Macromol. Symp. **2010**, 291–292, 12–16 DOI: 10.1002/masy.201050502

Modular Approaches to Star and Miktoarm Star Polymers by ATRP of Cross-Linkers

*Haifeng Gao, Krzysztof Matyjaszewski**

Summary: The topologies and site-specific functionalities of a variety of star and miktoarm star copolymers can be easily manipulated by copolymerization of monomers and cross-linkers using the ATRP technique. The polymerization of monomer prior to addition of cross-linker produced core cross-linked star polymers with initiating sites in the core, while polymerization of cross-linker before monomer led to the core cross-linked star polymers with initiating sites on the star periphery. When a mixture of linear macroinitiator and/or macromonomer was cross-linked in a one-pot reaction, miktoarm star copolymers with freely-varied arm compositions and ratios were obtained.

Keywords: arm-first; atom transfer radical polymerization (ATRP); cross-linker; miktoarm star copolymer; star polymer

Introduction

The growing demand for soft nanoscale materials with uniform particle size and multiple functionalities is a motivation for development of new procedures that combine architectural control with incorporation of site-specific functional groups into well-defined macromolecules.[1,2] One major effort focuses on the synthesis of architecturally well-defined macromolecules with precise control over the incorporation of branching points and chain-end functionality. The use of multifunctional initiators, multifunctional coupling agents and/or multifunctional monomers (cross-linkers) in controlled/living polymerization techniques, such as anionic polymerization[3] and controlled radical polymerizations (CRPs),[4] allows branching points to be precisely introduced into the polymer chains in a controlled manner.[5,6]

Herein, we report our recent progress on a systematic study of a remarkably simple method for manipulating the topologies of functional star and miktoarm star copolymers by using the atom transfer radical polymerization (ATRP) technique.[7–10] The essence of the study, illustrated in Figure 1, was the use of multivinyl cross-linkers, especially divinyl cross-linkers, providing an easier and more efficient strategy to synthesize functional star polymers with controlled structures.

By rationally selecting functional initiators, monomers and/or divinyl cross-linkers for the copolymerization, a variety of functionalities can be systematically incorporated into the degradable and/or biocompatible star materials. For instance, the polymerization of monomer prior to the addition of cross-linker or the polymerization of the monomer after the cross-linker results in star-like polymers with a cross-linked core, but with different site-specific functionality.[11–17] Copolymerization of monomer and cross-linker together with the same molar ratios of reagents generates randomly-branched polymers or randomly-cross-linked networks (gels)[18–21] (Figure 1). ATRP was used to illustrate the scope of these novel synthetic methodologies, although the same strategies can be easily applied to other CRP techniques.

Department of Chemistry, Carnegie Mellon University, 4400 Fifth Avenue, Pittsburgh, Pennsylvania 15213, USA
E-mail: km3b@andrew.cmu.edu

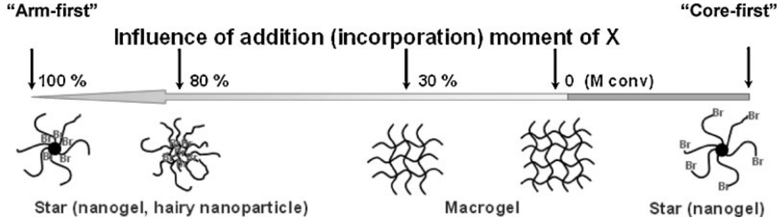

Figure 1.
Influence of addition moment of cross-linker (X) on polymer architectures during ATRP of monomer (M) and cross-linker by using R-Br as initiator.

Results and Discussion

Star polymers, containing multiple linear arms connected at a central branched core, represent one of the simplest nonlinear polymers with three-dimensional structures.[5,22] The core of a star polymer could be an atom, a small molecule, or a macromolecule. Although the use of multifunctional initiators (''core-first'' method)[22–26] and/or multifunctional coupling agents (''coupling-onto'' method)[27–30] can produce star polymers with a well-defined number of arms, the sequential copolymerization of monomers and a divinyl cross-linker in a controlled process represents a simpler method for the synthesis of multi-arm star polymers with a statistical distribution of the number of their arms. The star-like polymers obtained in this process resemble highly cross-linked hairy nanoparticles with a core/shell structure, which is an important category of soft nanomaterials with many potential applications in drug delivery and nano-lithography.[1] Based on the polymerization sequence of monomers and cross-linkers, the core cross-linked star polymers can be synthesized by two strategies.

Synthesis of Star Polymers by the ''Arm-First'' Method: Polymerization of Monomer Before the Addition of Cross-Linker

In the ''arm-first'' method, the linear arms of the star polymers are synthesized first by the polymerization of the monomer, followed by the binding of the arms to form the core, usually by the addition of a divinyl cross-linker. The resulting star polymers have a statistical distribution of the number of arms and a highly cross-linked core (Figure 2).[31–34] The reactive arm precursors could be either linear macroinitiators (MIs)[12,35] or macromonomers (MMs),[14,36,37] and the structures

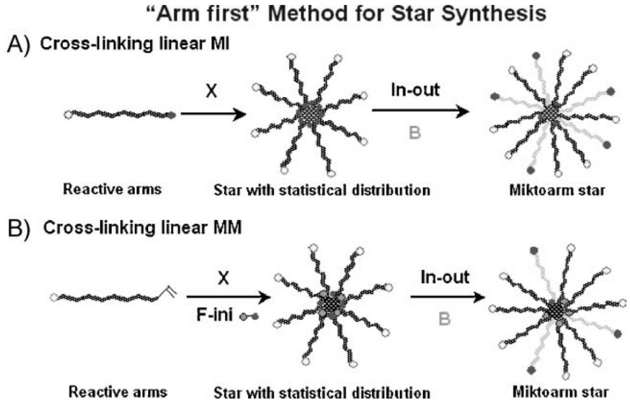

Figure 2.
Synthesis of star polymers using the ''arm-first'' method and subsequent synthesis of miktoarm star copolymers using the ''in-out'' method.

of the star polymers would be largely controlled by rationally adjusting various experimental parameters, including the arm length, the amount of cross-linker and the moment of addition of the cross-linker.[12,35] The star macromolecules formed by cross-linking linear MI, where both the initiating sites and the arms of the star molecule originate from the MI, differ from the stars formed by the copolymerization of linear MM with divinyl cross-linker using an added low molar mass initiator. In the latter case, the incorporated initiating sites and arms are derived from the initiator and the MM, respectively.[14] A low molar ratio of initiator to MM would cause a reduction in the number of initiating sites in the star core, which would effectively limit the extent of star-star coupling reactions and would result in the formation of star polymers with low polydispersity. Moreover, additional functional groups could easily be introduced into the star core through use of functional ATRP initiators for the copolymerization of MM and cross-linker.[37]

The star polymers synthesized by the ''arm-first'' method preserve the initiating sites within the star cores, which can be further employed as star MIs to initiate the polymerization of another monomer to form miktoarm star copolymers by the ''in-out'' method (Figure 2).[11,13,38] Due to the congested environment around the cross-linked core in the star MI, not all of the initiating sites can participate in the formation of the second generation of arms and the initiation efficiency (IE) of the star MI is less than 100%. The IE of the star MI is significantly affected by several factors, including the arm length of star MI, the structural compactness of star MI and the chemical compatibility of the two types of arms in one miktoarm star molecule. It was found that the IE value of the star MI decreased with increasing arm length and structural compactness. When the two arms had the same chemical composition, the star MI had the highest IE value ($\sim 54\%$). In other words, the ratio of the two types of arms can be as high as one half.[13] The incomplete initiation of the star MI indicates that the number of the second generation of arms would always be lower than the number of first generation arms and it is conceptually impossible to synthesize a miktoarm star copolymer containing more than two kinds of arms using the ''in-out'' method based on homopolymerization.

Synthesis of Miktoarm Star Copolymers by the One-Pot ''Arm-First'' Method

In order to synthesize miktoarm star copolymers with potentially any desired molar ratio and composition of the arms, we recently reported a new strategy for the synthesis of miktoarm star copolymers using a simple and general ''arm-first'' method, i.e. one-pot ATRP cross-linking a mixture of different linear MIs and/or MMs with a divinyl cross-linker (Figure 3).[15,16,39] The star structure was proven to be a miktoarm star copolymer containing two or more compositionally different arm species in one molecule, instead of a mixture of different homoarm

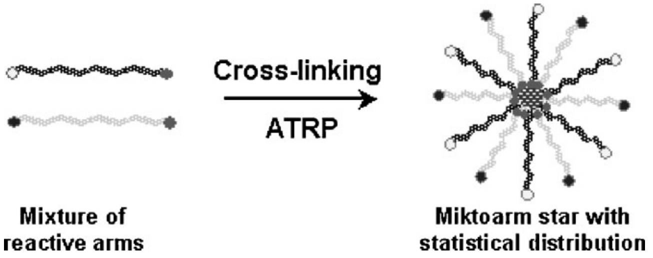

Figure 3.
Synthesis of miktoarm star copolymers by cross-linking two kinds of linear arm precursors (MIs and/or MMs) via the ''arm-first'' method.

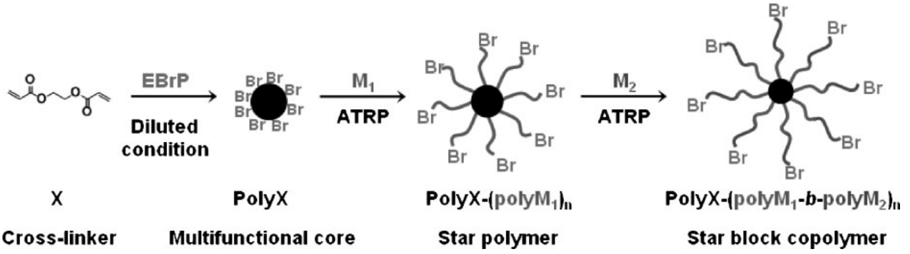

Figure 4.
Synthesis of star polymers using a new "core-first" method: polymerization of cross-linker before the addition of monomer.

star polymers. Miktoarm star copolymers containing five kinds of arms were synthesized for the first time by copolymerizing a mixture of five linear MIs with different chemical composition.[15] When linear MMs were partially or completely used as arm precursors instead of MIs, miktoarm star copolymers with a high star yield and a low polydispersity were successfully synthesized.[16]

Synthesis of Star Polymers by a New "Core-First" Method: Polymerization of Cross-Linker Before the Addition of Monomer

Compared to the "arm-first" method for the synthesis of star and miktoarm star copolymers, an alternative strategy for the synthesis of core cross-linked star polymers is the polymerization of a cross-linker prior to the addition of monomer. To illustrate this concept for synthesis of star polymers, ATRP was applied for the homopolymerization of a diacrylate cross-linker (X) to generate a multifunctional cross-linked core (nanogel) containing a statistical distribution of many initiating sites (Figure 4). At high cross-linker conversion, a monovinyl monomer (M_1) was added to the system and polymerized from the multifunctional nanogel MI to form the star polymer, polyX-(polyM$_1$-Br)$_n$, where n is the average number of polyM$_1$ arms per star molecule. Since a highly cross-linked core is formed (by cross-linker homopolymerization) before the growth of the arms, this synthetic strategy belongs to the category of the "core-first" methods.[40,41] The star polymers synthesized by this new "core-first" method had a similar structural compactness to those from the traditional "arm-first" method. However, in contrast to the star polymers formed by the "arm-first" method, which contained dormant initiating sites in the star core, the star polymers produced by the new "core-first" method preserved the initiating sites at the chain ends, located at the periphery of the star. Thus, the chain extension of the star MI by the polymerization of a second monomer (M_2) formed star block copolymers with the structure polyX-(polyM$_1$-*b*-polyM$_2$)$_n$.[17]

Conclusion

The structure and preselected site-specific functionality of star and miktoarm star copolymers formed by the sequential copolymerization of monomers and cross-linkers in an ATRP depend on the sequence and timing of the addition of the comonomers. The polymerization of monomer prior to addition of cross-linker produced core cross-linked star polymers with initiating sites in the core, which can be further used as star MIs for the synthesis of miktoarm star copolymers via the "in-out" method. In contrast, the polymerization of cross-linker before monomer led to the core cross-linked star polymers with initiating sites on the star periphery. When a mixture of linear MIs and/or MMs was cross-linked in a one-pot reaction, miktoarm star copolymers with freely-varied arm compositions and molar ratios were obtained.

Acknowledgements: The financial support from NSF (DMR-05-49353) and the CRP Consortium at Carnegie Mellon University is greatly appreciated. H. Gao acknowledges the support from a McWilliams Fellowship at Carnegie Mellon University.

[1] C. J. Hawker, K. L. Wooley, *Science* **2005**, *309*, 1200–1205.

[2] K. Matyjaszewski,, Y. Gnanou,, L. Leibler, Eds. *Macromolecular Engineering: From Precise Macromolecular Synthesis to Macroscopic Materials Properties and Applications*; Wiley-VCH: Weinheim, 2007.

[3] M. Szwarc, *Nature* **1956**, *178*, 1168–1169.

[4] W. A. Braunecker, K. Matyjaszewski, *Prog. Polym. Sci.* **2007**, *32*, 93–146.

[5] N. Hadjichristidis, H. Iatrou, M. Pitsikalis, J. Mays, *Prog. Polym. Sci.* **2006**, *31*, 1068–1132.

[6] H. Gao, K. Matyjaszewski, *Prog. Polym. Sci.* **2009**, *34*, 317–350.

[7] J.-S. Wang, K. Matyjaszewski, *J. Am. Chem. Soc.* **1995**, *117*, 5614.

[8] K. Matyjaszewski, J. Xia, *Chem. Rev.* **2001**, *101*, 2921.

[9] M. Kamigaito, T. Ando, M. Sawamoto, *Chem. Rev.* **2001**, *101*, 3689.

[10] N. V. Tsarevsky, K. Matyjaszewski, *Chem. Rev.* **2007**, *107*, 2270–2299.

[11] H. Gao, N. V. Tsarevsky, K. Matyjaszewski, *Macromolecules* **2005**, *38*, 5995–6004.

[12] H. Gao, K. Matyjaszewski, *Macromolecules* **2006**, *39*, 3154–3160.

[13] H. Gao, K. Matyjaszewski, *Macromolecules* **2006**, *39*, 7216–7223.

[14] H. Gao, S. Ohno, K. Matyjaszewski, *J. Am. Chem. Soc.* **2006**, *128*, 15111–15113.

[15] H. Gao, K. Matyjaszewski, *J. Am. Chem. Soc.* **2007**, *129*, 11828–11834.

[16] H. Gao, K. Matyjaszewski, *Macromolecules* **2008**, *41*, 4250–4257.

[17] H. Gao, K. Matyjaszewski, *Macromolecules* **2008**, *41*, 1118–1125.

[18] H. Gao, K. Min, K. Matyjaszewski, *Macromolecules* **2007**, *40*, 7763–7770.

[19] H. Gao, W. Li, K. Matyjaszewski, *Macromolecules* **2008**, *41*, 2335–2340.

[20] H. Gao, A. Miasnikova, K. Matyjaszewski, *Macromolecules* **2008**, *41*, 7843–7849.

[21] W. Li, H. Gao, K. Matyjaszewski, *Macromolecules* **2009**, *42*, 927–932.

[22] K. Matyjaszewski, *Polym. Int.* **2003**, *52*, 1559–1565.

[23] J.-S. Wang, D. Greszta, K. Matyjaszewski, *Polym. Mater. Sci. Eng.* **1995**, *73*, 416–417.

[24] J. Ueda, M. Matsuyama, M. Kamigaito, M. Sawamoto, *Macromolecules* **1998**, *31*, 557–562.

[25] S. Angot, K. S. Murthy, D. Taton, Y. Gnanou, *Macromolecules* **1998**, *31*, 7218–7225.

[26] K. Matyjaszewski, P. J. Miller, E. Fossum, Y. Nakagawa, *Appl. Organomet. Chem.* **1998**, *12*, 667–673.

[27] H. Gao, K. Matyjaszewski, *Macromolecules* **2006**, *39*, 4960–4965.

[28] M. R. Whittaker, C. N. Urbani, M. J. Monteiro, *J. Am. Chem. Soc.* **2006**, *128*, 11360–11361.

[29] O. Altintas, G. Hizal, U. Tunca, *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 5699–5707.

[30] O. Altintas, B. Yankul, G. Hizal, U. Tunca, *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 6458–6465.

[31] J. Xia, X. Zhang, K. Matyjaszewski, *Macromolecules* **1999**, *32*, 4482–4484.

[32] X. Zhang, J. H. Xia, K. Matyjaszewski, *Macromolecules* **2000**, *33*, 2340–2345.

[33] K. Y. Baek, M. Kamigaito, M. Sawamoto, *Macromolecules* **2001**, *34*, 215–221.

[34] K.-Y. Baek, M. Kamigaito, M. Sawamoto, *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 633–641.

[35] K.-Y. Baek, M. Kamigaito, M. Sawamoto, *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 2245–2255.

[36] K. Ishizu, K. Sunahara, *Polymer* **1995**, *36*, 4155–4157.

[37] H. Gao, K. Matyjaszewski, *Macromolecules* **2007**, *40*, 399–401.

[38] J. Z. Du, Y. M. Chen, *Macromolecules* **2004**, *37*, 3588–3594.

[39] J. T. Wiltshire, G. G. Qiao, *Macromolecules* **2006**, *39*, 9018–9027.

[40] H. Eschwey, M. Hallensleben, W. Burchard, *Makromol. Chem.* **1973**, *173*, 235–239.

[41] Y. Gnanou, P. Lutz, P. Rempp, *Makromol. Chem.* **1988**, *189*, 2885–2892.