This is an *Accepted Manuscript*, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this *Accepted Manuscript* with the edited and formatted *Advance Article* as soon as it is available.

You can find more information about *Accepted Manuscripts* in the **Information for Authors**.

Journal Name

COMMUNICATION

Initiator-Chain Transfer Agent Combo in the RAFT Polymerization of Styrene

Ying Wu, Wei Zhang, Zhengbiao Zhang, Xiangqiang Pan, Zhenping Cheng, Jian Zhu*, and Xiulin Zhu*

The combo agent with roles of initiator and chain transfer agent was demonstrated in RAFT polymerization of styrene. Polymers with defined structures at both α and ω ends were obtained, which was verified by the successful synthesis of seven-block segments of PS and PMA by sequential addition of monomers in one pot.

Reversible addition fragmentation chain transfer (RAFT) as one of reversible deactivation radical polymerization (RDRP) [1] methods, has been well known for its versatility in terms of monomer choice, polymer architectures and reaction conditions, and has been used to synthesize various polymers with complex topologies such as block copolymer, star polymer, comb copolymer, hyperbranched polymer, and cyclic polymer. [2, 3] According to the mechanism of RAFT, the polymerization was initiated by external radicals, which can be created by radical initiator, heat or light, *etc.*[4] As the result, the polymers obtained by RAFT would contain some polymer chain derived from the initiating radicals which has initiator moiety at the α-end. Thus, it was difficult to synthesize polymers with predetermined α-end structure polymers through RAFT except for the use of same structured R group in RAFT agent with initiator, for example 2-cyanoprop-2-yl dithionaphthalenoate and azodiisobutyronitrile.[5] It was considered that the preparation of polymers with high end functionality in both ends was important for their applications, especially in functional polymer or further modification such as the synthesis of cyclic polymers etc.[6] Yamago *et al.* [7] first quantitatively analysed the polymer obtained from RAFT polymerization initiated with azo initiators. It was found that in case of styrene and isoprene, serious situation was found. The percentage of polymer with initiator derived α-end structure was increased to as high as 5~12% in most of the cases. Thus it would be valuable to explore the way for synthesis polymers with predetermined α-end structure through RAFT.

The most convenient way to improve the degree of α-end structure controllability in RAFT polymerization was excluded the use of external initiation species. Quinn *et al.*[8] reported RAFT polymerization of styrene and MMA under UV radiation using RAFT agent as the source of primary radicals at 42 ℃. However, the polymerization only showed controlled in low conversion (<40%). Kwark *et al.*[9] synthesized a xanthate as a radical source and chain transfer agent simultaneously in the photo-initiated RAFT polymerization. But it was only used for the polymerization of vinyl acetate.

Furthermore, the requirement of external initiator in RAFT polymerization would limit the application in the synthesis of multiblock copolymer. Although there were some examples in literature for the synthesis of multiblock copolymers using RDRP techniques,[10] such copolymer was difficult to prepare by RAFT till now, especially in case of the multiblock copolymer containing block components more than three. Recently, Perier *et al.* [11] successfully realized the synthesis of acrylamide based multiblock copolymer (20 blocks) through RAFT polymerization after optimized the monomer, initiator and polymerization conditions. However, the synthesis of multiblock copolymer based on other monomers in RAFT polymerization still remains as a challenge.

Considered that the external primary radicals in RAFT polymerization showed negative effect on controlling the structure of final polymers. It would be valuable to combine the initiator structure with dithiocarbonyl structure together for the benefits of excluding external radicals accompanied with the minimal disturb of the RAFT polymerization. Recently, we synthesized a combo agent(X6) with an azo initiator structure and a trithiocarbonyl agent through the esterification reaction showed in Scheme 1. The structure of X6 was confirmed by NMR, EA, and MS which was shown in the experimental section (as shown in Fig. S1~4. ESI†). Furthermore, the half-life of X6 was measured as 4.99 h by Thermo Gravimetric Analyzer at 60℃ (as shown in Fig. S5. ESI†). The preparation of polystyrene (PSt), polymethacrylate (PMA), and poly(N-isopropylacrylamide) (PNIPAM), were performed using X6 as initiator and chain transfer agents combo at 60 ℃ in bulk or

solution. The polymerization conditions and results were summarized in Table 1. It showed that the molecular weight of polymers could be controlled by both of the molar ratio of monomer to X6 and the conversion. The molecular weight distribution of obtained polymers was narrow ($M_w/M_n < 1.21$)
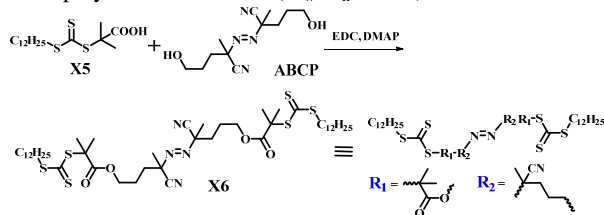
Scheme 1 The synthesis of diazene-1, 2-diylbis(4-cyanopentane-4,1-diyl) bis(2-(((dodecylthio)carbonothioyl)thio)-2-methylpropanoate) (X6)

Table 1 Molecular weight/conversion data for polymers obtained by polymerization of various monomers in the presence of X6 at 60 °C in bulk.

Entry	Monomer	Time (h)	Conv. (%)	$M_{n,th}^{a}$ (g/mol)	$M_{n,NMR}^{c}$ (g/mol)	$M_{n,GPC}$ (g/mol)	M_w/M_n
1	St	24	64.1	13400	12500	12700	1.11
2	St	24	45.3	23500	23300	22500	1.15
3	MA	3	62.0	10700	15600	17000	1.09
4	MA	3	64.8	27900	32100	33100	1.17
[b]5	NIPAM	12	71.3	40400	55400	47800	1.28

$^{a}M_{n, th} = ([\text{Monomer}]_0/[X6]_0) \times M_{monomer} \times \text{conversion} \%$. ^{b} in toluene with the concentration of 2 M. $[M]_0 : [X6]_0$ of entry 1 and 3 is 200 : 1 , $[M]_0 : [X6]_0$ of entry 2, 4, 5 is 500 : 1. For PSt, $^{c}M_{n, NMR} = M_{St} \times [(I_{6.2-7.4}/5)/(I_{3.16-3.32}/4)] + 735.34$. For PMA, $^{c}M_{n, NMR} = M_{MA} \times [(I_{3.50-3.80}/3) / (I_{3.16-3.32}/4)] + 735.34$. For PNIPAM, $^{c}M_{n, NMR} = M_{NIPAM} \times [I_{6.80-8.0} / (I_{3.16-3.32}/4)] + 735.34$. 735.34 was the mass of moiety derived from X6.

To confirm the "living" character of current system, the polymerization kinetic of St in the presence of X6 was investigated in bulk at 60 °C with the $[St]_0:[X6]_0$ ratio of 400:1. The result in Fig. 1(a) showed linear relationship between ln $([M]_0/[M])$ and polymerization time, which implied the successfully maintaining of constant propagating radicals during the polymerization process in the presence of X6. Linear increasing of molecular weight with the conversion was also found during the polymerization, which was showed in Fig. 1(b). The polymers showed narrow molecular weight distribution. The high end functionality was verified by the chain extension experiment. Fig. 2 showed the GPC traces of polymers before and after the chain extension. Further investigation of the polymerization under different molar ratio between St and X6 was carried out (Table S1, ESI†). It showed that X6 acted as a good controlling agent of the polymerization in the ratio from as high as 2000:1 to 100:1 and leading to polymers with molecular weight close to that expected in wide range, e.g. from 4200 g/mol to 56700 g/mol and narrow molecular weight distribution ($M_w/M_n < 1.21$).

The structure of polymers was analyzed to explore the efficiency of such polymerization system. The polymer was characterized by ^{1}H NMR spectroscopy in CDCl$_3$ (Fig. 3) and the structure of obtained PS was further characterized by MALDI-TOF (Fig. S6,

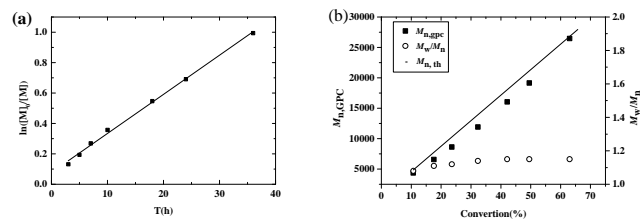see in the ESI†). MALDI-TOF analysis also gave data consistent with NMR.

Fig. 1 (a) ln($[M]_0/[M]$) as a function of polymerization time for bulk polymerization of St at 60 °C. (b) Dependence of M_n and M_w/M_n on monomer conversion. Polymerization conditions: $[St]_0:[X6]_0 = 400:1$, $[St]_0 = 0.5$ mL (4.35 mmol), $[X6]_0 = 10.5$ mg (0.0108 mmol).
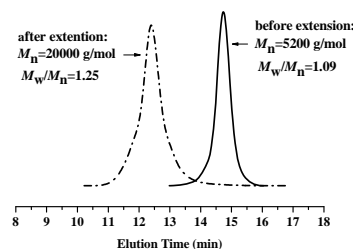

Fig. 2 GPC curves before and after chain extension with PS as the macroCTA at 110 °C. $[St]_0 : [PS]_0 = 200:1$, 72 h.
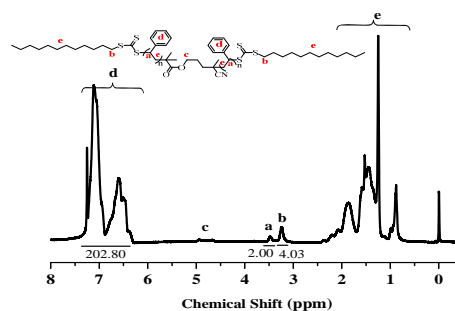

Fig. 3 ^{1}H NMR of spectrum of PS ($M_{n,GPC} = 5000$ g/mol, $M_w/M_n = 1.08$) with CDCl$_3$ as solvent and tetramethylsilane (TMS) as internal standard.
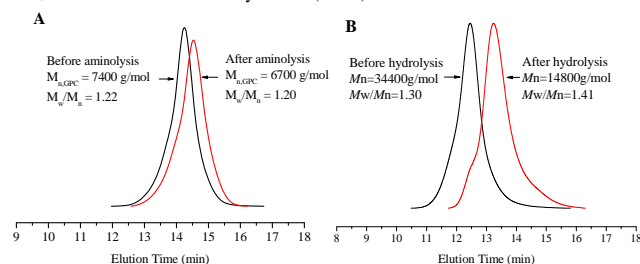

Fig. 4 The GPC traces of polymer before and after aminolysis and hydrolysis. A) before aminolysis, $M_{n,GPC} = 7400$ g/mol, $M_w/M_n = 1.22$, after aminolysis, $M_{n,GPC} = 6700$ g/mol, $M_w/M_n = 1.20$. B) before hydrolysis, $M_{n,GPC} = 34400$ g/mol, $M_w/M_n = 1.30$, after hydrolysis, $M_{n,GPC} = 14800$ g/mol, $M_w/M_n = 1.41$.

In order to investigate the mechanism of polymerization, the structure of obtained PS was further verified by decomposing under different conditions. Firstly, the bi-trithiocarbonate end groups were decomposed from PS by aminolysis using isopropyl amine according to reference.[12] The molecular weight of PS after aminolysis was reduced to 6700 g/mol from the original 7400 g/mol (as shown in Fig. 4A). The molecular weight loss of 700 was close

to the loss of two trithiocarbonate groups derived from Z group of X6 (M_n = 490 g/mol) after aminolysis, assuming that both ends of the PS was terminated by trithiocarbonate structures. The slight deviation between 700 and 490*2 may due to the different hydraulics size of the trithiocarbonate group with styrene in GPC conditions. Secondly, the obtained PS was decomposed by the sodium hydroxide solution. The GPC traces of PS before and after the hydrolysis was showed in Fig. 4B. The unimodal GPC trace was found after hydrolysis. The molecular weight of PS after hydrolysis was 14800 g/mol which was close to the half of original value (34400 g/mol). From above results, we proposed the possible polymerization mechanism (see in the Scheme S3, ESI†).

Table 3. Multiblock copolymerization of MA and St in the presence of X6 at 60 ℃ in toluene.

Run	M	t (h)	Conv. (%)	$M_{n,th}$	$M_{n,GPC}$	M_w/M_n	Copolymer
1	S	24	> 98	2000	2600	1.10	PS
2	MA	6	> 99	4600	6100	1.18	PMA-*b*-PS-*b*-PMA
3	S	24	> 99	6600	7900	1.20	PS-*b*-PMA-*b*-PS-*b*-PMA-*b*-PS
4	MA	6	> 99	9200	8500	1.40	PMA-*b*-PS-*b*-PMA-*b*-PS-*b*-PMA-*b*-PS-*b*-PMA

$[St]_0$ = 0.5 mL, $[MA]_0$ = 0.6 mL with the concentration of 2.9 M. The molar ratio between monomer and X6 or macro-X6 was: [St]:[X6] = 20:1, [MA]:[X6] = 30:1.

The current polymerization system was further applied to synthesize multiblock copolymer of MA and styrene for examining its efficiency by sequential monomer addition in one-pot. The results were summarized in Table 3. The results indicated that multiblock copolymer of MA and styrene with narrow molecular weight distribution was synthesized. The GPC trace of copolymer (as shown in Fig. 5) shifted to high molecular weight region step by step with the addition of monomer. The seven-block copolymer with molecular weight of 8500 g/mol and molecular weight distribution of 1.40 was obtained after three monomer adding steps, which highly improved the synthesis efficiency of multiblock copolymer by similar sequential monomer addition method using the normal RAFT agent.[13] However, due to the possible side reactions, the obtained multi-block copolymer was a mixture, which containing major of well-defined DCBA-ABCD and minor of DCBA-BCD, DCBA-CD, DCBA-D, DCBA, and more complicated polymers.

In this communication, the combo RAFT agent X6 combined initiator and dithiocarbonyl structure demonstrated a new efficient way for the synthesis of bi-trithiocarbonate end functionalized polymers. Such polymerization system showed effective for various monomers, styrene, methyl acrylate, and N-isopropylacrylamide. The detailed structure analysis revealed that the final polymer containing bi-trithiocarbonate end functional groups in high degree. The efficiency of current system was superior due to the bi-trithiocarbonate functional polymer formed during the polymerization, which offered an efficient way to synthesize multiblock copolymers, especially for the introducing of PS segment. Furthermore, the ester structure in the middle of polymer chain increasing the stability for further application compared to those polymers obtained by normal trithiocarbonate, which contained trithiocarbonate groups in the middle of polymer chain.
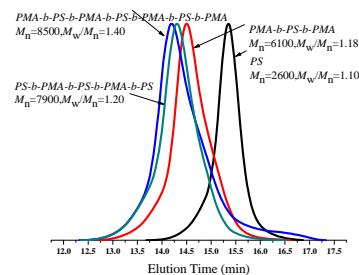

Fig. 5 The GPC trace of multi-block copolymer of MA and styrene synthesized by one-pot polymerization in the presence of X6 with sequential monomer adding at 60°C in toluene.

Notes and references

1   A. D. Jenkins, R. G. Jones and G. Moad, *Pure Appl. Chem.,* 2010, **82,** 483-491.

2   A. H. Soeriyadi, C. Boyer, J. Burns, C. R. Becer, M. R. Whittaker, D. M. Haddleton and T. P. Davis, *Chem. Commun.,* 2010, **46,** 6338-6340.

3   a) X. Zhu, N. C. Zhou, J. Zhu, Z. B. Zhang, W. Zhang, Z. P. Cheng, Y. F. Tu and X. L. Zhu, *Macro. Chem. Phys.,* 2013, **214,** 1107-1113; b) X. Zhu, N. C. Zhou, J. Zhu, Z. B. Zhang, W. Zhang, Z. P. Cheng, Y. F. Tu and X. L. Zhu, *Macro. Rapid Commun.,* 2013, **34,** 1014-1019.

4   G. Moad, E. Rizzardo and S. H. Thang, *Aust. J. Chem.,* 2012, **65,** 985-1076.

5   (a) J. Zhu, X. L. Zhu, Z. P. Cheng, F. Liu and J. M. Lu, *Polymer,* 2002, **43,** 7037-7042; (b) J. Cao, L. Zhang, X. Pan, Z. Cheng and X. Zhu, *Chin. J. Chem.,* 2012, **30,** 2138-2144.

6   H. Zhang, N. C. Zhou, X. Zhu, X. R. Chen, Z. B. Zhang, W. Zhang, J. Zhu, Z. J. Hu and X. L. Zhu, *Macro. Rapid Commun.,* 2012, **33,** 1845-1851.

7   Y. Nakamura, Y. Kitada, Y. Kobayashi, B. Ray and S. Yamago, *Macromolecules,* 2011, **44,** 8388-8397.

8   J. F. Quinn, L. Barner, C. Barner-Kowollik, E. Rizzardo and T. P. Davis, *Macromolecules,* 2002, **35,** 7620-7627.

9   M. Y. Khan, M.-S. Cho and Y.-J. Kwark, *Macromolecules,* 2014, **47,** 1929-1934.

10 (a) A. Anastasaki, C. Waldron, P. Wilson, C. Boyer, P. B. Zetterlund, M. R. Whittaker and D. Haddleton, *ACS Macro. Letters,* 2013, **2,** 896-900; (b) A. H. Soeriyadi, C. Boyer, F. Nystrom, P. B. Zetterlund and M. R. Whittaker, *J. Am. Chem. Soc.,* 2011, 133, 11128-11131; (c) C. Boyer, A. H. Soeriyadi, P. B. Zetterlund and M. R. Whittaker, *Macromolecules,* 2011, **44,** 6.

11 G. Gody, T. Maschmeyer, P. B. Zetterlund and S. Perrier, *Nat. Commun.,* 2013, 4.

12 J. Xu, J. He, D. Fan, X. Wang and Y. Yang, *Macromolecules*, 2006, **39,** 8616-8624.

13 G. Gody, T. Maschmeyer, P. B. Zetterlund and S. Perrier, *Macromolecules*, 2014, **47,** 639-649.