"Click"-Based Covalent Layer-by-Layer Assembly on Polyethylene Using Water-Soluble Polymeric Reagents

David E. Bergbreiter* and Brandon S. Chance

Department of Chemistry, Texas A&M University, College Station, Texas 77842-3012

Received January 15, 2007; Revised Manuscript Received May 17, 2007

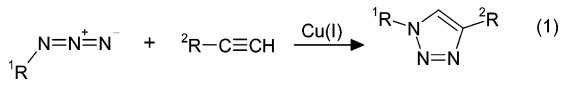
ABSTRACT: The use of copper(I)-catalyzed "click" reactions of azides and alkynes for covalent layer-by-layer grafting on polyethylene is described. Water-soluble poly(*N*-alkylacrylamide) copolymers that contain pendant azide or alkyne groups that can be thermally separated from aqueous solutions were used to alternately "click" together azide and alkyne polymers via 1,2,3-triazole formation onto a prefunctionalized alkyne-containing surface. The layer-by-layer self-assembly process proceeds under ambient conditions and was followed by ATR-IR spectroscopy using control reactions to show that azide groups and copper catalysis are required for the assembly process. Post-graft functionalization of the hyperbranched assembly is used to demonstrate that the functional interfaces so formed can be further derivatized for other functions.

The formation of robust multilayer assemblies on surfaces via noncovalent polyvalent H-bonding or ionic interactions has been of increasing interest.[1−3] Similar strategies that use covalent bonding for hyperbranched grafting have been explored by our group and others.[4,5] We are particularly interested in applying such chemistry to traditionally unreactive surfaces using air- and water-compatible chemistry. The work below describes a straightforward approach to this objective, using Sharpless' "click" chemistry and water-soluble polymers to prepare functional grafts on polyethylene (PE) films.

Modification of polyolefin surfaces is a process of continuing interest. A variety of approaches using noncovalent interactions to modify surfaces of nonpolar polymers by entrapment functionalization or by layer-by-layer ionic assembly have been described.[6−8] Covalent modification of polyethylene surfaces either by simple oxidation or by grafting chemistry is also of broad interest because such chemistry leads to polyolefin films and powders that have enhanced functionality without modification of the bulk properties of the polymeric substrate. While these procedures effectively modify polyolefins, the most common and most effective procedures still employ covalent grafting, often using either plasma polymerizations or photoinitiated polymerizations.[9]

While grafting of linear polymers to surfaces works, other grafting chemistry has advantages, too. For example, procedures that produce irregular hyperbranched grafts provide a different way to modify surfaces including polyethylene surfaces. Hyperbranched covalent graft chemistry provides a route to functional surfaces with a very high density of surface functional groups in a synthetically forgiving fashion.[3,10,11] Our initial studies of hyperbranched covalent grafting on surfaces used a graft-on-a-graft strategy and employed polyvalent poly(acrylic acid) derivatives as reagents using either condensation reactions or a mixture of condensation reactions and subsequent radical grafting chemistry to form the necessary covalent bonds.[12,13] More recently, we described faster, more practical chemistry using commercially available polyanhydrides and polyamines as nucleophilic and electrophilic components for formation of covalent hyperbranched grafts in a covalent layer-by-layer approach.[14−16] All of these methods lead to functionalized surfaces that contain unreacted electrophilic or nucleophilic functionality that can be used to further tailor the chemistry of the resulting grafts. Extension of such strategies to use other reactions that do not involve condensation reactions remains of interest, however, especially if new chemistry can be developed that is experimentally simple. The recent development by Sharpless of "click" chemistry employing an azide−alkyne [3 + 2] cycloaddition that is insensitive to water and oxygen and that has been demonstrated to be exceptionally broad in scope[17] was of particular interest to us in this regard.

Conventional [3 + 2] cyclizations of azides and alkynes to form triazoles would normally be wholly unsuitable for polyethylene modification because of the required reaction conditions (e.g., temperatures above the melting point of polyethylene).[18] However, the recent Cu(I)-catalyzed variant of this reaction (eq 1) discovered by Sharpless is much more suitable.[17] Sharpless'



(1)

Cu(I)-catalyzed "click" chemistry also has been successfully used both for modification of surfaces and of polymers.[19,20] For example, this cyclization reaction was used to modify inorganic surfaces in a layer-by-layer process that is similar to that described below. In that initial report, an initial functionalization of a silica surface by ionic self-assembly was used as a prelude to subsequent covalent layer-by-layer grafting using Cu(I)-catalyzed "click" chemistry.[20] This Cu(I)-catalyzed [3 + 2] cyclization process is regioselective and is a reaction that can be carried out in water in air under mild conditions, making it a very promising process for covalent polyvalent layer-by-layer modification of polyethylene surfaces. It has the further advantage that the covalent links formed are aromatic 1,2,3-triazoles—functionality that is stable to strong aqueous acid or strong aqueous base conditions that might degrade a grafted surface assembled ionically or prepared by condensation chemistry.

Results and Discussion

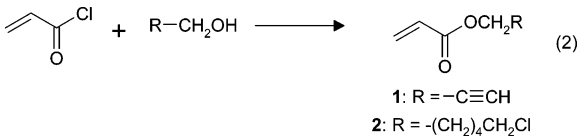
While the Sharpless variant of the Huisgen reaction meets many of our objectives as a candidate reaction for layer-by-layer graft modification of PE surfaces, PE surfaces unlike silica

* Corresponding author. E-mail: Bergbreiter@tamu.edu.

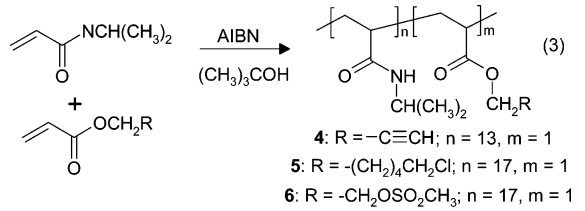
10.1021/ma0701134 CCC: $37.00
Published on Web 06/23/2007

or functional polymers do not contain functional groups that can initiate the graft chemistry. Inert polymers such as polyolefins require the use of an initial oxidation reaction to functionalize these polymers' surfaces. This can be accomplished in an industrially practical manner using corona discharge or plasma treatments to introduce $-CO_2H$ groups.[9] In our case, we opted to use a Cr(IV) oxidant in sulfuric acid as a convenient albeit "non-green" laboratory-scale route to introduce the same sorts of carboxylic acid functionality.[21] Our group has earlier shown how the carboxylic acid functionality so formed can be used to further functionalize polyethylene by various procedures including by covalent layer-by-layer assembly using various sorts of condensation reactions.[11,16,22,23]

To take advantage of "click" chemistry for covalent layer-by-layer grafting on PE, we prepared monomers propargyl acrylate (**1**) and 1-chlorohexyl acrylate (**2**) from acryloyl chloride and the appropriate alcohol (eq 2). 2-(Methylsulfonyloxy)ethyl



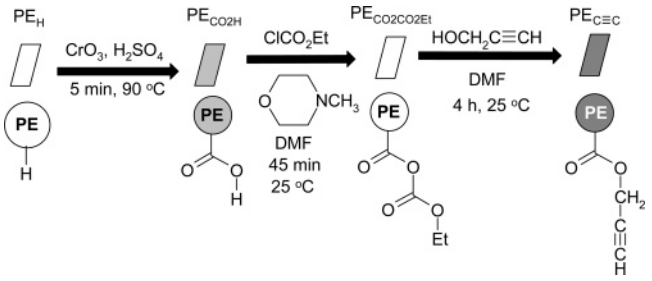
acrylate (**3**) was prepared by mesylation (CH_3SO_2Cl, Et_3N, CH_2Cl_2) of the commercially available monomer hydroxyethyl acrylate. Monomers **2** and **3** were chosen as they possess leaving groups that could be substrates in a post-polymerization S_N2 reaction with NaN_3. Such chemistry affords azide-containing polymers, avoiding possible safety problems associated with purifying low molecular weight azides. Copolymers containing the above monomers were prepared by conventional free radical polymerization using azobis(isobutyronitrile) (AIBN) in *tert*-butanol or benzene using an excess of *N*-isopropylacrylamide as a comonomer (eq 3).

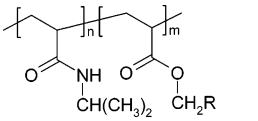


The first copolymer made was poly((*N*-isopropylacrylamide)-*co*-(propargyl acrylate)) (**4**) ($PNIPAM_{C\equiv C}$). Using *tert*-BuOH as a solvent, molecular weights of 6.0×10^4 Da (GPC) were obtained. Poly((*N*-isopropylacrylamide)-*co*-(6-chlorohexyl acrylate)) (**5**) and poly((*N*-isopropylacrylamide)-*co*-(2-(methylsulfonyloxy)ethyl acrylate)) (**6**) were also prepared using AIBN from NIPAM and **2** or **3** in benzene. In these cases, a precipitate formed. All these PNIPAM-based polymers were purified by dissolution/precipitation using THF, acetone, or chloroform as "good" solvents with successive precipitations with hexanes.

Polymers **5** and **6** were converted to the $PNIPAM_{N=N=N}$ azide-containing polymers by dissolving each in DMF, adding sodium azide, and heating to 90 °C overnight. The product polymers **7** and **8** had an M_n of 1.4×10^5 and 2.2×10^5 Da (GPC), respectively. Purification of these polymers from excess sodium azide, sodium chloride, or sodium mesylate was effected by taking advantage of the fact that polymers **7** and **8** like most other PNIPAM-like materials have a lower critical solution temperature (LCST). In these cases, the LCSTs were 30 and 29 °C, respectively. When an aqueous solution of these polymers was heated at 60 °C and the resulting suspension was centrifuged, the polymer precipitate of **7** or **8** could easily be separated from any water-soluble byproducts or from unreacted monomer. Such temperature-induced precipitations have previously been used by us to purify products,[24,25] to sequester metals,[26,27] to sequester pollutants,[28] or to sequester catalysts[29] from aqueous solutions.

Scheme 1. Functionalization of Polyethylene Films with Alkyne Groups To Prepare a Substrate for Subsequent Covalent Layer-by-Layer Grafting Using Cu(I)-Catalyzed "Click" Reactions Water-Soluble Alkyne and Azide-Containing Polymers $PNIPAM_{C\equiv C}$ and $PNIPAM_{N=N=N}$



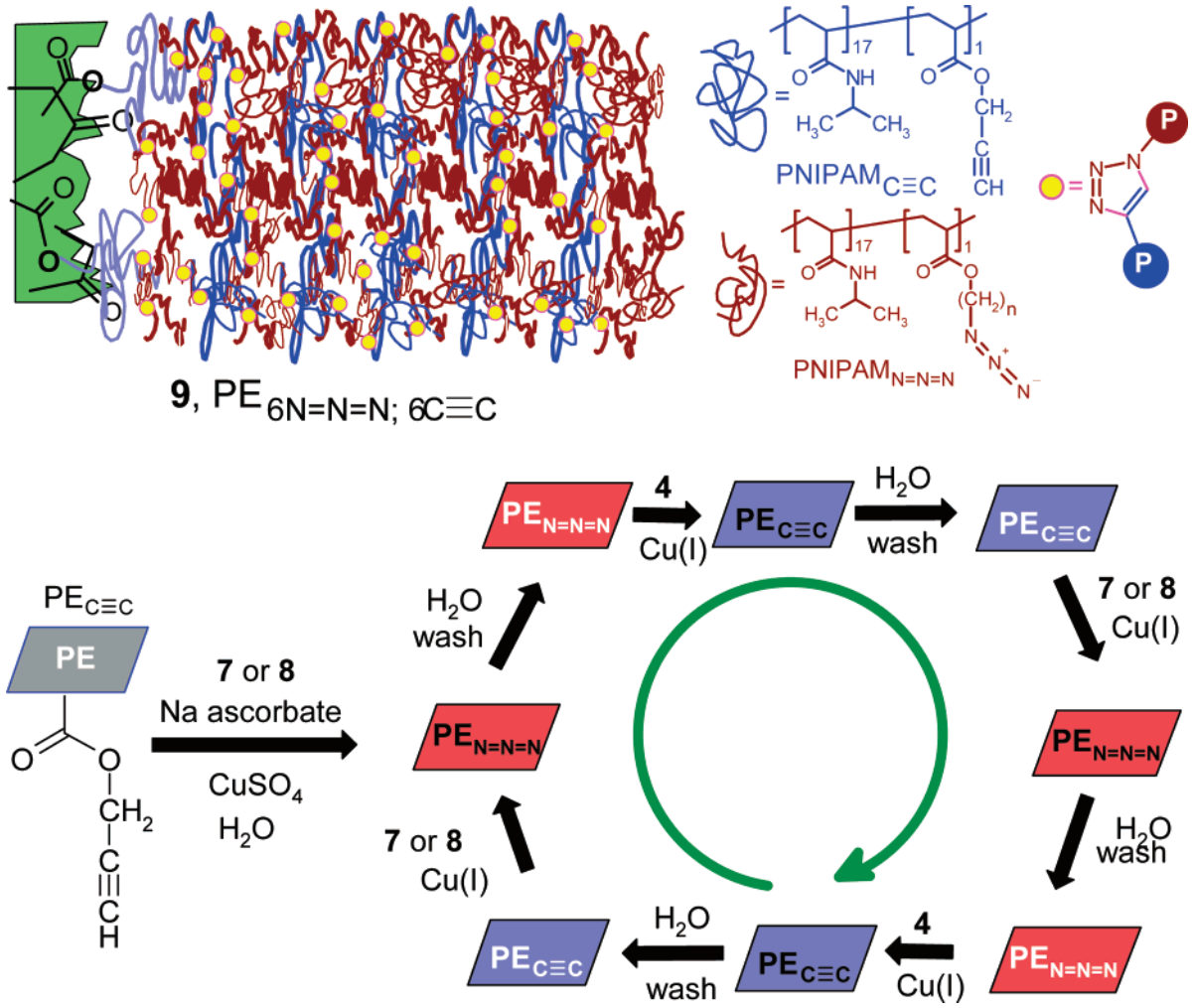


7: R = -(CH2)4CH2N3; n = 17, m = 1
8: R = -CH2N3; n = 17, m = 1

Test reactions using either a THF solution of **8** with octyne, $(PPh_3)_3CuBr$, and Hunig's base or with an aqueous solution of $HC\equiv CCH_2OH$, $CuSO_4-(H_2O)_5$, and sodium ascorbate at 60 °C over 12 h produced the expected triazole products, showing that these polymers are effective substrates for "click" chemistry. In these reactions, ^1H NMR analysis showed complete disappearance of the starting polymer and the appearance of a distinctive aromatic $-C-H$ triazole signal at δ 7.5 or δ 7.4, respectively.

Given that polymers **4**, **7**, and **8** are soluble in water and are suitable substrates for "click" chemistry, we proceeded to explore their use in formation of hyperbranched grafts by a covalent layer-by-layer assembly process on polyethylene. The necessary functionalized polyethylene substrate was prepared by oxidation, mixed anhydride formation, and esterification with $HOCH_2C\equiv CH$. Polyethylene films were first oxidized by immersion of the polyethylene film in a sulfuric acid solution containing chromium(III) oxide.[21] This reaction was allowed to proceed for 5 min at 90 °C. The introduction of carboxylic acid groups onto the product surface was verified by the appearance of a carbonyl stretch at 1708 cm^{-1} in the attenuated total reflectance infrared (ATR-IR) spectrum of the film. The oxidized polyethylene film (PE_{CO_2H}) was then immersed in a solution of dichloromethane containing ethyl chloroformate and *N*-methylmorpholine—a process that introduces mixed anhydrides to the surface. This reaction was allowed to proceed at room temperature for 45 min. Mixed anhydride formation was evident by the appearance of a new peak in the ATR-IR spectrum at 1825 cm^{-1}. The mixed anhydride polyethylene film ($PE_{CO_2CO_2Et}$) was then allowed to react with propargyl alcohol and triethylamine to introduce the alkyne functionality. The appearance of an ester stretch at 1740 cm^{-1} in the ATR-IR spectrum indicated the formation of $PE_{C\equiv C}$ with propargyl ester groups on the surface. An alkyne peak was not seen. The entire reaction scheme introduction of a surface alkyne group is depicted in Scheme 1.

Scheme 2. Cycle of Steps for Covalent Layer-by-Layer Assembly Starting with a Alkyne-Containing Functionalized PE Film Using "Click" Reactions Alternately Using $PNIPAM_{N=N=N}$ or $PNIPAM_{C\equiv C}$ Polymeric Reagents 7 (or 8) and 4 in the Presence of a Cu(I) Catalyst To Form Triazole Links and Azide- or Alkyne-Rich Surfaces



The polyethylene films with alkyne groups $PE_{C\equiv C}$ were then subjected to a series of alternating reactions using aqueous solutions of the $PNIPAM_{N=N=N}$ azide (**7** or **8**)- or $PNIPAM_{C\equiv C}$ alkyne-containing polymers (**4**) in the presence of copper sulfate and sodium ascorbate (Scheme 2). In a typical procedure, a total of six azide and six alkyne steps could be completed in 1 day. The reactions are presumably facilitated by the large excess of polymeric reagent in the solution phase. The final $PE_{x,N=N=N;y,C\equiv C}$ product consists of a covalent assembly that is the product of *x* stages of coupling with the $PNIPAM_{N=N=N}$ polymeric reagent and *y* stages of treatment with $PNIPAM_{C\equiv C}$ polymeric reagent. The product $PE_{6N=N=N;6C\equiv C}$ (**9**) is drawn in Scheme 2—the drawing highlights the number of stages or layers, but the actual product covalent assembly does not necessarily have the highly ordered structure shown. This final product $PE_{6N=N=N;6C\equiv C}$ was formed from $PE_{C\equiv C}$ using five alternating "click" reactions using $PNIPAM_{N=N=N}$ and $PNIPAM_{C\equiv C}$ with a final $PNIPAM_{N=N=N}$ "click" reaction leaving a product film with excess azide groups at the surface. The progress of this covalent layer-by-layer grafting process was followed by ATR-IR spectroscopy (Figure 1). Previous reports involving layer-by-layer assembly on organic polymer substrates used X-ray photoelectron spectroscopy to follow the assembly progress and to assay the stepwise, stratified nature of the product surfaces.[8] However, that was not possible in this case due to the similarity of the polymers used in the assembly process. The alkyne- and azide-containing polymer reagents both contain significant and similar amounts of nitrogen (12 and 13 atom %, respectively), making XPS monitoring less useful. XPS analysis of the surface at the $PE_{2N=N=N;1C\equiv C}$ point showed that the atom % N was 13.4%, consistent with what would be expected for a graft with a topmost $PNIPAM_{N=N=N}$ layer atop

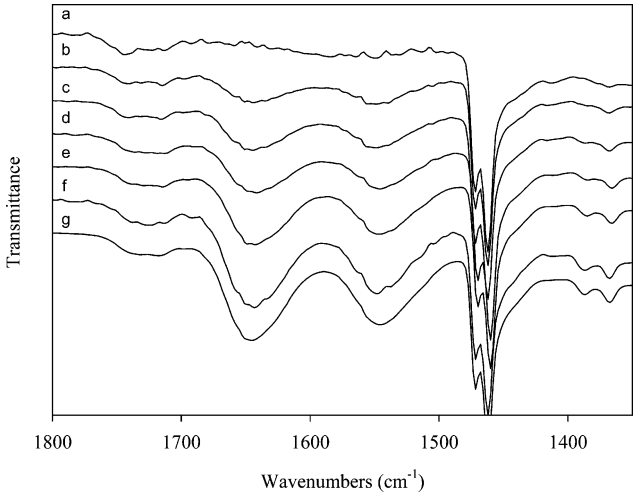


Figure 1. ATR-IR spectra showing the gradual increase in intensity of the $\nu_{C=O}$ absorbances for the amide graft in layer-by-layer covalent assembly on PE using **4** and **8** (a, $PE_{C\equiv C}$; b, $PE_{1N=N=N;1C\equiv C}$; c, $PE_{2N=N=N;2C\equiv C}$; d, $PE_{3N=N=N;3C\equiv C}$; e, $PE_{4N=N=N;4C\equiv C}$; f, $PE_{5N=N=N;5C\equiv C}$; g, $PE_{6N=N=N;6C\equiv C}$).

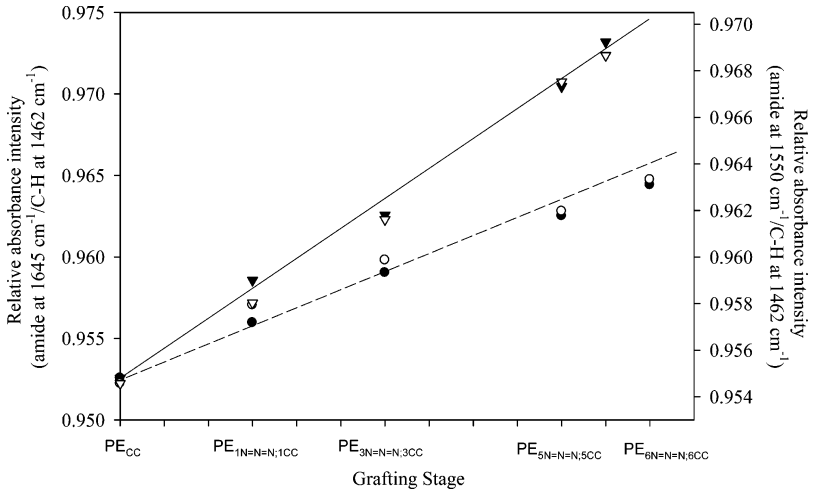


Figure 2. Layer growth on PE film followed by the ratio of areas for the IR absorbances due to the amide $\nu_{C=O}$ peaks (1645 or 1462 cm^{-1}) and the background polyethylene (1462 cm^{-1}) using **8** (C_2 linker; ●, 1645 cm^{-1} ratio; ○, 1550 cm^{-1} ratio) vs **7** (C_6 linker; ▼, 1645 cm^{-1} ratio; ▽, 1550 cm^{-1} ratio) as the azide component in "click" layer-by-layer assembly.

a $PNIPAM_{C\equiv C}$ substrate. Since the depth sensitivity of the XPS analysis <10 nm and the atom % N at this point corresponds to the atom % N of the polymeric reagents (the starting surface contained no detectable N), the surface grafts are at least this thick when at this point in the layer-by-layer grafting process.

The use of water and polyvalent PNIPAM macromolecular reagents has several advantages. First of all, the need for organic solvents is eliminated. Second, an inexpensive copper catalyst-(I) is used, and the polymeric reagents are both stable and are easily recovered from aqueous solutions. Third, the reaction can be carried out in air at room temperature in a relatively short period of time. The time required for each grafting step in Scheme 2 including washing is ca. 1 h. Fourth, the products at each step contain either an excess of azide functionality if $PNIPAM_{N=N=N}$ is used as the polymeric reagent or an excess of alkyne groups if $PNIPAM_{C\equiv C}$ is used as the polymeric reagent. This facilitates the subsequent grafting step in exactly the same way as an excess of amines facilitates covalent hyperbranched grafting[30] and just as an excess of cationic or anionic groups facilitates ionic layer-by-layer assembly on other functional surfaces.[31] In addition, since the steps that bind a subsequent azide or alkyne polymer to the surface do not consume all the azide or alkyne groups from the earlier steps, azide or alkyne groups that can be used in further chemistry to further modify the functionalized interfaces so formed.

The success of the covalent layer-by-layer assembly process was affected by the conditions of the grafting and by the type of $PNIPAM_{N=N=N}$ polymer used. Temperatures below the LCST of the polymers were generally used to get a regular increase in grafting from step to step. If the grafting temperature was above the $PNIPAM_{N=N=N}$'s LCST, a variable amount of grafting occurred. The efficiency of the process was also affected by the type of $PNIPAM_{N=N=N}$ polymer used. The polymer **7** with six methylene spacer groups separating the $-N_3$ group from the PNIPAM chain was more effective in covalent layer-by-layer assembly than $PNIPAM_{N=N=N}$ **8** which had only two methylene groups between the azide and the polymer chain (Figure 2). Polymers with higher mol % loadings of azide or alkyne groups were not studied, and such polymers' water solubility would be different that PNIPAM. Polymers with substantially lower mol % loadings (e.g., 1 mol % loading) of azide or alkyne groups would have required undesirably long reactions times. The polymers used here also had advantages in their synthesis/purification in that their azide or alkyne

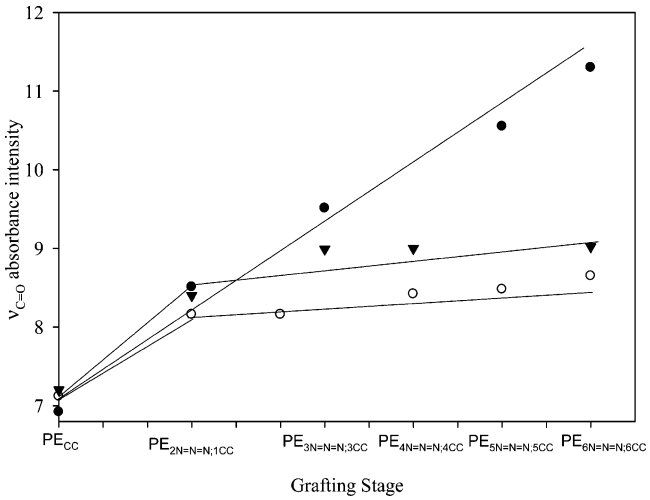
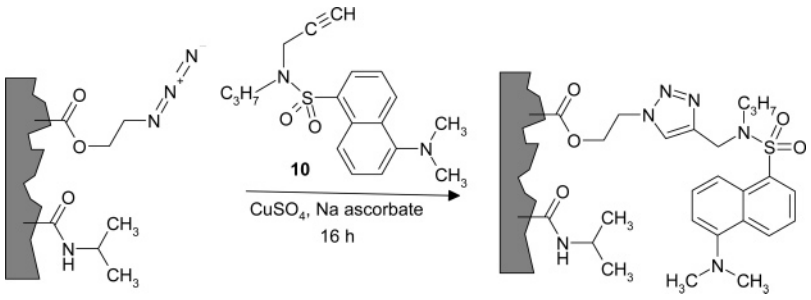


Figure 3. Scatter plot showing the contrast between normal layer growth with $PNIPAM_{N=N=N}$ (**8**) as the azide component and $PNIPAM_{C\equiv C}$ (**4**) as the alkyne component vs control reactions where no copper catalyst was present after the $PE_{2N=N=N;1C\equiv C}$ stage (▼) or where the azide groups at the $PE_{2N=N=N;1C\equiv C}$ stage were reduced with $LiAlH_4$ (○) showing essentially no growth in either control experiment based on the changes in the absorbance of the amide peak 1645 cm^{-1} in the ATR-IR spectra of the product films.

loadings are such that the polymers behave much like the parent PNIPAM polymer in that they are water-soluble and have an LCST near room temperature. Grafting beyond 12 layers was not studied.

Earlier work both by our group and others has shown that hydrogen bond donors and acceptors including acrylamides like PNIPAM can form noncovalent grafts on surfaces without covalent bonding.[1,30] Thus, we carried out a series of control reactions to show that the product **9** formed by PNIPAM-bound azides and alkynes is a covalent assembly formed via triazole links. In the first of these experiments, a $PE_{C\equiv C}$ film was alternately allowed to react with an aqueous solution of **8**, cupric sulfate, and sodium ascorbate and **4**, cupric sulfate, and sodium ascorbate to form $PE_{2N=N=N;1C\equiv C}$. This product film was washed three times with water and once with acetone to remove any copper catalyst. The film was then subjected to four alternating 1 h treatments with **4** and **8** without any copper catalyst being present. The intermediate and final products were analyzed by ATR-IR spectroscopy. Very little growth was seen in the absence of a copper catalyst.

Scheme 3



In a second control reaction, a $PE_{2N=N=N;1C\equiv C}$ was treated with a THF solution of $LiAlH_4$ to reduce the azides in the azide-rich surface to amines. This film was then allowed to react through four stages of alternate treatment with **4**, cupric sulfate, and sodium ascorbate and **8**, cupric sulfate, and sodium ascorbate. Once again, little growth in the $\nu_{C=O}$ peak was seen in the ATR-IR spectrum of the product films, suggesting the presumed reduction of the azide groups precluded significant further grafting of either $PNIPAM_{C\equiv C}$ or $PNIPAM_{N=N=N}$ in subsequent treatments. The results of these control experiments are illustrated in Figure 3.

Washing experiments using aqueous acid or base that in our earlier work disassembled hydrogen-bond-based grafts involving PNIPAM polymers[30] were also carried out. Grafts like **9** proved to be stable to these conditions.

There is a little grafting in the first control reaction that may reflect some interaction of the $PNIPAM_{N=N=N}$ reagent with alkyne groups from the $PE_{C\equiv C}$ or the $PE_{1N=N=N;1C\equiv C}$ stage possibly due to Cu(I) entrained in the surface. However, these control experiments show that noncovalent absorption of the $PNIPAM_{N=N=N}$ or the $PNIPAM_{C\equiv C}$ reagents due to noncovalent interactions has contributed little to the overall process seen in Figures 1 and 2.

Other surface analyses were also performed using X-ray photoelectron spectroscopy (XPS), fluorescence microscopy, and contact angle goniometry. To further establish the presence of triazoles throughout the multilayer assembly, a $PE_{3N=N=N;3C\equiv C}$ film prepared using **4** and **7** was allowed to react with methyl iodide in chloroform at 40 °C for 3 days. Experiments with a soluble polymer containing pendant triazoles that were formed by a "click" reaction showed that methylation with methyl iodide led to alkylation of ca. 40% of the triazole groups. The methylated film product was analyzed by XPS and was shown to contain 0.1 atom % iodine. This was taken as positive evidence for the presence of triazole groups since no alkylation of the PNIPAM would be expected under these conditions. While it is difficult to assess the extent of the alkylation, we estimate that a level of 0.4 atom % iodine would have corresponded to complete alkylation of all the triazole groups that could have formed. The observed 0.1 atom % iodine then corresponds to an extent of alkylation of the triazole groups of ca. 25%. Copper ions were also detected via XPS at ca. 0.2 atom % in the grafted surfaces. However, because copper can bind to both triazoles and amides, its presence alone is not independent evidence for the formation of triazole functionality.

Fluorescence microscopy experiments were also performed to demonstrate the accessibility of azides in the layer-by-layer graft assembly for subsequent reaction. A PE_{CO_2H}, a $PE_{2N=N=N;1C\equiv C}$, and a $PE_{6N=N=N;6C\equiv C}$ product film were allowed to react using Cu(I) catalysis with a 10:1 water/THF solution of a dansyl fluorescent label (**10**) that contained an alkyne group (Scheme 3). The products were then analyzed by fluorescence microscopy. The intensities of the dansyl-labeled $PE_{2N=N=N,1C\equiv C}$ film (whose last "click" reaction before fluorescence labeling was a $PNIPAM_{N=N=N}$ treatment) and the dansyl-labeled $PE_{6N=N=N,6C\equiv C}$ film (whose last "click" reaction before fluorescence labeling was treatment with $PNIPAM_{C\equiv C}$) were roughly equivalent. These experiments show that azide groups are available for reaction with low molecular weight reagents even if an alkyne-rich film is used. Essentially no labeling was seen with the starting oxidized polyethylene, as expected.

Finally, contact angle goniometry was briefly used to examine the surfaces. In these experiments, the PE_{CO_2H} film had an advancing contact angle (θ_a) of 65°. A $PE_{6N=N=N;6C\equiv C}$ film prepared using **4** and **7** had a θ_a of 53°, showing $PE_{6N=N=N;6C\equiv C}$ was even more hydrophilic than the oxidized film. Finally, when this $PE_{6N=N=N;6C\equiv C}$ film was stirred in a 3:1 THF/water solution containing octadecyl azide, cupric sulfate, and sodium ascorbate, the azide-rich film surface was capped with hydrophopic octadecyl chains and the θ_a changed from 53° to 74°. While this is consistent with introduction of hydrophobic functionality at the surface, the relatively low contact angle (74°) suggests that resulting surface is still modestly hydrophilic, which is perhaps to be expected given the graft is mainly composed of PNIPAM.

Conclusion

Poly(*N*-isopropylacrylamide) copolymers functionalized with azides or alkynes can be used in sequential reactions to form covalent multilayer grafts on a polyethylene substrate. Covalent layer-by-layer assembly was achieved by using "click" chemistry to form triazoles that covalently link each layer and covalently attach the entire assembly to the polyethylene surface using triazole linkages to covalently bind alternating layers of polymeric reagents to the surface. The ability for PNIPAM-based copolymers to covalently assembly in a layer-by-layer fashion was established using attenuated total reflectance infrared spectroscopy. It was shown that increasing the number of carbons between the azide and the polymer backbone increases the amount of polymer grafting. Control reactions showed that the polymeric reagents were not simply physically absorbing on the polymer. Post-grafting reactions including methylation of the triazole linkers, fluorescence tagging using a dansyl-containing alkyne, and tagging of a surface with an octadecylazide showed that unreacted functionality within the graft is accessible to low molecular reagents for subsequent tailoring of a surface. The ability to use water as a grafting media, the potential for post-graft functionalization of the product interfaces, and the ability to recover and purify the polymeric reagents by simple heating make this covalent layer-by-layer approach a new green chemistry approach to modification of polyolefins that should be generally applicable to other surfaces that can be designed to include alkynes or azides.

Experimental Section

General Procedures. *N*-Isopropylacrylamide was recrystallized from a 9:1 mixture of hexane and benzene. Benzene, THF, and DMF were dried over 3 Å molecular sieves. *tert*-Butyl alcohol and 1,4-dioxane were used from new, sealed bottles, and no further drying was performed. Distilled water was used for all washings and reactions. All other reagents were purchased from commercial sources and used as received. NMR spectra were obtained using a Varian Mercury 300 MHz or Unity 300 MHz spectrometers. GPC measurements were carries out on a Viscotek model 270 detector equipped with a I-MBMMW-3078 mixed bed column using THF as a solvent and a model VE 3580 RI detector. Molecular weights were determined relative to polystyrene standards. ATR-IR spectra were obtained on a Bruker Tensor 27 series FT-IR spectrometer with a Pike MIRacle accessory using a ZnSe crystal. X-ray photoelectron spectroscopy (XPS) was carried out using a Kratos Axis Ultra XPS using a monochromatic Al Kα source (400 W) in a UHV environment (ca. 5×10^{-9} Torr). Surface atom % compositions were determined by normalized integration of the resulting peaks using Kratos software. Fluorescence microscopy images were taken using a Nikon Eclipse model E800 Advanced Research microscope with a UV-2E/C DAPI filter at a magnification of 10×. Contact angle measurements were carried out using a KSV Instruments CAM200 optical goniometer. All films were dried under vacuum for 4 h prior to fluorescence, XPS, or contact angle goniometry analyses.

Poly((*N*-isopropylacrylamide)-*co*-(propargyl acrylate)) **(4)** ($PNIPAM_{C\equiv C}$). *N*-Isopropylacrylamide (5 g, 44 mmol), propargyl acrylate (0.48 g, 4.3 mmol), and AIBN (7.5 mg, 0.046 mmol) were dissolved in 250 mL of *tert*-butanol. The reaction mixture was degassed for 45 min with N_2, and the reaction was allowed to proceed for 12 h at 70 °C under nitrogen. The solvent was removed under reduced pressure, and the crude polymer was dissolved in 50 mL of chloroform. The chloroform solution was precipitated into hexanes (500 mL). This precipitation was performed twice. The polymer was then dried under vacuum. ^{1}H NMR ($CDCl_3$): δ 0.71−2.61 (bm), 4.01 (bs), 4.66 (bs), 5.93−7.17 (bm); $M_n = 6.1 \times 10^4$ Da (GPC); PDI = 2.31.

Poly((*N*-isopropylacrylamide)-*co*-(6-chlorohexyl acrylate)) (**5**). *N*-Isopropylacrylamide (5 g, 44 mmol), 6-chlorohexyl acrylate (0.854 g, 2.9 mmol), and AIBN (15 mg, 0.092 mmol) were dissolved in 250 mL of benzene. The reaction mixture was degassed for 45 min with N_2, and the reaction was allowed to proceed for 12 h at 70 °C under nitrogen. After 12 h, a precipitate formed. The benzene was decanted, and the residue was dissolved in 70 mL of $CHCl_3$. The solution was then precipitated into 700 mL of hexanes (2 times), filtered, and dried under vacuum. The polymer product (4.5 g) was obtained in 81% yield. ^{1}H NMR ($CDCl_3$): δ 0.78−2.51 (bm), 3.53 (bt), 4.01 (bs), 5.78−7.04 (bm).

Poly((*N*-isopropylacrylamide)-*co*-(2-(methylsulfonyloxy)ethyl acrylate)) (**6**) was prepared from *N*-isopropylacrylamide (5 g, 44 mmol) and 2-methanesulfonylethyl acrylate (0.854 g, 4.5 mmol) using the procedure used to prepare **5**. The product was purified by precipitation from THF and isolated on a 4.5 g scale (83% yield). ^{1}H NMR ($CDCl_3$): δ 0.70−2.62 (bm), 3.17 (bs), 3.76 (bs), 4.00 (bs), 4.45 (bs), 5.66−7.20 (bm).

Poly((*N*-isopropylacrylamide)-*co*-(6-azidohexyl acrylate)) (**7**). Sodium azide (0.5 g, 7.0 mmol) and **5** (4.5 g, 1.7 mmol of functionalized polymer) were dissolved in 200 mL of DMF and heated to 90 °C for 12 h. DMF was removed under reduced pressure, and the crude polymer was dissolved in 150 mL of water. The polymer product had an LCST of 30 °C and could therefore be separated from other water-soluble species by centrifugation (1500 rpm, 20 min at 60 °C). Redissolving the polymer in 100 mL of water and a second centrifugation and drying of the resulting solid product yielded 3.38 g (75%) of the product polymer, causing the polymer product to precipitate. The polymer was again dissolved in 100 mL of water, and the centrifugation procedure was repeated. The polymer was filtered and dried under vacuum to yield 3.38 g (75%) of the product polymer **7**. ^{1}H NMR (D_2O): δ 0.77−2.42 (bm), 3.38 (bs), 3.94 (bs), 4.17 (bs); $M_n = 2.2 \times 10^5$ Da (GPC); PDI = 2.13.

Poly((*N*-isopropylacrylamide)-*co*-(2-azidoethyl acrylate)) (**8**) was prepared on a 1.75 g scale from sodium azide (0.123 g, 1.7 mmol) and **5** (2 g, 0.95 mmol of functionalized polymer) using the procedure used to prepare **7** from **5**. The product polymer **8** had an LCST of 29 °C and was purified by centrifugation to yield a 90% yield of the $PNIPAM_{N=N=N}$ product. ^{1}H NMR ($CDCl_3$): δ 0.66−2.77 (bm), 3.55 (bs), 4.03 (bs), 4.28 (bs), 5.8−7.25 (bm); $M_n = 1.4 \times 10^5$ Da (GPC); PDI = 2.01.

Dansyl-labeled alkyne (**10**). A mixture of *N*-propyl-5-dimethylaminonaphthalene-1-sulfonamide (0.87 g, 3.0 mmol) and cesium carbonate (1.17 g, 3.6 mmol) in 10 mL of dry DMF was placed in a flame-dried flask. The solution was allowed to stir at room temperature for 1 h. An 80 wt % toluene solution of propargyl bromide (4.45 g, 30 mmol) was then added, and the solution was heated at 80 °C for 48 h. The solution was then allowed to cool, and solvent was removed under vacuum. The crude product was purified by silica gel column chromatography (3:1, hexanes:ethyl acetate) to yield 0.874 g (88.6%) of product. ^{1}H NMR ($CDCl_3$): δ 0.78 (3H, t, $J = 7.3$ Hz), 1.54 (2H, m, $J = 7.6$ Hz), 2.08 (1H, t, $J = 2.4$ Hz), 2.82 (6H, s), 3.32 (2H, t, $J = 7.6$ Hz), 4.15 (2H, d, $J = 2.4$ Hz), 7.13 (1H, d, $J = 8.1$ Hz), 7.49 (2H, m, $J = 7.3$ Hz), 8.20 (1H, d, $J = 7.0$ Hz), 8.31 (1H, d, $J = 8.3$ Hz), 8.50 (1H, d, $J = 8.5$). ^{13}C NMR ($CDCl_3$): δ 10.79, 20.47, 35.38, 45.17, 47.86, 73.19, 77.12, 114.94, 119.41, 122.89, 127.79, 129.38, 129.78, 129.98, 130.26, 134.49, 151.44.

Alkyne-functionalized polyethylene ($PE_{C\equiv C}$). $PE_{CO_2CO_2Et}$ prepared by a literature procedure[11] was immersed in a solution of propargyl alcohol (6.98 g, 125 mmol) and triethylamine (1.37 g, 13.6 mmol). The film was stirred for 4 h before being washed with water (3 × 10 mL) and ethanol (1 × 10 mL). The film was dried under a stream of nitrogen for 2 min. The ATR-IR spectrum confirmed the ester formation with the disappearance of the anhydride peak at 1825 cm^{-1} and the appearance of an ester peak at 1740 cm^{-1}. No alkyne stretch was observed.

General Procedure for Layer-by-Layer Assembly on Polyethylene. Aqueous solutions (12 mL) of the 100 mg of the various alkyne or azide PNIPAM copolymers (**4**, **7**, or **8**) were combined with copper(II) sulfate pentahydrate (5 mg, 0.02 mmol) and sodium ascorbate (10 mg, 0.05 mmol). A PE film (e.g., $PE_{C\equiv C}$ or an azide- or alkyne-rich $PE_{x,N=N=N;y,C\equiv C}$) was then immersed in this solution for 1 h at 25 °C. The films were then washed with water (3 × 10 mL) and ethanol (1 × 10 mL) and dried with streaming nitrogen for 2 min. ATR-IR spectroscopy was used to monitor layering, and the appearance and increase in intensity of the $\nu_{C=O}$ peaks due to the amides of PNIPAM relative to the polyethylene peaks at 1462 cm^{-1} were used to follow the covalent layer-by-layer assembly process.

Control Reactions. In one series of control reactions, a $PE_{2N=N=N;1C\equiv C}$ film was prepared. Subsequent grafting steps that used $PNIPAM_{C\equiv C}$ **4** or $PNIPAM_{N=N=N}$ **7** were then carried out without addition of copper(II) sulfate pentahydrate or sodium ascorbate. In a second control reaction, a $PE_{2N=N=N;1C\equiv C}$ film was prepared. This film was then placed in a 30 mL of THF containing 400 mg of $LiAlH_4$ (10 mmol). Subsequent grafting steps that used $PNIPAM_{C\equiv C}$ **4** or $PNIPAM_{N=N=N}$ **7** were then carried out without addition of copper(II) sulfate pentahydrate or sodium ascorbate.

Azide Reduction on PE_{L3}. A PE_{L3} film placed in a solution of dry THF (30 mL) and $LiAlH_4$ (400 mg, 10 mmol). After 24 h, the excess $LiAlH_4$ was presumed to have reduced the azide groups at the surface. The film at this point was washed with 10% HCl (2 × 10 mL) and stirred in triethylamine (13.88 g, 0.137 mol) for 4 h. A decrease in the intensity in the $\nu_{C=O}$ amide peaks was seen in the ATR-IR spectrum which is consistent with reduction of some amide groups. The reduced film was then subjected to ordinary graft alternating graft stages using $PNIPAM_{C\equiv C}$ **4** or $PNIPAM_{N=N=N}$ **7** in the presence of copper sulfate and sodium ascorbate.

Methylation of a $PE_{2N=N=N;1C\equiv C}$ Layer-by-Layer Assembly. A $PE_{2N=N=N;1C\equiv C}$ was allowed to react with a solution of methyl

iodide (100 mg, 0.71 mmol) in chloroform (35 mL) for 3 days at 40 °C. At this point, the product film was washed with chloroform (3 × 10 mL) and dried under vacuum for 2 days. XPS analysis showed the presence of 0.1 atom % iodide on the surface with about 25% methylation based on the estimated number of triazoles.

Dansyl Labeling Experiments. A THF solution (10 mL) of dansyl alkyne (**10**) (0.6 mg/mL) was prepared and 1 mL of this solution was added to 10 mL of water. A PE_{CO_2H} film, a $PE_{2N=N=N;1C\equiv C}$ film, or a $PE_{6N=N=N=N;6C\equiv C}$ film was immersed in this solution. Copper(II) sulfate (5 mg, 0.02 mmol) and sodium ascorbate (10 mg, 0.05 mmol) were added, and the reaction was allowed to proceed at 25 °C for 1 h. The films were then washed with 0.1 M HCl (2 × 10 mL), 0.1 M NaOH (2 × 10 mL), water (2 × 10 mL), and ethanol (1 × 10 mL). The films were dried under a stream of nitrogen for 2 min. Fluorescent microscopy images were taken. The product of the $PE_{2N=N=N;1C\equiv C}$ film and of the $PE_{6N=N=N;6C\equiv C}$ film had intensities of 305 and 310 (arbitrary units), respectively.

Octadecyl Azide Capping. A $PE_{6N=N=N;6C\equiv C}$ film was immersed in a solution (12 mL) made up of 3:1 THF:water that contained octadecyl azide (30 mg, 0.1 mmol), copper(II) sulfate pentahydrate (5 mg, 0.02 mmol), and sodium ascorbate (10 mg, 0.05 mmol). This reaction mixture was allowed to stir for 1 h. The film was then removed, washed with THF (2 × 10 mL), water (2 × 10 mL), and ethanol (1 × 10 mL), and dried under a stream of nitrogen for 2 min. It was then dried in a vacuum for 4 h. Contact angle goniometry showed a modest increase in the water contact angle from 53° to 74°, consistent with introduction of some octadecyl groups.

Acknowledgment. Support of this work by the National Science Foundation (DMR-0348477) and the Robert A. Welch Foundation (A-0639) is gratefully acknowledged.

Supporting Information Available: Photomicrographs of fluorescently labeled grafts, experimental details for monomer syntheses, and the polyethylene oxidation and activation. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Jiang, C.; Tsukruk, V. V. *Adv. Mater.* **2006**, *18*, 829−840.
(2) Haynie, D. T.; Zhang, L.; Zhao, W.; Rudra, J. S. *Nanomedicine* **2006**, *2*, 150−15.
(3) Decher, G. *Science* **1997**, *277*, 1232−1237.
(4) Bergbreiter, D. E.; Kippenberger, A. M. *Adv. Polym. Sci.* **2006**, *198*, 1−49.
(5) Chan, E. W. L.; Lee, D.-C.; Ng, M.-K.; Wu, G.; Lee, K. Y. C.; Yu, L. *J. Am. Chem. Soc.* **2002**, *124*, 12238−12243.
(6) Bergbreiter, D. E.; Chen, Z.; Hu, H. P. *Macromolecules* **1984**, *17*, 2111−2116.
(7) Greene, G.; Yao, G.; Tannenbaum, R. *Langmuir* **2004**, *20*, 2739−2745.
(8) Chen, M.; McCarthy, T. J. *Macromolecules* **1997**, *30*, 78−86. Hsieh, M. C.; Farris, J.; McCarthy, T. J. *Macromolecules* **1997**, *30*, 8453−8458. Phuvanartnuruks, V.; McCarthy, T. J. *Macromolecules* **1998**, *31*, 1906−1914.
(9) Bergbreiter, D. E. *Prog. Polym. Sci.* **1994**, *19*, 529−560.
(10) Bergbreiter, D. E.; Kippenberger, A. M.; Lackowski, W. M. *Macromolecules* **2005**, *38*, 47−52.
(11) Bergbreiter, D. E.; Franchina, J. G.; Kabza, K. *Macromolecules* **1999**, *32*, 4993−4998.
(12) Bruening, M. L.; Zhou, Y.; Aguilar, G.; Agee, R.; Bergbreiter, D. E.; Crooks, R. M. *Langmuir* **1997**, *134*, 770−778.
(13) Bergbreiter, D. E.; Boren, D.; Kippenberger, A. M. *Macromolecules* **2004**, *37*, 8686−8691.
(14) Zhao, M.; Liu, Y.; Crooks Richard, M.; Bergbreiter David, E. *J. Am. Chem. Soc.* **1999**, *121*, 923−930.
(15) Bergbreiter, D. E.; Simanek, E. E.; Owsik, I. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 4654−4665.
(16) Kim, Y.-S.; Liao, K.-S.; Jan, C. J.; Bergbreiter, D. E.; Grunlan, J. C. *Chem. Mater.* **2006**, *18*, 2997−3004.
(17) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, *40*, 2004−2021. See also Tornoe, C. W.; Christensen, C.; Meldal, M. J. *Org. Chem.* **2002**, *67*, 3057−3064; Rostovtsev, V. V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem. Int. Ed.* **2002**, *41*, 2596−2599.
(18) Huisgen, R. *Angew. Chem., Int. Ed.* **1963**, *2*, 565−632.
(19) Kade, M.; Vestberg, R.; Malkoch, M.; Wu, P.; Fokin, V. V.; Finn, M. G.; Sharpless, K. B.; Hawker, C. *Polym. Prepr.* **2006**, *47*, 376−377. Collman, J. P.; Devaraj, N. K.; Eberspacher, T. P. A.; Chidsey, C. E. D. *Langmuir* **2006**, *22*, 2457−2464. Prakash, S.; Long, T. M.; Selby, J. C.; Moore, J. S.; Shannon, M. A. *Anal. Chem.*, in press. Binder, W. H.; Kluger, C. *Curr. Org. Chem.* **2006**, *10*, 1791−1815. White, M. A.; Johnson, J. A.; Koberstein, J. T.; Turro, N. J. *J. Am. Chem. Soc.* **2006**, *128*, 11356−11357. Nandivada, H.; Chen, H.-Y.; Bondarenko, L.; Lahann, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 3360−3363. Diaz, D. D.; Punna, S.; Holzer, P.; McPherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. G. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4392−4403.
(20) Such, G. K.; Quinn, J. F.; Quinn, A.; Tjipto, E.; Caruso, F. *J. Am. Chem. Soc.* **2006**, *128*, 9318−9319.
(21) Rasmussen, J. R.; Stedronsky, E. R.; Whitesides, G. M. *J. Am. Chem. Soc.* **1977**, *99*, 4736−4745. Rasmussen, J. R.; Bergbreiter, D. E.; Whitesides, G. M. *J. Am. Chem. Soc.* **1977**, *99*, 4746−4756.
(22) Bergbreiter, D. E.; Tao, G.; Kippenberger, A. M. *Org. Lett.* **2000**, *2*, 2853−2855.
(23) Bergbreiter, D. E.; Tao, G. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 3944−3953.
(24) Huang, X.; Witte, K. L.; Bergbreiter, D. E.; Wong, C.-H. *Adv. Synth. Catal.* **2001**, *343*, 675−681.
(25) Zhou, M.; Sivaramakrishnan, A.; Ponnamperuma, K.; Low, W.-K.; Li, C.; Liu, J. O.; Bergbreiter, D. E.; Romo, D. *Org. Lett.* **2006**, *8*, 5247−5250.
(26) Bergbreiter, D. E.; Osburn, P. L.; Frels, J. D. *J. Am. Chem. Soc.* **2001**, *123*, 11105−11106.
(27) Bergbreiter, D. E.; Koshti, N.; Franchina, J. G.; Frels, J. D. *Angew. Chem., Int. Ed.* **2000**, *39*, 1040−1042.
(28) Gonzalez, S. O.; Furyk, S.; Li, C.; Tichy, S. E.; Bergbreiter, D. E.; Simanek, E. E. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 6309−6317.
(29) Bergbreiter, D. E.; Case, B. L.; Liu, Y.-S.; Caraway, J. W. *Macromolecules* **1998**, *31*, 6053−6062.
(30) Bergbreiter, D. E.; Tao, G.; Franchina, J. G.; Sussman, L. *Macromolecules* **2001**, *34*, 3018−3023.
(31) Kleinfield, E. R.; Ferguson, G. S. *Science* **1994**, *265*, 370−373.

MA0701134