Syndio- and cis-1,4 dually selective copolymerization of polar fluoro styrene and butadiene using rare-earth metal catalysts†

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Synthesizing functional butadiene–styrene rubber through coordination polymerization is a theoretical challenge for polymer science, since functional monomers usually deactivate to the applied catalyst. Herein, we report the coordination copolymerization of polar para-fluorostyrene (pFS) and butadiene (BD) using pyridyl–methylene–fluorenyl supported complexes [(Py–CH2–flu)(CH2SiMe3)2(THF)] (Ln = Sc (1a), n = 0; Ln = Lu (1b), n = 1) and pyridyl–cyclopentadienyl supported complexes [(Py–Cp)Ln(η3–C5H5)2 (Ln = Sc (2a), Lu (2b))]. Strikingly, complexes 2a and 2b exhibited dually >99% syndio- and >95% cis-1,4 regio- selectivities and showed obvious characteristics of living polymerization. The insertion of pFS can be facilely tuned in the full range of 0–100% by changing the pFS-to-BD feed ratio. Diblock P(pFS–BD) copolymers were isolated by concurrent addition of monomers and the kinetics study of the copolymerization reaction revealed that BD had the privilege to coordinate to the active metal center. Interestingly, the polymerizations of BD and pFS via pulse loading of BD afforded multi-block copolymer of a novel type of fluoro styrene–butadiene rubber with high thermal stability (Tg = 368 °C). The micro-structures of resultant copolymers were confirmed by 1H and 13C NMR measurements and different phase morphologies of the di- and multi-block polymers were displayed through atomic force microscopy (AFM).

Introduction

Synthetic rubbers have played an irreplaceable role in our modern society since we are living in a world “on wheels”.1 On the other hand these materials are difficult to reuse and recycle and it is nearly impossible for them to be bio-degraded, and so they are the main source of “black pollution”.2,3 For the sustainable development of tyre and rubber industries, fabricating “green tyres” has been the challenging project in the past three decades.4 One of the strategies is to synthesize functional rubbers to improve their compatibility with polar fillers, anticipated to endow tyres with excellent wear resistance (prolonged use time) and low rolling resistance without compromising the wet-skid resistance.5,5 Styrene–butadiene rubber (SBR) is the most widely used synthetic rubber in passenger cars, to fabricate green tyres, by mixing SBR with functionalized fillers.6–9 End-functionalizing SBR prepared by anionic solution polymerization with a halogen group is a convenient method to achieve this target; however, obviously, the number of the incorporated functional groups is rather limited.10,11 Copolymerization with polar group modified monomers is an alternative, anticipated to control the amount and distribution of polar groups in the main chain.12–15 Radical copolymerization of styrene with nitrile-functionalized butadiene,16 2,3-bis (4-ethoxy-4-oxobutyl)-1,3-butadiene18 or N,N-diethyl-2-methylene-3-butynamide (DEA),19 respectively, provides functionalized poly(styrene–butadiene) rubbers, where the cis-1,4 selectivity of the functional butadiene is rather low and its incorporation also needs to improve. Coordination copolymerization is the most powerful method to adjust the regio- and stereoregularity, when the active species are prone to be deactivated by functional groups.20–22 We reported for the first time the coordination homo- and copolymerizations of polar styrene monomers including methoxystyrene (MOSt) and halogen substituted styrenes with the use of side-armed half-sandwich rare-earth metal complexes, with styrene exhibiting high activity and stereoselectivity.23–25 Thereafter copolymers composed of polar styrenes/ethylene and anisylpropynes/ethylene were obtained.26–28 With respect to polar dienes, copolymerization of 2-(2-methylidenebut-3-enyl)furan (MBEF) with isoprene without a masking reagent was achieved by using the bis
(phosphino)carbazolideytrium precursor. The amino-functionalized styrene and butadiene were mediated to copolymerize; however, a solvent fractionation experiment was needed to obtain pure copolymers. Guo et al. recently realized the copolymerization of 4-(N,N-diphenylamino)styrene and isoprene to produce functionalized poly(isoprene-styrene).

Despite remarkable characteristics such as low surface energy and superior chemical resistance of fluoropolymers as well as the excellent properties of thermoplastic syndiotactic poly(p-fluorostyrene) and elastic cis-1,4-PBD, incorporating all these factors into one macromolecular chain, such as fluorinated butadiene-styrene copolymers, with highly regulated microstructures has remained a promising but challenging subject for academic and industrial fields.

Herein, we report the coordination copolymerization of p-fluorostyrene (pFS) and butadiene (BD) by using rare-earth metal precursors bearing various sterics and electronics (Chart 1). When the sterically less hindered and Lewis acidic rare-earth metal precursors are used, copolymerization of pFS and BD occurs rather successfully, in particular in the living mode. The incorporation of polar pFS can be adjusted facilely by adjusting the feed-ratio, and its distribution can be di-block and multi-block according to the loading mode. The resultant P(pFS-BD) copolymers have >99% syndioregularity for P(pFS) sequences and >95% cis-1,4-tacticity for PBD sequences, which show a much higher thermal stability ($T_d = 368$ °C) than that of commercial SBR.

**Experimental section**

**General experimental procedures**

All experiments were performed under a dry and oxygen-free nitrogen atmosphere using standard high vacuum Schlenk techniques or in a glove box. All solvents were purified via a solvent purification system. p-Fluorostyrene was purchased from Aldrich and dried by CaH$_2$ under stirring for 48 hours and distilled before use. Catalysts 1 and 2 were synthesized according to the literature. $^1$H, $^{13}$C NMR spectra were recorded on a Bruker AV400 (FT, 400 MHz for $^1$H; 100 MHz for $^{13}$C) or AV500 (FT, 500 MHz for $^1$H; 125 MHz for $^{13}$C) at 25 °C and CDCl$_3$ was used as the solvent with CHCl$_3$ as the internal standard (7.26 ppm in $^1$H NMR and 77.16 ± 0.06 ppm in $^{13}$C NMR). The molecular weights ($M_n$) and molecular weight distributions of the polymers ($M_n$/$M_w$) were measured by TOSOH HLC-8220 GPC at 40 °C using THF as the eluent (the flow rate was 0.35 mL min$^{-1}$) against polystyrene standards. Differential scanning calorimetry analyses were carried out on a Q100 DSC from TA Instruments under a nitrogen atmosphere at heating and cooling rates of 10 °C min$^{-1}$. Thermo-gravimetric analysis (TGA) was carried out on the TA Instruments SDT Q600 under a nitrogen atmosphere to characterize the thermal stability. AFM was used to study the surface topography of the spin-coated film. Images were obtained using a SPI3800N AFM (Seiko Instruments Inc., Japan). The cantilevers were operated slightly below their resonance frequency of around 20–150 kHz. Image acquisition was performed under ambient conditions. AFM was used in the tapping mode to reduce tip-induced surface degradation and sample damages. Imaging was conducted in the height and phase modes. The sample was prepared by dipping a silicon wafer into a tetrahydrofuran solution of a polymer sample and then placing it on a flat poly(tetrafluoroethylene) plate to allow the solvent to gradually evaporate. Next, the wafer was heated in a vacuum oven at 40 °C to eradicate the solvent before test.

**Homopolymerization of pFS**

A typical procedure for polymerizing pFS is as follows (Table 2, entry 1): under a nitrogen atmosphere and at 20 °C, a toluene (0.5 mL) solution of [Ph$_3$C][B(C$_6$F$_5$)$_4$] (4.8 mg, 5 μmol) and a toluene solution (0.5 mL) of complex 2a (1.9 mg, 5 μmol) were added to a 10 mL flask. Then purified pFS (0.122 g, 1.0 mmol) was added under stirring to initiate the polymerization. The reaction was terminated after 20 min by the addition of a small amount of acidic methanol and the mixture was poured into methanol (50 mL). The precipitated polymer was collected by filtration and dried under vacuum at 40 °C to a constant weight (0.122 g, >99%). All other polymerization data were obtained by following the same procedure but with different pFS or catalyst feed amounts.

**Copolymerization of pFS and BD**

A typical procedure for butadiene and pFS copolymerization by the concurrent addition of both monomers is as follows (Table 1, entry 5): a toluene (1 mL) solution of [Ph$_3$C][B(C$_6$F$_5$)$_4$] (4.8 mg, 5 μmol) and a toluene solution (1 mL) of complex 2a (1.9 mg, 5 μmol) were added to a 10 mL flask under a nitrogen atmosphere and the mixture was kept under stirring for a few minutes. Then a mixture of pFS (0.30 g, 2.5 mmol) and butadiene (0.135 g, 2.5 mmol, 19%w/w in toluene) was added. The reaction was terminated after 10 min by the addition of a small amount of acidic methanol and the mixture was poured into methanol (50 mL). The precipitated polymer was collected by filtration and dried under vacuum at 40 °C to a constant weight (0.294 g, 66%). All other polymerization data were obtained following the same procedure but with different pFS-to-BD feed ratios or catalyst.

**Synthesis of multi-block P(pFS-BD)**

A typical procedure for synthesizing a multi-block P(pFS-BD) is as follows: a toluene (0.5 mL) solution of [Ph$_3$C][B(C$_6$F$_5$)$_4$] (4.8 mg, 5 μmol) and a toluene solution (0.5 mL) of complex 2a (1.9 mg, 5 μmol) were added to a 10 mL flask under a nitro-
gen atmosphere. The mixture was stirred at room temperature for a few minutes. As soon as purified pFS (0.3 g, 2.5 mmol) was added into the above system, butadiene (0.26 g, 4.8 mmol, 13% mol in toluene) was added dropwise over 10 min. Then the reaction was terminated by the addition of a small amount of acidic methanol followed by pouring the mixture into methanol (50 mL) to precipitate the copolymer product. The copolymer was collected by filtration and dried under vacuum at 40 °C to a constant weight (0.47 g, 84%).

Kinetics studies for pFS and BD copolymerization

To a 50 mL flask were added a toluene solution (5 mL) containing [Ph3C][B(C6F5)4] (24 mg, 25 μmol) and complex 2a (9.5 mg, 25 μmol), under a nitrogen atmosphere at 20 °C. After vigorous stirring for a few minutes, a mixture of pFS (0.61 g, 5.0 mmol) and butadiene (0.27 g, 5.0 mmol, 17% mol in toluene) was added to the above system, which was evenly divided into five portions, and the reaction was terminated by adding acidic methanol at the set time (44s, 61s, 75s, 92s, 122s), respectively. Each copolymer was collected by filtration and dried under vacuum at 40 °C and weighed for calculating the conversions of BD and pFS. The kinetics study for the copolymerization of pFS and BD by complex 2b was performed following the same procedure as described above.

When switched to catalyst 1b (Flu-cent-Lu–N (92.16%)) the polymerization activity turned out to be very slow. The GPC curve of the isolated polymer shows multi-peaks, suggesting poor controllability of catalyst 1b during polymerization (Table 1, entries 1 and 2). Catalytic systems based on complexes 2a and 2b with smaller bite angles (Cpcent-Sc–N (86.6°) and Cpcent-Lu–N (84.1°)) possess dual cis-1,4 regio- and perfect stereo-selectivities for the polymerization of butadiene and styrene, respectively; however, whether they are tolerant to polar fluorine substituted monomers is still unknown. Thus the homopolymerization of pFS using complex 2a or 2b upon activation with [Ph3C][B(C6F5)4] was first attempted. Complex 2a showed a high activity to consume pFS completely in 20 min and provided perfect syndiotactic P(pFS) (rrrr > 99%, Fig. 1, entry 1). Changing the pFS-to-scandium molar ratio from 200:1 to 400:1, the molecular weight (Mn) of the resultant poly(pFS) increased from 5.2 × 10^4 to 10.3 × 10^4 while the molecular weight distribution remained constant and narrow (Table 2 entries 1 and 2). In addition, the Mn of P(pFS) increased linearly in proportion to the monomer conversion ([pFS]/[Complex 2a][[Ph3C][B(C6F5)4]] = 1000/1/1) as shown in Fig. 2, suggesting a living polymerization mode. On the other

Results and discussion

First, the copolymerization of p-fluorostyrene (pFS) and butadiene (BD) in toluene at room temperature was investigated by using the catalytic systems of 1/[Ph3C][B(C6F5)4]/[AliBu], which are highly active towards the homopolymerization of pFS and the copolymerization with styrene and ethylene, respectively. The polymerization catalyzed by 1a (Flu-cent-Sc–N (96.26%)) occurred fast but gave a copolymer insoluble in many solvents even under a high temperature of 160 °C. We proposed that cross-linking took place, since the scandium active species is Lewis acidic and can initiate polymerization of the dangling C==C bonds of the 1,2-regulated PBD segments.

<table>
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<th>Entry</th>
<th>Cat</th>
<th>pFS fed (mol %)</th>
<th>Time/min</th>
<th>Conv. (%)</th>
<th>pFS b (mol%)</th>
<th>rrrr b (%)</th>
<th>Selectivity b (%)</th>
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feed ratios, indicating distinguished high activities. The 1H high conversions were obtained in the full range of monomer fraction varying from 10 to 90 mol%. As shown in Table 1, molecular weights are high (\(M_n \approx 5.2 \times 10^4\)). The catalytic behavior to \(2a\) prompted us to explore its copolymerization with BD. The copolymerization with \(2a\) was performed in toluene at 20 °C for 10 min by the concurrent addition of the two monomers under the pFS molar fraction varying from 10 to 90 mol%. As shown in Table 1, high conversions were obtained in the full range of monomer feed ratios, indicating distinguished high activities. The 1H NMR spectrum of the resultant polymer (Fig. 3 (top) (Table 2, entry 4)) shows that the peaks assigned to phenyl protons in the 1,4-tactic PBD segments appear at \(\delta = 6.29-6.89\) ppm, whilst the peaks arising from olefinic protons in the 1,4-tactic PBD segments appear at \(\delta = 5.30-5.46\) ppm. According to the integration intensity ratio of the phenyl and olefinic protons, it was found that the pFS molar fraction in the copolymers varies corresponding to the loaded one, reaching up to 89.1 mol% when the pFS feed ratio was 90 mol%. Catalyst \(2b\) showed a parallel catalytic behavior to \(2a\) albeit with lower activity, which is much better than its performance for the homopolymerization of pFS.

Gel permeation chromatography (GPC) analyses of these crude pFS-BD copolymers without extraction show that the molecular weights are high (\(M_n = 12.4-25.7 \times 10^3\)) and the molecular weight distributions are unimodal and narrow (PDI = 1.1–1.5), suggesting that copolymers were obtained successfully instead of a mixture of homopolymers, which is consistent with the single-sited catalytic behavior and obvious characteristics of the living copolymerization fashion.

The microstructures of these copolymers were defined by 13C NMR spectroscopy analyses. The representative spectrum of a poly(pFS-BD) product with a moderate pFS content of 63.8 mol% is shown in Fig. 3 (bottom) (Table 2, entry 4). The ipso-carbon \(C_c\) giving a doublet at \(\delta = 140.02\) ppm with a coupling constant \(J_{C-F} = 2.5\) Hz indicates the syndiotactic (\(J_{C-F} > 99\%\)) P(BD) block. The strong singlet at \(\delta = 27.42\) ppm indicates a high degree of cis-1,4-PBD unit (>95%). However, the resonances arising from the carbon–carbon linkages of pFS-BD joints are not observed. The 13C NMR spectra of the copolymers with different pFS contents show similar topologies. Meanwhile, the cis-1,4 tacticity of the PBD segments remains unchanged (95–97%) in all copolymers, which is not affected by the pFS content. All these characterizations suggest that the copolymers obtained by using \(2a\) might have a diblock sequence. To confirm this deduction, a kinetics study of the copolymerization reaction in toluene at 20 °C by the concurrent addition of both monomers was carried out. As shown in Fig. 4 (top), when the polymerization catalyzed by \(2a\) was carried out for 1 min, the isolated product was almost pure PBD corresponding to the almost complete conversion of BD (>99%), whereas no pFS incorporation was found. With the polymerization going on and consumption of BD monomer, the pFS fraction in the copolymer increased dramatically. A similar phenomenon was observed using the \(2b\) system (Fig. 4 (bottom)). These results indicate that in the presence of pFS, BD has the priority when coordinating to the active metal center and propagating into polymer. Until BD is almost fully consumed, pFS starts to insert into Sc-PBD active species to generate the diblock structure without homopolymer contaminants.

Multi-block copolymers as a kind of significant macromolecular materials exhibit outstanding properties. To reuse and
strengthen the interfaces of abandoned PE and iPP, Coates et al. produced PE/iPP multi-block polymers by pyridylamido-hafnium catalyst activated with B(C6F5)3.37 Miller and Ellison synthesized multi-block poly(ethylene terephthalate)-polyethylene, which enhances the ability to recycle PET/PE mixed waste streams.38 In other aspects, multi-block sulfonated poly(arylene ether sulfone)s are used in polymer electrolyte membrane fuel cells.39 According to the living polymerization mode of BD and pFS in the catalyst 2a system, a multiple BD feeding method was adopted to exclude the formation of long BD and pFS sequences for preparing multi-block P(pFS-BD) copolymers. A typical procedure was carried out in which pFS (0.3 g) was added in one portion into the polymerization system catalyzed by 2a/[Ph3C][B(C6F5)4] (5 μmol), and then a BD solution (2.0 g, 13%wt) was added over 10 min. As soon as the addition of the BD solution was completed, the copolymerization was terminated and a copolymer with 26.7 mol% pFS content was isolated (0.47 g, Mn = 13.9 × 10^4, PDI = 1.9). Its molecular weight distribution gives a unimodal peak (Fig. S32†), suggesting successful copolymerization. All the resonances in the 1H NMR spectrum of the multi-block copolymer are broadened as compared to the corresponding resonances in the diblock copolymer, especially in the aromatic region (Fig. 5). In the 13C spectrum, the resonances of carbons from the joints of the multi-block copolymer are observed (m, n, o, p and q points in Fig. 6). The averaged chain lengths of PBD and P(pFS) in the multi-block copolymer obtained by calculating the ratios of the integration intensities of the corresponding repeat units and the joints in the quantitative 13C NMR spectrum are 161 and 27, respectively (Fig. S21†). Since the highly syndiotactic P(pFS) is crystalline,35 the diblock copolymer with a 27.0 mol% P(pFS) content (one long sequence) has a micro-phase separation rather different from the multi-block copolymer with a similar P(pFS) content (26.7 mol%, many short sequences). As shown in Fig. 7, the AFM micrograph of the diblock copolymer (left) reveals a larger degree of phase separation than the multi-block one (right). In addition, there is no
obvious melting point in the multi-block P(pFS-BD) as compared with the di-block one \( T_m = 316 \, ^\circ\text{C} \) in the curves of the differential scanning calorimetric analyses (Fig. S34†). The 5% mass loss temperature of the multi-block copolymer is at 368 °C, which is much higher than that of the commercial SBR (Fig. 8),\textsuperscript{40} indicating that it is a quite different and more thermally stable material.

### Conclusions

In summary, we have demonstrated the unprecedented highly cis-1,4 selective (>95%) and perfectly syndiospecific (>99%) copolymerization of BD and pFS using pyridyl functionalized Cp ligated CGC rare-earth metal bis(allyl) complexes, which provide an active rare-earth metal center with an open coordination sphere to avoid low cis-1,4 selectivity and cross-linking process. In addition, the excellent tolerance for polar groups of these catalysts permits the insertion of pFS facilely tuned in the full range of 0–100% by changing the pFS-to-BD ratio. The diblock sequence copolymer is obtained by the concurrent addition of pFS and BD, with BD as the privilege, which is consistent with the kinetics study. By the merit of the living copolymerization characteristics, remarkably, a multi-block copolymer is isolated, for the first time, via pulse loading of butadiene. An unexpectedly high thermal stability was found for the multi-block copolymer during TGA testing. This work paves a new way to access functional styrene–butadiene copolymers with controllable regio- and stereo-regularities as well as sequence distribution. The mechanical properties of the di- and multi-block copolymers and the comparison of these copolymers with the SBR prepared by the traditional anionic mechanism are under investigation.

### Conflicts of interest

There are no conflicts to declare.

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