# Quasi-Controlled Polymerization through a Nickel Catalyst Process of a Functionalized Thiophene Monomer: Kinetic Studies and Application to the Synthesis of Regioregular Poly(thiophene-3-acetic acid)

**P. Vallat, J.-P. Lamps, F. Schosseler, M. Rawiso, and J.-M. Catala***

*Institut Charles Sadron (CNRS-ULP), 6 rue Boussingault, 67083 Strasbourg, France*

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## Introduction

Within the past few years the synthesis of regioregular polythiophene has been the object of a renewed interest due to an original approach[1−5] which allows a chain growth polymerization of alkylthiophene monomers. This process is based on the association of a nickel catalyst with an activated monomer. The active site can be a chloro-zinc or a halogenomagnesium species according to the chemical nature of the monomer and the reagent used. Kinetic studies and characterizations have shown that the degree of polymerization increases with conversion, that samples exhibit a low polydispersity, and that the molecular weight depends on the nickel−monomer ratio as in a living polymerization. In order to synthesize well-defined regioregular polyelectrolyte polythiophene based on carboxylate group, we applied this process to a functionalized monomer **2** able to be hydrolyzed after polymerization (Scheme 1).

The monomer **2** exhibits only one methylene group between the ester group and the thiophene ring in order to minimize, after hydrolysis, the hydrophobic part of the polyelectrolyte and the interaction of the carboxylate group with the conjugated backbone. Regioregular poly(alkyl thiophene-3-carboxylate) were recently synthesized by using the Ni catalyst process with dibromo monomers.[6] Regioregular poly(thiophene-3-alkanoic acid) with two and seven methylene groups have also been prepared[7] through another process. For monomers of the **2** type, it was found that the methyl acetate−thiophene[8] was polymerized through an oxidative method. This route leads to nonregioregular samples with high polydispersity. To obtain a regioregular polythiophene with a rather low polydispersity, the new process was applied to a monomer bearing a bromo and an iodo group on positions 2 and 5. A more bulky side group, the hexyl acetate one, was introduced in order to limit a possible aggregation or precipitation that could occur during the propagation step.

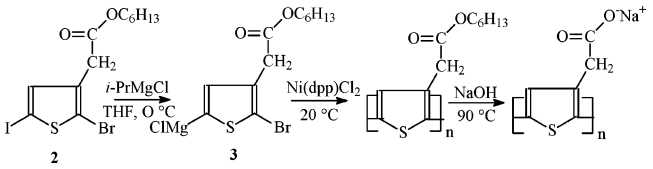
In this paper, we suggest that the polymerization of a functionalized acetate thiophene can be achieved through a Ni catalyst process leading to a regioregular polymer whose molecular weight depends of the feed ratio of monomer to Ni catalyst.

## Experimental Section

**Materials.** 3-Thiopheneacetic acid (98%), 1-hexanol (98%), *N*-bromosuccinimide (98%), iodobenzene diacetate (98%) , and Ni(dpp)$Cl_2$ (99%) were obtained from Acros and used without further purification. THF (Carlo Erba, 99.5%) was distillated twice on benzophenone sodium radical anion before use.

**Synthesis of 2-Bromo-3-thiopheneacetic Acid.** 3-Thiopheneacetic acid (10 g, 70 mmol) was added to 100 mL of THF in a 250 mL flask. The solution was cooled to 0 °C, and *N*-bromosuccinimide (15 g, 84 mmol) was introduced under stirring. After 4 h, the mixture was warmed up and maintained at room temperature overnight. The solution was then filtered and evaporated, and the residue was submitted to successive dissolution and filtration in ethyl ether and pentane before evaporation. It has to be noted that *N*-bromosuccinimide was used in excess to avoid the remaining of 3-thiopheneacetic acid which leads to difficult purifications in the following step. The final residue 12 g (78%) contained 10% of 2,5-dibromothiopheneacetic acid.

**Scheme 1**




2 3

**Synthesis of 2-Bromo-3-hexyloxycarbonylmethylthiophene (1).** The 2-bromo-3-thiopheneacetic acid (12 g) of the previous synthesis was added to 70 mL of hexanol containing a few drops of sulfuric acid (96%) in a 250 mL flask. The solution was heated at 100 °C for one night. After cooling at room temperature, 50 mL of ether was introduced, and the solution was washed twice with a saturated aqueous solution of $K_2CO_3$. The ethereal solution was dried over $MgSO_4$ before evaporation under vacuum. The residue was than purified by flash chromatography using silica gel and cyclohexane/$Et_2O$ (95/5) as eluent. 6.9 g (40%) of the expected compound was isolated after evaporation. $^1$H NMR ($CDCl_3$): $\delta$ = 0.89 (t, $J$ = 6.8 Hz, C**H**$_3$), 1.30 (m, (C**H**$_2$)$_3$), 1.63 (m, C**H**$_2$−$CH_2O$), 3.63 (s, C**H**$_2$−C(O)O), 4.12 (t, C**H**$_2$O), 6.94 (d, $J$ = 5.8 Hz, $C_4$**H**), 7.24 ppm (d, $J$ = 5.8 Hz, $C_5$**H**). $^{13}$C NMR: $\delta$ = 170.08 (**C**(O)O), 133.83 (**C**$_3$) , 128.80 (**C**$_4$), 125.76 (**C**$_5$), 111.56 (**C**Br), 65.24 (**C**$H_2$O), 35.18 (**C**$H_2$−C(O)O), 31.49 (**C**$H_2CH_2$O), 28.64 (**C**$H_2$), 25.63 (**C**$H_2$), 22.66 (**C**$H_2CH_3$), 14.55 ppm (**C**$H_3$).

**Synthesis of 2-Bromo-3-hexyloxycarbonylmethyl-5-iodothiophene (2).** 2-Bromo-3-hexyloxycarbonylmethylthiophene (**1**) (5.57 g, 17.4 mmol) was introduced in a 100 mL flask containing 50 mL of dichloromethane. After cooling to 0 °C, iodine (2.4 g, 9.55 mmol) and iodobenzene diacetate (3.08 g, 9.55 mmol) were added successively to the stirred solution. The mixture was stirred during 4 h until a solution of $Na_2S_2O_3$ (10 mmol) was added. The organic phase was dried over $MgSO_4$ before filtration and evaporation. The major part of iodobenzene remaining in the raw product was removed at 40 °C under vacuum. The residue was purified by flash chromatography using silica gel (eluent: cyclohexane/$Et_2O$, 95/5) to give 4.9 g (65%) of **2**. $^1$H NMR ($CDCl_3$): $\delta$ = 0.89 (t, $J$ = 7.1 Hz, C**H**$_3$), 1.26 (m, (C**H**$_2$)$_3$), 1.63 (m, C**H**$_2$−$CH_2O$), 3.60 (s, C**H**$_2$−C(O)O), 4.12 (t, $J$ = 6.8 Hz, C**H**$_2$O), 7.13 ppm (s, $C_4$**H**). $^{13}$C NMR: $\delta$ = 170.18 (**C**(O)O), 138.79 (**C**$_4$), 136.21 (**C**$_3$), 114.87 (**C**Br), 72.21 (**C**I), 65.87 (**C**$H_2$O), 35.20 (**C**$H_2$−C(O)O), 31.86 (**C**$H_2CH_2$O), 28.98 (**C**$H_2$), 26.02 (**C**$H_2$), 23.06 (**C**$H_2CH_3$), 14.55 ppm (**C**$H_3$).

**General Procedure of Polymerization.** A three-neck flask (100 mL) containing 483.6 mg of **2** (1.12 mmol) was placed under argon before addition of 25 mL of THF (anionically pure). After cooling at 0 °C, *i*-PrMgCl (2.0 M solution in THF, 0.56 mL, 1.12 mmol) was added via a syringe. The reaction medium was maintained at 0 °C under stirring for 20 min. After a fast warming at 20 °C, 20 mL of the solution was added in a new flask containing 9.7 mg of Ni(dpp)$Cl_2$ (0.018 mmol). The mixture was stirred at 20 °C for 1 h before a small aliquot was withdrawn and quenched with $CH_3$-OD. The reaction solution was then deactivated by addition of 0.5 mL of water. After filtration, the solid content was obtained by evaporation of the solvent and drying under vacuum. The amount of monomer polymerized was evaluated from $^1$H NMR ($CDCl_3$) of the withdrawal. The molecular weight was determined on the

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crude solid by dissolution in THF, filtration, and injection in GPC. Yield: 82%; $M_n = 9100$, $M_w/M_n = 1.25$.

NMR of a precipitated sample: $^1$H NMR ($CDCl_3$): $\delta = 0.87$ (t, $J = 7.2$ Hz, C**H**$_3$), 1.30 (m, (C**H**$_2$)$_3$), 1.65 (m, C**H**$_2$−$CH_2O$), 3.81 (s, C**H**$_2$−C(O)O), 4.16 (t, $J = 6.8$ Hz, C**H**$_2$O), 7.19 ppm (s,$C_4$**H**). $^{13}$C NMR: $\delta = 170.53$ (**C**(O)O), 138.44 , 133.32, 131.26 (**C**$_2$ ,**C**$_3$, and $C_5$), 129.97 (**C**$_4$H), 65.39 (**C**H$_2$O), 35.03 (**C**H$_2$−C(O)O), 31.40 (**C**H$_2$CH$_2$O), 28.54 (**C**H$_2$), 25.55 (**C**H$_2$), 22.52 (**C**H$_2$CH$_3$), 13.98 ppm (**C**H$_3$).

**Hydrolysis Reaction.** A solution of 0.1 g of polymer (0.45 mmol) dissolved in THF (5 mL) was added dropwise in 20 mL of NaOH solution (14.2 mmol) and placed under argon. After heating 2 h at 70 °C, under argon, the reaction medium was kept at 90 °C for 15 h. After cooling at room temperature, dilute chlorhydric acid was added on the final homogeneous solution until the pH reaches 9. At this pH, the polymer is under its salt form. The solution was then dialyzed and freeze-dried.

**Characterizations.** $^1$H and $^{13}$C NMR measurements were performed on a Bruker AC 400 spectrometer in $CDCl_3$ or $D_2O$. Molecular weight was determined at room temperature, with a size exclusion chromatography (SEC) apparatus equipped with a refractometer (Shimadzu) and five columns PL GEL(10 $\mu$m particles) (3 mixed B, $10^3$ Å, $10^5$ Å), using THF as eluent (flow rate: 1 mL/min). One precipitated sample of high molecular weight was characterized with a similar apparatus equipped with a light scattering detector (Dawn).The d*n*/d*c* of the poly(3-(hexyloxycarbonylmethyl)thiophene) has been found equal to 0.200 mL g$^{-1}$. From the $M_w$* determined with a polystyrene calibration curve and the $M_w$ obtained by light scattering, the ratio of proportionality was calculated: $M_w/M_w^* = 30\,200/23\,200 = 1.3$. The $M_n$ value is then equal to $M_n = M_n^* \times 1.3 = 15\,000 \times 1.3 = 19\,500$. The UV−vis spectra were obtained with a UV−vis spectrophotometer (Varian Cary 50).

## Results and Discussion

**Magnesium−Halogen Exchange Reaction.** The first step of the process is a magnesium−halogen exchange reaction applied on monomer **2** by addition of *i*-PrMgCl in stoechiometry. This Grignard reagent can react on the ester group and/or lead to an exchange reaction with the bromine atom as observed for the hexyl 2,5-dibromothiophene acetate.[6] Therefore, the first step of the process, generation of the 2-bromo-5-chloromagnesiohexyloxycarbonylmethylthiophene (**3**), was checked. The reaction was followed by NMR from withdrawals quenched with $CH_3OD$. The replacement of the active site by a deuterium atom simplifies the $^1$H NMR spectrum in the aromatic region and allows to observe eventual proton deactivation. The expected 2-bromo-5-deuterio-3-hexyloxycarbonylmethylthiophene leads to one peak corresponding to one single aromatic proton ($\delta =$ 6.95 ppm), whereas the formation of 2-bromo-3-hexyloxycarbonylmethylthiophene (**1**) by protonation gives two doublets corresponding to the two protons of the thiophene ring. Usually, under these experimental conditions (reactants concentration and temperature), 15 min is necessary to obtain a complete formation of species **3**. In the $^1$H NMR and $^{13}$C NMR spectra, neither substitution of the ester by an isopropyl group nor exchange of the bromine atom is detected. This last point confirms the regiospecific exchange between the Grignard and the thienyl iodide observed previously for the 2-bromo-3-alkyl-5-iodothiophene.[9] Nevertheless, spectra indicate the formation of 10% of protonated monomer **1**. This observation can be a result of residual protonated species present in the medium and/or to a deactivation reaction. Therefore, the stability of species **3** was studied by $^1$H and $^{13}$C NMR at two temperatures, 0 and 20 °C. For this last experiment, a part of the solution prepared at 0 °C was introduced ($t = 30$ min) in a new flask maintained at room temperature. Figure 1 shows that the activated monomer **3** is stable only at 0 °C. At 20 °C, **3** leads to the formation of **1** (identified by $^1$H NMR and $^{13}$C NMR) through a protonation reaction. The rate of this reaction (Figure 1) seems constant until 50% of conversion of species **3**, and this suggests a first-order kinetic. This first-order kinetic implies that the concentration of the compound, involved in the protonation of **3**, is very high in comparison to **3** concentration. Only the solvent agrees with this requirement, but "metalation" of tetrahydrofuran occurs with organolithium compounds and not with Grignard reagents. Nevertheless, the presence of this side reaction, at room temperature, implies also that the polymerization process can be applied successfully, at this temperature, only if the propagation rate is much higher than the protonation rate.

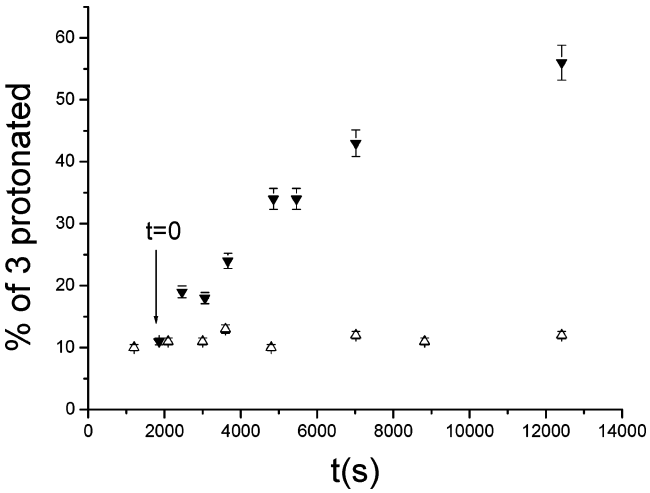


**Figure 1.** Percent of monomer **3** deactivated by protonation vs time, [**2**] = 4.5 × 10$^{-2}$ M: (△) $T = 0$ °C, (▲) $T = 20$ °C.

**Table 1. Effect of the Ratio $r$ = [2]/[Catalyst] or $r'$ = [3 Polymerized]/[Catalyst] on the Number-Average Molecular Weight of the Poly (3-(hexyloxycarbonylmethyl)thiophene)[a]**

| $r$ | $M_n$* | $M_w/M_n$ | yield (%) | **1** (%) | $r'$ | $M_n$ |
|---|---|---|---|---|---|---|
| 147 | 15500 | 1.5 | 78 | 22 | 117 | 20200 |
| 100 | 13100 | 1.45 | 80 | 20 | 80 | 17000 |
| 50 | 7000 | 1.35 | 82 | 18 | 40 | 9100 |
| 25 | 4200 | 1.25 | 81 | 19 | 20 | 5500 |
| 10 | 2100 | 1.25 | 81 | 19 | 8 | 2730 |

[a] [**2**] = 4.5 × 10$^{-2}$ M, $T = 20$ °C, $M_n$* polystyrene calibration curve, $M_n$ polythiophene calibration.

**Propagation Step.** The activated monomer **3** being stable at 0 °C, several attempts of polymerization were first carried out at this temperature. They were unsuccessful especially as regards to the control of the molecular weight because polymer aggregation occurs more rapidly than propagation. To limit this phenomenon, it was decided to apply the process at room temperature. The same volume of the activated monomer was added to different amounts of catalyst to check the effect of the ratio $r$ = [**2**]/[catalyst] on the polymer molecular weight. Data in Table 1 show that the number-average molecular weight $M_n$ depends on the ratio $r$ but more precisely on $r'$ ($r'$ = [**3** polymerized]/[catalyst]), which has been determined by taking into account the species **3** lost by formation of **1** (18−20%). For $r' < 80$ , the plot of $M_n$ vs $r'$ (Figure 2) shows a linear increase of the molar mass close to the theoretical line established by considering one Ni catalyst molecule per chain. For $r' > 80$, the $M_n$ value is lower than the one expected. At the same time, the molecular weight distribution (Table 1) of the nonprecipitated polymer is rather narrow for low $r'$ values (PDI = 1.25) but broadens as $r'$ increases (PDI = 1.5). This implies that the initiation rate is fast compared to the propagation

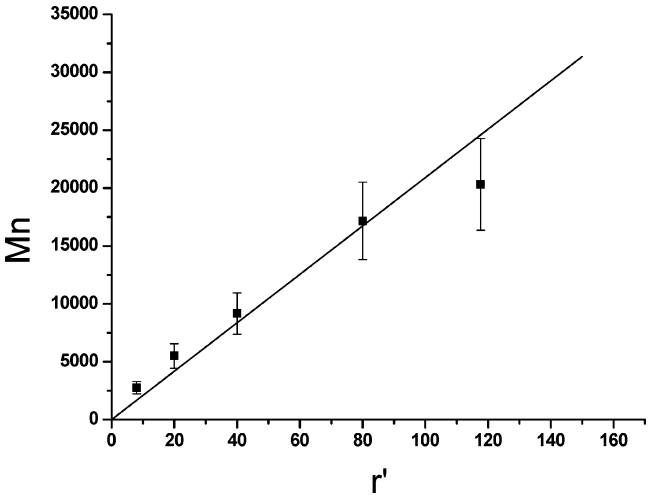


**Figure 2.** $M_n$ vs $r'$ = [**3** polymerized]/[catalyst] from data of Table 1.

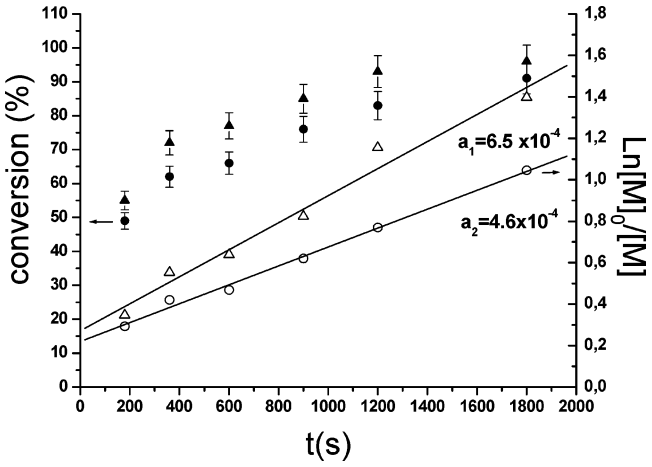


**Figure 3.** Conversion yield of monomer **3** vs time and $\ln[M]_0/[M]$ vs time, [**2**] = $4.2 \times 10^{-2}$ M, $T$ = 20 °C: (▲) $r$ = 97, (▽) $r$ = 147.

rate and that a part of the active sites lead to a transfer reaction or to a termination reaction or become inaccessible to monomer as the chain length increases. Data also points out that 8−10% of species **3** are protonated during the polymerization step at 20 °C since 10% are protonated at 0 °C during the activation step. This suggests, in relation to the graph in Figure 1, that this deactivation occurs in the first 15 min and that the propagation step is mainly completed during this period. To verify this last hypothesis and also the stability of the propagating species, the monomer consumption was followed during two experiments (Figure 2) carried out for two distinct $r$ values.

In Figure 3, it can be observed that more than 50% of monomer are consumed in less than 3 min and that the propagation rate is higher for the lowest $r$ value. The plot, $\ln[M]_0/[M]$ vs time (Figure 3), shows that the fast propagation reaction, occurring at the beginning of the process, is followed by a polymerization rate much slower. However, during this step, the concentration of the active species remains unchanged, and the ratio of the corresponding slopes ($a = k_p$[active sites]) is close to the theoretical ratio (established from eq 1):

$$\ln[M]/[M]_0 = k_p[\text{active sites}]_t = k_p[Ni]_t \qquad (1)$$

$$k_p[\text{active site}]_1/k_p[\text{active site}]_2 = a_1/a_2 = 6.5/4.6 = 1.41$$

$$[Ni]_1/[Ni]_2 = 147/97 = 1.5$$

This observation suggests that the increase in polydispersity and the decrease of the polymerization rate are not related to a termination reaction but to the aggregation of the polymer chains which disfavors propagation on the active sites. Nevertheless, for $r' > 80$, the $M_n$ value being lower than the theoretical value, only the formation of new growing chains by a transfer reaction permits to explain this result.

**Polymer Characterization and Hydrolysis Reaction.** The different samples were precipitated in methanol, and after drying, their regioregularity was evaluated by NMR spectroscopy. As expected, the process permits to access to HT-polythiophene since only one peak is observed in $^1$H NMR for the aromatic proton $\delta = 7.18$ ppm and in $^{13}$C NMR (DEPTH 45) $\delta = 129.9$ ppm. The examination of the complete spectrum shows that no side reactions occur on the ester group during the propagation. The UV spectrum in THF presents a maximun at $\lambda = 422$ nm.

The hydrolysis reaction was carried out with a sample presenting the following characteristics: $M_n = 20\,900$, $M_w/M_n = 1.45$. The $^1$H NMR spectrum of the freeze-dried sample, in $D_2O$, shows a complete disappearance of the protons of the hexyl groups. Three broad peaks are observed. The first one ($\delta = 9.8$ ppm) corresponds to some carboxylic groups issued of a proton exchange reaction with the distilled water (pH = 6) during the dialysis. The two others peaks can be attributed to the protons of the thiophene ring ($\delta = 6.8$ ppm) and of the $CH_2$ ($\delta = 3.5$ ppm) group of the side chain. The UV−vis absorption spectrum, carried out at room temperature, in water after adjusting the pH to 9 (polymer under its salt form) presents a maximum at $\lambda = 512$ nm.

## Conclusion

In this paper, we have shown that a functionalized thiophene monomer (**2**) can be polymerized in a quasi-controlled manner by using Ni(dpp)$Cl_2$ as catalyst and by adjusting the ratio $r$ = **[2]**/[Ni catalyst]. Despite a protonation reaction of the activated monomer **3**, initiation and propagation rates are sufficiently high to achieve the desired molecular weight. The hydrolysis of these highly regioregular polythiophenes in polyelectrolytes was achieved at 90 °C. The thermodynamics and structure of their aqueous solution are currently under study.

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