1.11
11	PMA-trithiocarbonatete ^h	UV LED ^f	0.50	75	>99	2900	1.10

^a Determined by ¹H NMR. ^b Determined by SEC. ^c $[RAFT\ group]_0/[Ph_3SiH]_0 = 40/80$ mM in toluene, PVAc-xanthate: $M_n = 4600$, $M_w/M_n = 1.13$. ^d $[AIBN]_0 = 20$ mM at 80 °C. ^e $[TPO]_0 = 20$ mM under blue LED (470 nm, 70 mW/cm²) at 20 °C. ^f UV LED (365 nm, 0.70 mW/cm²) at 80 °C. ^g $[RAFT\ group]_0/[Ph_3SiH]_0 = 20/40$ mM in toluene, PSt-dithiobenzoate: $M_n = 5300$, $M_w/M_n = 1.07$. ^h $[RAFT\ group]_0/[Ph_3SiH]_0 = 40/80$ mM in toluene, PMA-trithiocarbonate: $M_n = 2900$, $M_w/M_n = 1.09$.

hydrosilane (Ph_3SiH and Et_3SiH) coupled with *n*-dodecanethiol ($C_{12}H_{25}SH$) in various conditions, where the radical species was generated from a thermal radical initiator (2,2'-azobisisobutyronitrile (AIBN)), a photo radical initiator (biphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO)) under blue LED irradiation, or directly from the polymer terminal under UV LED irradiation (Scheme S1).

To demonstrate the efficacy of polarity reversal catalysis, we focused on the reduction of the xanthate terminal of PVAc, which has been performed only with *n*-Bu₃SnH.¹⁵ In this study, PVAc-xanthate was prepared using a bifunctional R-type RAFT agent (**1**) (Fig. S1), which generates a vinyl ether-type radical in the presence of AIBN. The obtained PVAc had controlled molecular weights ($M_n = 4600$, $M_w/M_n = 1.13$; M_n : number-average molecular weight, M_w : weight-average molecular weight) and well-defined chain-end groups (Fig. S2). This result is the first result in which the RAFT agent that generates the vinyl ether-derived radical is effective for controlling VAc as in the previously reported for radical copolymerization of VAc and vinyl ether.¹⁹

The reduction of the obtained PVAc-xanthate was examined using the 2-fold excess of Ph_3SiH over the xanthate moiety in conjunction with a low amount of $C_{12}H_{25}SH$ in the presence of AIBN as a radical source at 80 °C

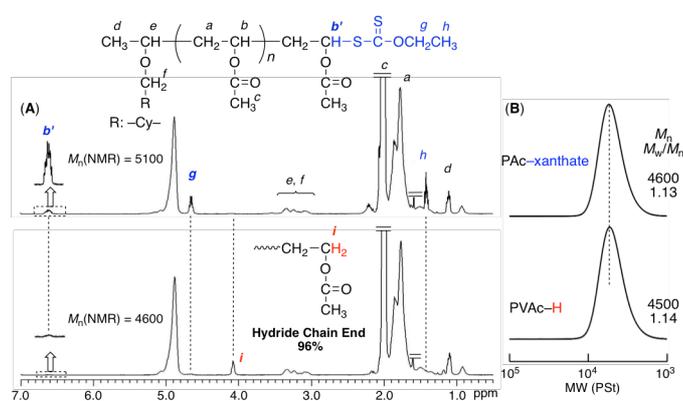
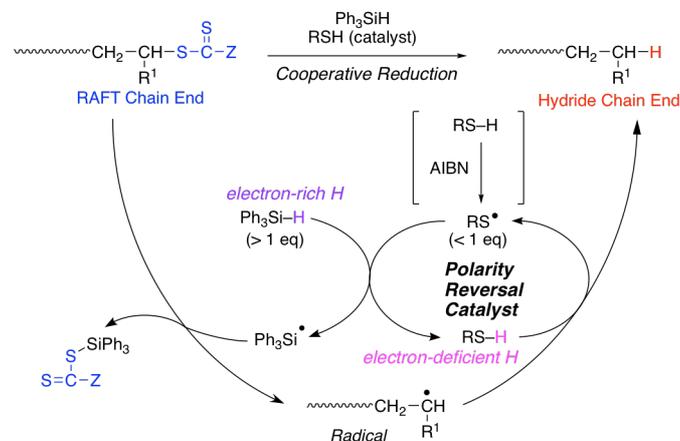


Fig. 1 ¹H NMR spectra (A) and SEC curves (B) for reduction of PVAc-xanthate: $[xanthate]_0/[Ph_3SiH]_0/[C_{12}H_{25}SH]_0/[AIBN] = 40/80/20/20$ mM in toluene at 80 °C.

($[xanthate]_0/[Ph_3SiH]_0/[C_{12}H_{25}SH]_0/[AIBN]_0 = 40/80/20/20$ mM). The reduction proceeded smoothly and almost quantitatively (96%) in 12 h (Fig. S3). As shown in ¹H NMR spectra of the polymers, the peak of methine proton (*b'*) adjacent to xanthate at 6.6 ppm disappeared and a new peak of methylene protons of the hydrogenated PVAc chain end (*i*) appeared at 4.1 ppm (Fig. 1A). In addition, almost no changes were observed in the size-exclusion chromatography (SEC) curves and the M_n and M_w/M_n values during the reaction (Fig. 1B). These results indicate that the reduction of the PVAc-xanthate chain end successfully occurred using Ph_3SiH and $C_{12}H_{25}SH$ in the presence of AIBN without any undesirable side reactions (entry 1 in Table 1).

Conversely, reduction only with either of the hydrides, namely, solely Ph_3SiH or $C_{12}H_{25}SH$, was unsuccessful (<10%) even in the same conditions with AIBN (entries 2 and 3 in Table 1 and Fig. S3 and S4). Therefore, both hydrosilane and thiol are necessary for efficient reduction of the thiocarbonylthio polymer terminal.

Analogous with the reduction of haloalkane with hydrosilane in conjunction with thiol, we speculate the reaction mechanism, as shown in Scheme 1. The reaction is triggered by the AIBN-derived radical, which abstracts hydrogen from thiol



Scheme 1 Proposed mechanism of cooperative reduction using hydrosilane and a catalytic amount of thiol.

to generate the thiyl radical. The electrophilic thiyl radical efficiently abstracts electron-rich hydrogen from Ph_3SiH to afford the silyl radical. The silyl radical is sulfurphilic to efficiently remove the thiocarbonylthio group from the polymer terminal to produce the carbon-centered polymer radical. Since thiol is an excellent chain-transfer agent in the radical polymerization of VAc,⁴ the resulting PVAc radical efficiently abstracts electron-deficient hydrogen from thiol to produce a hydrogenated polymer terminal and regenerate the thiyl radical, which starts another catalytic cycle. Thus, thiol catalytically functions for the reduction of the thiocarbonylthio terminal in collaboration with hydrosilane as the reducing agent.

To clarify the cooperative or concerted reduction mechanism, a model compound of PVAc-xanthate, i.e., VAc unimer with the same xanthate (*S*-1-acetoxyethyl *O*-ethyl xanthate: **2**) (Fig. S5), was prepared and employed for the reduction with Ph_3SiH in conjunction with a catalytic amount of $\text{C}_{12}\text{H}_{25}\text{SH}$ in the presence of AIBN in toluene-*d*₈, where the reaction was directly monitored by ¹H NMR. As occurs the reduction of PVAc, a new peak was assignable to the methylene proton that was generated via the reduction of **2** with a decrease in methine proton adjacent to xanthate (Fig. S6), which indicates that the reduction similarly occurred for **2** (Fig. S7). In addition, other new peaks were observed at 4.0 ppm, 5.0 ppm, and 7.7 ppm, which can be assignable to triphenylsilyl xanthate ($\text{Ph}_3\text{Si}-\text{SC}(\text{S})\text{OEt}$) that was generated via removal of xanthate by the silyl radical, although this product was unstable in these conditions. Since the sole reduction by Ph_3SiH was not effective, these model reactions support the cooperative reduction mechanism catalyzed by $\text{C}_{12}\text{H}_{25}\text{SH}$, which switches the polarity of hydrogen via the delivery from silicon to sulfur.

The effect of decreasing the catalytic amount of thiol was investigated for PVAc-xanthate, where $\text{C}_{12}\text{H}_{25}\text{SH}$ was decreased from 0.50 eq to 0.25 and 0.10 eq to the xanthate group (entries 1 and 2 in Table S1). The reduction proceeded sufficiently (90%) even with 0.25 eq of $\text{C}_{12}\text{H}_{25}\text{SH}$ to xanthate, whereas a further decrease of thiol to 0.10 eq caused inefficient reduction (68%). Et_3SiH was employed instead of Ph_3SiH but was not efficient (20%) due to a hydrogen donor that was less efficient than Ph_3SiH (entry 3 in Table S1), as previously reported.¹⁰

The photo-induced processes were investigated for more efficient reduction in milder conditions. TPO was employed as a photo radical initiator under blue LED (470 nm, 70 mW/cm²) at a lower temperature (20 °C) in conjunction with Ph_3SiH and $\text{C}_{12}\text{H}_{25}\text{SH}$. The reduction proceeded much faster and completely (>99%) in 4 h to produce the hydrogenated chain end without any trace of the xanthate moiety in the polymer (entry 4 in Table 1 and Fig. S9 and S10). No substantial reaction (3% in 4 h) without TPO in dark at 20 °C indicates the radical pathway. In addition, direct activation of PVAc-xanthate by UV irradiation (365 nm, 0.70 mW/cm²) without any radical initiators also enabled a quantitative reduction (>99%) with Ph_3SiH and $\text{C}_{12}\text{H}_{25}\text{SH}$ as indicated by ¹H and MALDI-TOF-MS spectra (entry 5 in Table 1 and Fig. S9–S11). The photo-induced reaction was more effective for the cooperative reduction.

Versatility of the reduction with hydrosilane and thiol was examined for other polymers with other thiocarbonylthio chain ends. PSt with dithiobenzoate terminal was prepared ($M_n = 5300$, $M_w/M_n = 1.07$) by RAFT polymerization of St using cumyl dithiobenzoate (**3**) as the RAFT agent (Fig. S12).²⁰ The reduction of PSt-dithiobenzoate was examined using the combination of Ph_3SiH and $\text{C}_{12}\text{H}_{25}\text{SH}$ and a series of conditions that were similar to those employed for PVAc-xanthate (entries 6–8 in Table 1). Because methylene peaks of the hydrogenated PSt terminal were overlapped with the large main-chain methine peaks (Fig. S12A), the reduction was evaluated by a decrease in the methine peaks of the dithiobenzoate terminal at 4.8 ppm.

When using AIBN as a radical source for PSt-dithiobenzoate, the removal was slow and incomplete (Fig. S13A and S14) in the same conditions for PVAc-xanthate. Conversely, both photo-induced systems, i.e., TPO/blue LED and UV LED, enabled complete removal of the dithiobenzoate moiety (>99%) (Fig. S13A and S14). However, the SEC curves showed a small shoulder peak, which has almost double the molecular weight of the main peaks (Fig. S13B) and can be assigned to coupling of the PSt radical, as previously reported using different methods.¹⁰ Although a small amount of coupling byproducts forms, the cooperative reduction by Ph_3SiH and $\text{C}_{12}\text{H}_{25}\text{SH}$ also efficiently works in the removal of the dithiobenzoate terminal from PSt, especially under photo irradiations.

PMA with trithiocarbonate terminal (PMA-trithiocarbonate) ($M_n = 2900$, $M_w/M_n = 1.09$) (Fig. S15) was prepared using *S*-2-cyano-2-propyl *S'*-2-ethyl trithiocarbonate (**4**)²¹ and subjected to the reductions in similar conditions (entries 9–11 in Table 1 and entries 4–6 in Table S1). The reduction was similarly evaluated by a decrease in the terminal methine peaks of PMA-trithiocarbonate at 4.9 ppm due to overlapping of the methylene peaks of the hydrogenated PMA terminal with the large main-chain methylene peaks (Fig. S16A).

The binary hydrides, Ph_3SiH and $\text{C}_{12}\text{H}_{25}\text{SH}$, enabled

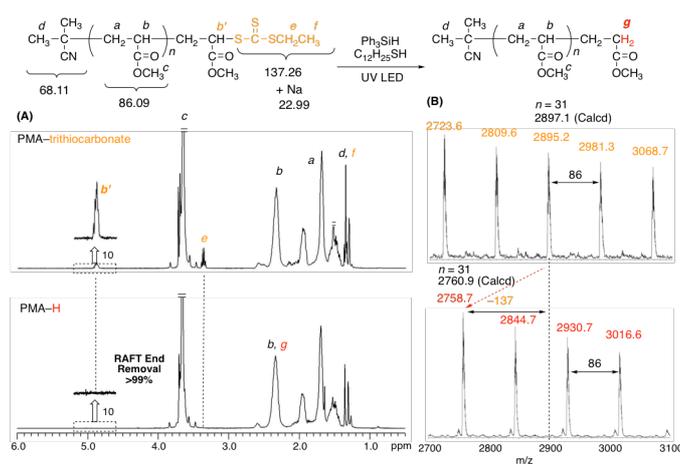


Fig. 2 ¹H NMR (A) and MALDI-TOF-MS spectra (B) for cooperative reduction of PMA-trithiocarbonate: $[\text{trithiocarbonate}]_0/[\text{Ph}_3\text{SiH}]_0/[\text{C}_{12}\text{H}_{25}\text{SH}]_0 = 40/80/40$ mM in toluene at 80 °C under UV LED (365 nm, 0.70 mW/cm²).

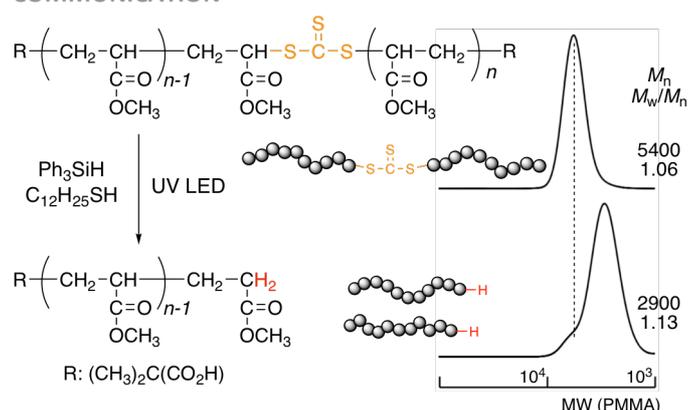


Fig. 3 SEC curves for reduction of PMA-trithiocarbonate-PMA: 2[trithiocarbonate]₀/[Ph₃SiH]₀/[C₁₂H₂₅SH]₀ = 40/80/40 mM in toluene at 80 °C under UV LED (365 nm, 0.70 mW/cm²).

efficient reductions (>90%) of the PMA-trithiocarbonate terminal for all conditions using AIBN, TPO/blue LED, and UV LED (Fig. S17 and S18), with the exception of the case with AIBN and a small amount of C₁₂H₂₅SH (entry 9 in Table 1). UV LED induced a complete reduction, which is indicated by the ¹H NMR and MALDI-TOF-MS spectra (Fig. 2) without any significant coupling byproducts, as shown in the SEC curves (Fig. S16).

To further demonstrate the efficient reduction, PMA that possesses a trithiocarbonate in the middle of the chain (PMA-trithiocarbonate-PMA) was synthesized ($M_n = 5400$, $M_w/M_n = 1.06$) by RAFT polymerization of MA using a Z-type bifunctional RAFT agent (**5**)²² (Fig. S19) and was subjected to the reduction using Ph₃SiH and C₁₂H₂₅SH under UV LED. The complete removal was confirmed by disappearance of the methine proton adjacent to the trithiocarbonate group (Fig. S20). After the reduction, the SEC curve shifted to a low-molecular-weight region to produce the polymer (Fig. 3), which has approximately half of the original molecular weight and similarly narrow MWDs ($M_n = 2900$, $M_w/M_n = 1.13$), which indicates that PMA-trithiocarbonate-PMA was cleaved at the middle of the chain due to the complete removal of trithiocarbonate, though a slight amount of coupling byproducts were observed. These results demonstrate that a combination of Ph₃SiH and C₁₂H₂₅SH is also effective for removal of trithiocarbonate from the PMA terminal.

The cooperative reduction induced by polarity reversal catalysis of thiol for hydrosilane is effective for removal of various thiocarbonylthio groups, including xanthate, dithiobenzoate, and trithiocarbonate, from the chain ends of an extensive range of vinyl polymers, such as poly(vinyl acetate), polystyrene, and polyacrylates. The effective radical triggers include thermal radical initiator, photo radical initiator under blue LED, and UV LED, among which photo-induced systems are more efficient. This method can contribute to further development and improvement of polymer materials based on RAFT polymerization for industrial and biological applications.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- R. P. Allen, B. P. Roberts and C. R. Willis, *J. Chem. Soc., Chem. Commun.* 1989, 1387–1388.
- S. J. Cole, N. K. Kirwan, B. P. Roberts and C. R. Willis, *J. Chem. Soc. Perkin Trans. 1* 1991, 103–112.
- B. P. Roberts, *Chem. Soc. Rev.* 1999, **28**, 25–35.
- G. Moad and D. H. Solomon, *The Chemistry of Radical Polymerization*, 2nd ed.; Elsevier Science: Oxford, UK, 2006.
- G. Moad, E. Rizzardo and S. T. Thang, *Polym. Int.* 2011, **60**, 9–25.
- G. Moad, Y. K. Chong, A. Postma, E. Rizzardo and S. H. Thang, *Polymer* 2005, **46**, 8458–8468.
- C. Boyer, V. Bulmus, T. P. Davis, V. Ladmiraal, J. Liu and S. Perrier, *Chem. Rev.* 2009, **109**, 5402–5436.
- H. Willcock and R. K. O'Reilly, *Polym. Chem.* 2010, **1**, 149–157.
- G. Moad, M. Chen, M. Häussler, A. Postma, E. Rizzardo and S. H. Thang, *Polym. Chem.* 2011, **2**, 492–519.
- Y. K. Chong, G. Moad, E. Rizzardo and S. H. Thang, *Macromolecules* 2007, **40**, 4446–4455.
- M. Chen, K. P. Ghiggino, S. H. Thang, J. White and G. J. Wilson, *J. Org. Chem.* 2005, **70**, 1844–1852.
- A. Postma, T. P. Davis, R. A. Evans, G. Li, G. Moad and M. S. O'Shea, *Macromolecules* 2006, **39**, 5293–5306.
- C. H. Hornung, A. Postma, S. Saubern and J. Chiefari, *Macromol. React. Eng.* 2012, **6**, 246–251.
- A. O. Moughton, K. Stubenrauch and R. K. O'Reilly, *Soft Matter* 2009, **5**, 2361–2370.
- Y.-Y. Tong, Y.-Q. Dong, F.-S. Du and Z.-C. Li, *J. Polym. Sci.: Part A: Polym. Chem.* 2009, **47**, 1901–1910.
- K. M. Mattson, C. W. Pester, W. R. Gutekunst, A. T. Hsueh, E. H. Discekici, Y. Luo, B. V. K. J. Schmidt, A. J. McGrath, P. G. Clark and C. J. Hawker, *Macromolecules* 2016, **49**, 8162–8166.
- E. H. Discekici, S. L. Shankel, A. Anastasaki, B. Oshmann, I.-H. Lee, J. Niu, A. J. McGrath, P. G. Clark, D. S. Laitar, J. R. de Alaniz, C. J. Hawker and D. J. Lunn, *Chem. Commun.* 2017, **53**, 1888–1891.
- R. N. Carmean, C. A. Figg, G. M. Scheutz, T. Kubo and B. S. Summerlin, *ACS Macro Lett.* 2017, **6**, 185–189.
- K. Satoh, Y. Fujiki, M. Uchiyama and M. Kamigaito, *ACS Symp. Ser.* 2018, **1284**, 323–334.
- G. Moad, J. Chiefari, Y. K. Chong, J. Krstina, R. T. A. Mayadunne, A. Postma, E. Rizzardo and S. H. Thang, *Polym. Int.* 2000, **49**, 993–1001.
- K. Ishitake, K. Satoh, M. Kamigaito and Y. Okamoto, *Angew. Chem. Int. Ed.* 2011, **48**, 1991–1994.
- J. Lai, D. Filla and R. Shea, *Macromolecules* 2002, **35**, 6754–6756.