

Characteristics and mechanism of L-lactide polymerization by lanthanide 2,6-dimethylaryloxyde

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Abstract

Single component rare earth 2,6-dimethylaryloxyde ($\text{Ln}(\text{ODMP})_3$) is used as catalyst or initiator for the ring-opening polymerization of L-lactide (LLA) for the first time. The effects of reaction conditions on the LLA polymerization with $\text{Ln}(\text{ODMP})_3$ have been examined in detail. The polymerization activity of various rare earth 2,6-dimethylaryloxyde is in the order: $\text{La} > \text{Nd} > \text{Sm} > \text{Gd} > \text{Er} > \text{Y}$. The optimum conditions of the ring-opening polymerization of LLA are as follows: $[\text{LLA}] = 2.0 \text{ mol/l}$, $[\text{LLA}]/[\text{La}] = 1000$ (molar ratio), 80°C , 40 min, in toluene. The mechanism study by $^1\text{H NMR}$ indicates that the monomer inserts into Ln-O bond of catalyst through acyl-oxygen bond cleavage. © 2004 Elsevier B.V. All rights reserved.

Keywords: L-Lactide; Ring-opening polymerization; Characteristics; Mechanism; Lanthanide 2,6-dimethylaryloxyde

1. Introduction

Biodegradable poly(L-lactide) (PLLA) is promising in the biological and medical fields for instance as surgical sutures, vehicles for drug delivery, resorbable prostheses, and agricultural membranes due to its biocompatibility and biodegradability with releasing nontoxic by-products. PLLA can be prepared with ring-opening polymerization from LLA catalyzed by organometallic compounds containing aluminum [1–3], tin [4], calcium [5], and iron [6]. Quite recently, it has been reported that trivalent lanthanide compounds are efficient for such ring-opening polymerization reaction, and some of them exhibit exceptionally high reactivity and generate living polymerization. Feijen and coworkers used lanthanide tris(2,6-di-*tert*-butylphenolate)s and various alcohols for the preparation of polyesters [7,8]. In our previous work, rare earth catalysts and one component rare earth catalysts have successfully developed for the synthesis of polyester [9–12]. However, there is no study on the ring-opening polymerization of LLA by single component rare earth aryloxyde catalyst. In this article, we report the ring-opening polymerization of LLA using single

component lanthanide 2,6-dimethylaryloxyde [$\text{Ln}(\text{ODMP})_3$] (Scheme 1) as catalyst, with emphasis on the polymerization characteristics and mechanism.

2. Experimental

2.1. Materials

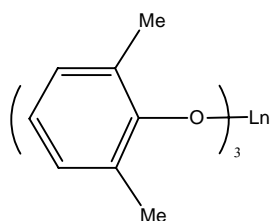
LLA was prepared from L-lactic acid as previously reported [13]. The crude product was purified by recrystallization three times from dried ethyl acetate, then dried for 24 h in vacuum at 30°C . Toluene and tetrahydrofuran (THF) were dried by refluxing over the blue benzophenone–Na complex and distilled prior to use. Ethyl acetate was distilled from P_2O_5 . Methanol was used without further purification. Rare earth oxides with a purity of 99.99% were purchased from Shanghai Yuelong factory.

2.2. Catalyst preparation

Anhydrous rare earth chlorides were prepared by sublimating the mixture of hydrated rare earth chloride and ammonium halide under reduced pressure [14]. $\text{Ln}(\text{ODMP})_3$ was synthesized by the reaction of the anhydrous rare earth chloride and sodium 2,6-dimethylaryloxyde as described in [15].

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Ln(ODMP)₃: Ln = La, Nd, Sm, Gd, Er, Y

Scheme 1. The Structure of Ln(ODMP)₃, Ln = La, Nd, Sm, Gd, Er, Y.

2.3. Polymerization

All glass ampoules for the polymerization were flamed and purged with dry nitrogen several times. LLA polymerization was carried out in dried glass ampoule with toluene as the solvent under a nitrogen atmosphere. In a typical procedure, LLA and toluene were transferred into the ampoule, and then appropriate catalyst was injected by a syringe. After the desired reaction time, polymerization was terminated by introducing methanol with 5% HCl. The mixture was poured into an excess of methanol, then filtrated and washed with methanol several times. The purified polymer was dried in vacuum at 40 °C for 24 h.

2.4. Measurements

Intrinsic viscosity of polymer was determined in CHCl₃ at 25 °C with Ubbelohde viscometer. The viscosity average molecular weight (M_v) was calculated using the following equation: $[\eta] = 5.45 \times 10^{-4} M_v^{0.7}$ [16]. The number average molecular weight (M_n) and molecular weight distribution (MWD) were measured by gel permeation chromatograph (GPC) (Waters 150) at 25 °C, polystyrene as the calibration standards, and THF as the eluent (1.0 ml/min). ¹H NMR was performed in CDCl₃ on a Bruker Avance DWX500 spectrometer at room temperature and with tetramethylsilane (TMS) as internal standard. The thermal behavior of the polymer was studied by using a differential scanning calorimeter (DSC) on Perkin-Elmer Pyris apparatus. The sample was heated from 60 to 190 °C at a rate of 10 °C/min, cooled to 60 °C and then heated to 190 °C again at a rate of 10 °C/min. The maximum of the endothermic peak was taken as the melting temperature.

3. Results and discussion

3.1. Characteristics of polymerization

Various rare earth 2,6-dimethylaryloxides including light and heavy rare earth compounds have been examined for the LLA polymerization in toluene and the results are compiled in Table 1. The data indicate that LLA polymerization can be conducted with all of rare earth catalysts tested, but

Table 1
Ring-opening polymerization of LLA by Ln(ODMP)₃

No.	Ln(ODMP) ₃	Temperature (°C)	[LLA]/[Ln]	Conversion (%)	M _v × 10 ⁻⁴
1	La	70	1000	87.2	4.49
2		80	1000	96.8	5.22
3	Nd	70	1000	73.3	3.75
4		80	1000	85.0	4.23
5	Sm	70	1000	64.7	2.81
6		80	1000	77.9	3.70
7	Gd	70	800	69.6	2.58
8		80	800	80.4	3.13
9	Er	70	400	31.1	1.35
10		80	400	46.8	2.04
11	Y	70	200	9.12	–
12		80	200	20.5	0.77

Conditions: [LLA] = 2.0 mol/l, 40 min, in toluene.

it is noteworthy that the relatively higher molecular weight and yield polymers are formed with light rare earth catalysts, especially for La(ODMP)₃. In contrast, Y(ODMP)₃ shows very low catalytic activity for LLA polymerization, even with the monomer to initiator molar ratio as low as 200, the monomer conversion is only 20% after 40 min at 80 °C. The catalytic activity of different rare earth compounds follows the order: La > Nd > Sm > Gd > Er > Y, which may result from different coordination abilities of these rare earth elements with the monomer. The influence of different organic solvents on the polymerization of LLA with La(ODMP)₃ is summarized in Table 2. It can be seen that the molecular weight of PLLA and the conversion of LLA achieved in non-polar solvent are higher than those in polar solvents.

Table 3 gives the influences of LLA concentration and monomer to initiator ([LLA]/[La]) molar ratio on the LLA polymerization with La(ODMP)₃ in toluene. As seen in Table 3, PLLA with yield above 95% and molecular weight of 5.2×10^4 is obtained at the concentration of 2.0 mol/l in the concentration range studied. With higher concentration, the monomer conversion and molecular weight of PLLA decrease and the molecular weight distribution broadens. It is also found from Table 3 that the monomer conversion and the molecular weight of polymer increase with the

Table 2
The effect of solvent on LLA polymerization by La(ODMP)₃

No.	Solvent	Temperature (°C)	Conversion (%)	M _v × 10 ⁻⁴
1	Toluene	70	87.2	4.49
2		80	96.8	5.52
3	CHCl ₃	70	39.5	1.75
4		80	58.6	2.43
5	THF	70	26.0	1.14
6		80	43.4	1.86

Conditions: [LLA] = 2.0 mol/l, [LLA]/[La] = 1000, 40 min.

Table 3

The effect of the monomer and catalyst concentration on LLA polymerization by La(ODMP)₃

No.	[LLA] (mol/l)	[LLA]/[La]	Conversion (%)	Mv × 10 ⁻⁴	Mn × 10 ⁻⁴	MWD
1	1.0	1000	80.2	3.94	3.48	1.41
2	2.0	1000	96.8	5.22	4.73	1.54
3	3.0	1000	92.7	4.39	3.85	1.57
3	4.0	1000	87.4	3.60	3.24	1.61
5	2.0	600	88.3	3.55	3.07	1.63
6	2.0	800	93.1	4.48	4.05	1.58
7	2.0	1200	85.5	4.02	3.69	1.54

Conditions: 80 °C, 40 min, in toluene.

Table 4

The effect of reaction temperature and time on polymerization by La(ODMP)₃

No.	Temperature (°C)	Time (min)	Conversion (%)	Mv × 10 ⁻⁴	Mn × 10 ⁻⁴	MWD
1	70	40	87.2	4.49	4.01	1.48
2	80	40	96.8	5.22	4.73	1.54
3	90	40	92.5	4.66	4.23	1.61
4	100	40	84.9	3.75	3.46	1.70
5	80	10	45.4	2.63	2.25	1.18
6	80	20	68.0	3.91	3.50	1.27
7	80	30	89.7	4.52	4.24	1.41
8	80	50	93.0	4.80	4.39	1.57

Conditions: [LLA] = 2.0 mol/l, [LLA]/[La] = 1000, toluene.

increasing of the [LLA]/[La] molar ratio, but they do not parallel the [LLA]/[La] molar ratio. [LLA]/[La] of 1000 molar ratio is essential for preparing high yield and molecular weight polymer simultaneously. Increasing catalyst content presumably leads to the formation of more active species, thus producing more and shorter polymeric chains.

Polymerization temperature and time significantly affect the ring-opening polymerization of LLA, as shown in Table 4. It can be seen that 80 °C is the most suitable temperature for the LLA polymerization with La(ODMP)₃ in toluene. At higher temperature, PLLA is easily degraded, whereas below 80 °C the polymerization reaction proceeds slowly. The results in Table 4 also show the conversion of LLA is nearly complete in 40 min with [LLA]/[La] of 1000 molar ratio at 80 °C. A further prolongation of the reaction time results in lower molecular weight and broader molecular weight distribution because the usually slow transesterification is not negligible after reaching the reaction equilibrium.

The thermal property of the PLLA obtained from DSC is presented in Fig. 1. It is noticed that DSC of PLLA sample reveals a crystallization exotherm at 108 °C, and a single melting peak at 172 °C. This is in close agreement with the behavior of optically pure PLLA reported in [17].

3.2. Polymerization mechanism

The effects of solvents on the LLA polymerization catalyzed by La(ODMP)₃ discussed above imply that the ring-opening polymerization of LLA proceeds via a coordination mechanism. In order to confirm the bond cleavage mode, a ¹H NMR spectrum shown in Fig. 2 is recorded

for the PLLA obtained with La(ODMP)₃ and terminated by isopropanol with a small amount of HCL. Fig. 2 shows a doublet at 1.24 ppm for the methyl (^aH) and a multiplet at 5.02 ppm for the methenyl (^bH) of isopropoxy end group of PLLA. The signal at 4.34 ppm corresponded to the methine (^cH) proton next to the hydroxy end group is also appeared on ¹H NMR spectrum. The additional signals appearing at 1.54 and 5.17 ppm can be assigned to the methyl (^dH) and methine (^eH) of main chain of PLLA, respectively. The above analytical results clearly confirm that LLA molecule inserts into the Ln-O of catalyst through the selective acyl-oxygen bond cleavage of the monomer, and the ring-opening polymerization of LLA with La(ODMP)₃ proceeds via the “coordination–insertion” mechanism. The reason that the dimethylphenoxy group was not observed for the obtained PLLA may be attributed to replacement by the isopropoxy group when terminating the polymerization

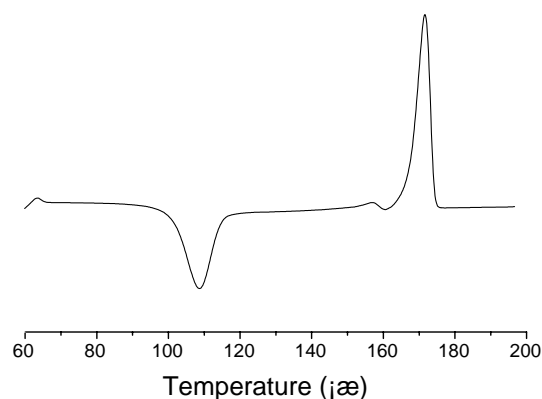


Fig. 1. DSC curve of PLLA (second scan) No. 2 in Table 2.

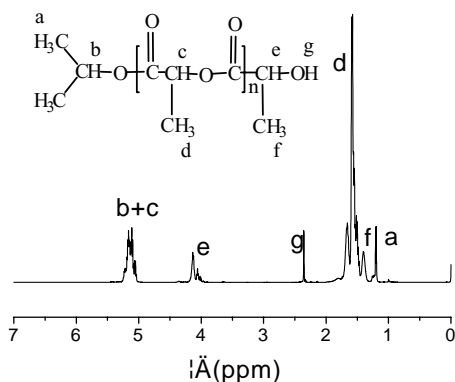


Fig. 2. ¹H NMR spectrum of PLLA terminated by isopropanol Graphical abstract.

with isopropanol containing 5% HCl because alkyl-ester group is more stable.

4. Conclusion

The ring-opening polymerization of LLA can be initiated efficiently by rare earth 2,6-dimethylaryloxide through the “coordination-insertion” mechanism. PLLA with molecular weight about 5.2×10^4 and molecular weight distribution of 1.54 can be prepared with $\text{La}(\text{ODMP})_3$ after 40 min in conversion of 96.8% at $[\text{LLA}]/[\text{initiator}]$ of 1000 in toluene at 80 °C.

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