RAFT: A Smarter Way to Develop Multi-Functional Polymers

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ABSTRACT

The RAFT (Reverse Addition-Fragmentation chain Transfer) process is ground breaking technology offering unprecedented control over the composition, functionality and architecture of polymers formed by radical polymerization. The versatility of the RAFT technology provides enormous potential for the design and development of multi-functional polymers that are optimised for performance in a range of application areas that includes: suractants, coatings, electronics, nanomaterials, biomaterials, therapeutic delivery and personal care.

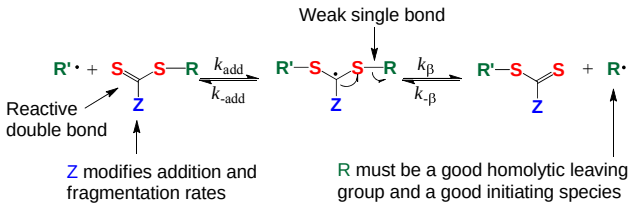
Keywords: RAFT, radical, polymerization

1 INTRODUCTION

RAFT is an acronym for Reversible Addition Fragmentation chain Transfer. It is a reversible deactivation radical polymerization (RDRP)[1] and arguably the most versatile method for providing living characteristics to radical polymerization.[2-7] The historical development of RAFT polymerization at CSIRO has been outlined in recent reviews.[3,6]

RAFT polymerization provides the ability to control polymerization of most monomers polymerizable by radical polymerization. These include (meth)acrylates, (meth)acrylamides, acrylonitrile, styrenes, dienes and vinyl monomers. It is tolerant of unprotected functionality in monomer and solvent (*e.g.* OH, NR_2, COOH, $CONR_2$, SO_3H). The process is compatible with a wide rage of reaction conditions (*e.g.* bulk, organic or aqueous solution, emulsion, miniemulsion, suspension). It is simple to implement and inexpensive in relation to competitive RDRP methods such as atom trabnsfer radical polymerization (ATRP) or nitroxide-mediate polymerization (NMP).

A mechanism for RAFT process is shown in Scheme 1. In an ideal living polymerization, all chains are initiated at the beginning of the process, grow at a similar rate and survive the polymerization (there is no irreversible chain transfer or termination). If initiation is rapid with respect to propagation the molecular weight distribution is very narrow and chains can be extended by the provision of further monomer. In a radical polymerization all chains cannot be simultaneously active. In RAFT polymerization, the majority of living chains are maintained in a dormant form. A rapid equilibrium between active (propagating radicals) and dormant chains (macroRAFT agents) ensures that all chains grow at a similar rate. Under these conditions, molecular weights can increase linearly with conversion and molecular weight distributions can be very narrow. The product of polymerization will comprise overwhelmingly dormant chains. It is a macroRAFT agent.



Scheme 1

The reactions associated with RAFT equilibria (Scheme 1) are in addition to those that occur during conventional radical polymerization (*i.e.* initiation, propagation and termination). The RAFT agent is a transfer agent and does not suppress termination. Retention of the thiocarbonylthio groups in the polymeric product is responsible for the living character of RAFT polymerization. RAFT polymerization can be used in the synthesis of well-defined homo-, gradient, diblock, triblock and star polymers and more complex architectures including microgels and polymer brushes. Many applications have been reported and are described in recent reviews.[8-10]

It is important to select the RAFT agent (ZC(=S)SR) according to the monomers being polymerized and reaction conditions. The effectiveness of RAFT agents is determined by the substituents R and Z and guidelines for selection have been proposed (Figure 1).[3,7] Dithioester and trithiocarbonate RAFT agents are appropriate for the polymerization of more activated monomers (MAMs) such as methyl methacrylate (MMA), methacrylic acid (MAA), hydroxypropyl methacrylamide (HPMAM), methyl acrylate (MA), acrylic acid (AA), acrylamide (AM), acrylonitrile (AN) and styrene (St). Xanthates and dialkyl dithiocarbamates are suited to the polymerization of less activated monomers (LAMs) such as vinyl acetate (VAc), *N*-vinylpyrrolidone (NVP) and *N*-vinylcarbazole (NVC). Recently, we reported 4-pyridinyl-*N*-methyldithiocarbamate derivatives that can be switched to allow control both MAMs and LAMs.[11,12]

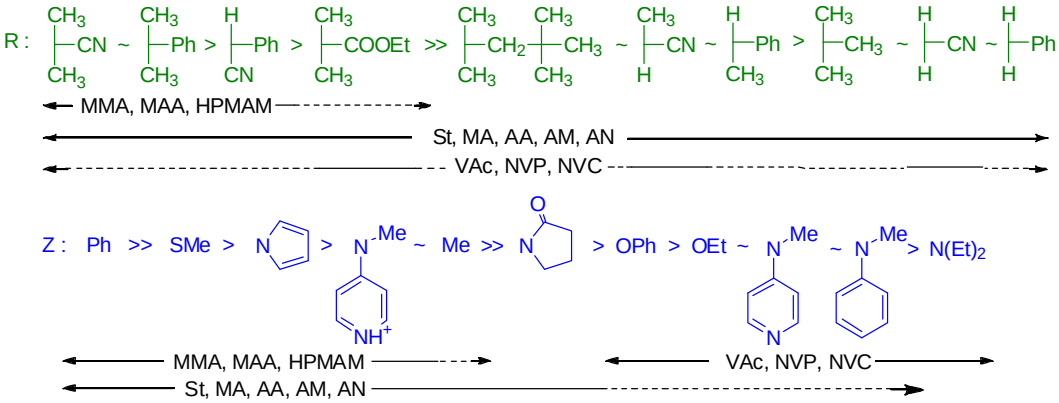
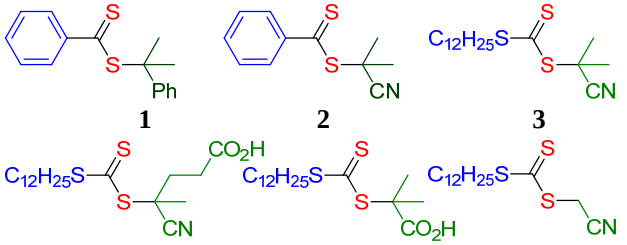


Figure 1. Guidelines for selection of RAFT agents (Z-C(=S)S-R) for various polymerizations [3,13] For 'Z', addition rates and transfer constants decrease and fragmentation rates increase from left to right. For 'R', fragmentation rates decrease from left to right. A dashed line indicates limited control (e.g., retardation, high dispersity likely).

2 RAFT POLYMERIZATION OF 'MORE-ACTIVATED' MONOMERS (MAMS)

Aromatic dithioesters (Z=aryl, e.g., **1**, **2**) are amongst the most active RAFT agents and have general utility in the polymerization of MAMs.[3,4] However, the latter RAFT agents may give retardation particularly when used in high concentrations and are more sensitive to hydrolysis and decomposition induced by Lewis acids. Trithiocarbonates (Z=S-alkyl, e.g., **3**-**6**) and also provide good control over polymerization of MAMs and have greater hydrolytic stability than the dithioesters. To avoid potential issues with odor, Z ishould be based on a thiol of low volatility..



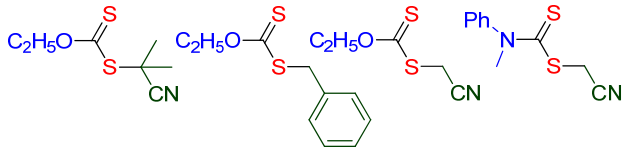
1 **2** **3**

4 **5** **6**

The choice of R is also important for good control. R must efficiently reinitiate polymerization and must be a good homolytic leaving group with respect to the propagating radical.[14] R· must also be efficient in reinitiating polymerization. The choice of 'R' is critical in the case of methacrylates. In some of the most effective RAFT agents R is tertiary cyanoalkyl (e.g., **2**-**4**). RAFT agents such as **5** and **6** are not suitable. A wider range of RAFT agents are suitable for controlling the polymerization of monosubstituted MAMs such as styrene, acrylates or acrylamides. The abovementioned RAFT agents (**1**-**4**) can be used and those where R is tertiary carboxylic acid (e.g**., 5**) or cyanomethyl (e.g., **6**) are also good choices for R for of these monomers.

3 RAFT POLYMERIZATION OF 'LESS-ACTIVATED MONOMERS' (LAMS)

Dithioesters and trithiocarbonates inhibit polymerization of LAMs. The less active RAFT agents with Z=NR'$_2$ (dithiocarbamates), Z=OR' (xanthates) where R' = alkyl or aryl offer good control over the polymerization of LAMs.



7 **8** **9** **10**

The choice of R group is also critical because most monomers in the class have a high propagation rate constant. In polymerization of VAc inhibition periods due to slow reinitiation are observed for RAFT agents such as **7** and **8** where R is benzyl or tertiary cyanoalkyl respectively. Some preferred RAFT agents are **9** and **10** where R is cyanomethyl.

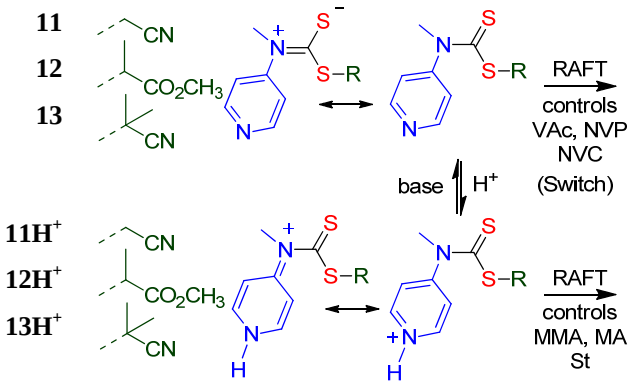
4 SWITCHABLE RAFT AGENTS

We recently reported on a new class of stimuli-responsive RAFT agents that can be "switched" to offer good control over polymerization of both MAMs and LAMs and thus a more convenient route to polyMAM-*block*-polyLAM with narrow molecular weight distributions.[11,12] This approach has been demonstrated with the use of 4-pyridinyl-*N*-methyldithiocarbamate derivatives (e.g., **11**-**13**) to prepare PMMA-*block*-PVAc[12] and PMA-*block*-PNVC[12] and PSt-*block*-PVAc.[11] The RAFT agents **11**-**13** provide effective control over polymerization of LAMs and, when protonated as **11H**$^+$-**13H**$^+$, also provide excellent control over the polymerization of MAMs.

5 REACTION CONDITIONS

The reaction conditions used for RAFT polymerization are those used for conventional radical polymerization. However, for optimal control of the RAFT process, it is important to pay attention to such factors as initiator

concentration and selection.[3] RAFT polymerization is usually carried out with conventional radical initiators. In principle, any source of radicals can be used but most often thermal initiators (*e.g.*, azobis(isobutyronitrile), potassium persulfate) are used. Styrene polymerization may be initiated thermally between 100-120 °C.



The initiator concentration and rate of radical generation in RAFT polymerization should be chosen to provide a balance between an acceptable rate of polymerization and an acceptable level of dead chains (radical-radical termination). One useful guideline is to choose conditions such that the target molecular weight is ~10% of that which would have been obtained in the absence of RAFT agent. The initiator concentration will usually be at least 5-fold less than the RAFT agent concentration. A common misconception is that it is necessary to use very low rates of polymerization in order to achieve narrow molecular weight distributions. Sometimes, using a high rate of polymerization and a correspondingly short reaction time can provide excellent results However, it is very important not to use prolonged reaction times when retention of the RAFT functionality is important. Once the monomer is fully converted, continued radical generation may still lead to formation of dead chains by termination and consequent loss of the thiocarbonylthio end group. Addition of initiator to a RAFT synthesized polymer is one recognized method for thiocarbonylthio end group removal.[15]

The molecular weight of the polymer formed can usually be estimated knowing the concentration of the monomer consumed and the initial RAFT agent concentration ($[T]_o$) using equation (1). Positive deviations from (1) indicate incomplete usage of RAFT agent. Negative deviations indicate other sources of polymer chains. These include the initiator-derived chains.[16]

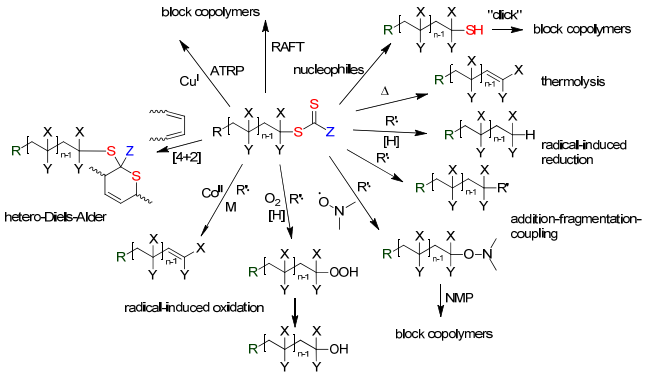
$$\overline{M}_n(\text{calc}) \sim \frac{[M]_o - [M]_t}{[T]_o} m_M \qquad (1)$$

The RAFT process is compatible with a wide range of reaction media including all common organic solvents, protic solvents such as alcohols and water and less conventional solvents such as ionic liquids and supercritical carbon dioxide. It is important that RAFT agent should be selected for solubility in the reaction medium. In polar media and in the presence of Lewis acids RAFT agents can show hydrolytic sensitivity.[17] We have found that this order roughly correlates with RAFT agent activity (dithiobenzoates> trithiocarbonates ~ aliphatic dithioesters).

Although some RAFT polymerization can be carried out in air, for optimal control they should be carried out in degassed media under an inert atmosphere.[3]

6 END GROUP REMOVAL/TRANSFORMATION

The reactions of the thiocarbonylthio-group are well known from small molecule chemistry and much of this knowledge has been shown applicable to transforming the thiocarbonylthio-groups present in RAFT-synthesized polymers. Many of the methods used for thiocarbonylthio-group removal are summarized in Scheme 1.[18] Note that some of these processes are specific to certain types of RAFT agent or to certain polymers. One of the best way of completely replacing the thiocarbonylthio functionality with hydrogen is by radical induced reduction in the presence of a hypophosphite.[19]

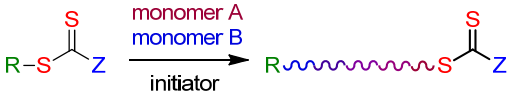


Scheme 1. Processes for RAFT End-group Transformation (R'· = radical, [H] = H atom donor, M = monomer, CoII = square planar cobalt complex). Adapted from ref. [18]

7 COPOLYMERIZATION

In radical copolymerization, the monomers are typically consumed at different rates dictated by the steric and electronic properties of the reactants. Consequently, both the monomer feed and copolymer composition will drift with conversion. Thus conventional copolymers are generally not homogeneous in composition at the molecular level. In RAFT polymerization processes, where all chains grow throughout the polymerization, the compositional drift is captured within the chain structure (Scheme 2). Therefore, essentially all chains will have similar composition. The copolymers are called gradient or tapered copolymers. Reactivity ratios are generally unaffected by the RAFT process. However, for very low conversions when molecular weights are low, copolymer composition may be different from that seen in conventional copolymerization depending on the specificity shown by the initiating species 'R'. A wide variety of gradient copolymers have been synthesized by RAFT

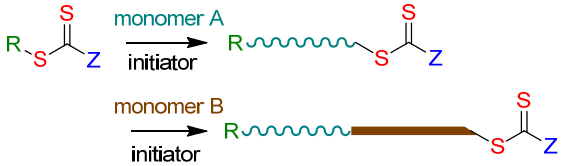
copolymerization. One application is the synthesis of dispersants for polymer-clay nanocomposites.[20]



Scheme 2. Gradient copolymer synthesis

8 BLOCK COPOLYMERIZATION

The synthesis of AB diblock copolymers (and ABA, ABC, etc.) can be accomplished by sequential of monomer as shown in Scheme 3.[21,22]



Scheme 3. AB diblock copolymer synthesis

Of interest has been the ability to make hydrophilic-hydrophobic or double hydrophilic block copolymers where the hydrophilic block is composed of unprotected monomers such as AA or DMAEMA.

The order of constructing the blocks is important.[14,21] In RAFT polymerization the propagating radical for the first formed block must be good homolytic leaving group with respect to that of the second block. This requires, for example, in the synthesis of a methacrylate-acrylate or methacrylate-styrene blocks, the methacrylate block should be prepared first.[14 ,21,23] The propagating radicals sited on a styrene or acrylate unit are very poor leaving groups with respect to methacrylate propagating radicals. The use of feed addition protocols, where the monomer concentration is kept low with respect to the RAFT agent concentration, can alleviate this requirement.[24]

Block copolymers based on polymers formed by other mechanisms can be by forming a macroRAFT agent by end group transformation. This methodology has been used to prepare PEO-*block*-PS from commercially available hydroxy end-functional PEO.[21,25]

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