Full Paper: The ring-opening polymerization of ω-pentadecalactone (PDL), a 16-membered lactone, in the bulk and in solution using yttrium isopropoxide as an initiator was investigated. All isopropoxide groups of yttrium isopropoxide participated in the initiation and the polymerization took place via acyl-oxygen cleavage of the monomer. The molecular weights of the resulting polymers could be controlled effectively by varying the monomer/initiator ratio. An induction period was observed for the bulk polymerization conducted at 60 °C. DSC analyses indicated that poly(ω-pentadecalactone) is a highly crystalline polymer, having a high crystallization rate.

Controlled ring-opening polymerization of ω-pentadecalactone with yttrium isopropoxide as an initiator

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Introduction

Interest in the design, synthesis and properties of biodegradable polymers is increasing steadily owing to the potential applications in biology, medicine, pharmacy and as environmentally friendly materials. Glycolide, lactides and ε-caprolactone are among the most used monomers for the synthesis of biodegradable polymers by ring-opening polymerization, and several efficient catalyst systems for their preparation have recently been developed[1–7, 21]. In contrast to the ring-opening polymerization of small and medium-membered lactones, polymerization of large-membered lactones has received less attention. It is well documented that large-membered lactones have little ring-strain and consequently are extremely difficult to polymerize by non-enzymatic methods. Several investigators have reported on polyesters derived from macrolactones[8–11], but in all cases, no detailed description of the polymerization was given. Just recently, it was demonstrated clearly that 12 and 13-membered lactones could undergo ring-opening polymerization using an alkali metal methoxide as initiator[12]. Nevertheless, relatively high temperatures of 90–150 °C for bulk polymerization, and long polymerization times were necessary to reach good yields, and only relatively low molecular-weight polymers accompanied by small amounts of cyclic and linear oligomers were obtained. Anionic polymerization of the 16-membered lactone, ω-pentadecalactone, initiated with potassium alkoxides under mild conditions was reported by Jedliński, et al.[13]. No direct correlation between the molecular weight of the resultant polymers and the monomer/initiator ratio was observed. In addition, the formation of cyclic oligomers via backbiting was confirmed by GPC and MS analyses. Hori, et al., gave an example for the ring-opening homopolymerization of a 16-membered dilactone, ethylene dodecanedioate, catalyzed by a distannoxane complex[14]. After 96 h polymerization in the bulk at 95 °C, the polymer was obtained in good yield.

Enzymatic ring-opening polymerization of macrolactones has recently been reported[15–17]. In contrast to the low polymerizability of macrolactones by non-enzymatic methods, it was found that monomers could be enzymatically polymerized even faster than ε-caprolactone, probably due to a better recognition of the macrolactone by lipase[17]. However, large quantities of enzymes and long reaction times were required. For the ring-opening polymerization of ω-pentadecalactone, enzyme/monomer ratios of 4/1 by weight and 24–72 h reaction at 80 °C were applied. The molecular weight of the polymers could not be controlled[15].

Previous research revealed that lanthanide catalysts have a high activity for the ring-opening polymerization of ε-caprolactone and lactides[7, 20–23]. In this paper, the ring-opening polymerization of ω-pentadecalactone both in solution and in bulk initiated by yttrium isopropoxide is described. ω-Pentadecalactone, a commercially available compound, was selected as a model compound to study the ring-opening polymerization of macrolactones.

Experimental part

Materials

ω-Pentadecalactone (Aldrich, Brussels, Belgium) was distilled under vacuum and stored in a glove box. Yttrium isopropoxide (Strem, Amsterdam, the Netherlands) was used without further purification. Toluene was dried by refluxing over sodium and distilled under argon prior to use. All glassware for the polymerization was dried overnight in an oven at 130 °C before use.

Polymerization

Polymerization reactions were carried out in a previously dried and Argon-purged ampoule. (1) Bulk polymerization: A certain amount of initiator and monomer were introduced into the ampoule equipped with a Teflon-coated magnetic stirrer in a glovebox. The ampoule was sealed with a stopper and transferred to a Schlenk line. The polymerization started after placing the reaction vessel into an oil bath thermostated at a prescribed temperature. After a predetermined time, 0.1 N aqueous HCl was quickly added to the reaction mixture to terminate the polymerization. The mixture was dissolved in CHCl$_3$, and a sample for ^{1}H NMR analysis to determine the conversion was taken. The remaining solution was washed with distilled water for three times, and then precipitated in an excess of methanol. The polymer was isolated by filtration, washed with methanol, and then dried at 40 °C in vacuo. (2) Solution polymerization: Since the ring-opening polymerization of ω-pentadecalactone in solution at room temperature is very slow, solutions of monomer and initiator in toluene were introduced into an ampoule in a glove box. The ampoule was then sealed with a stopper and transferred to a Schlenk line. The polymerization started after placing the ampoule into an oil bath thermostated at 80 °C. After 2 or 4 h polymerization, complete conversion was yielded. The post-treatment was as described above.

Measurements

^{1}H NMR spectra using CDCl$_3$ as a solvent were recorded on a 300 MHz Varian Inova and standardized by the CDCl$_3$ peak at $\delta = 7.25$. Conversions and the degree of polymerization (DP) were determined by integration of the relevant signals. Thermal analysis of polymers was carried out with a Perkin-Elmer DSC-7 differential scanning calorimeter. The samples were heated from -100 to 130 °C at a rate of 10 °C/min, kept at 130 °C for 2 min, cooled to -100 °C at a certain rate (10, 20 or 40 °C/min), and then a second heating scan (10 °C/min) was recorded. Gel permeation chromatography (GPC) was performed with a Waters 6000A GPC apparatus equipped with four Waters Styragel HR columns (10^5, 10^4, 500, 100 Å, pore diameter), combined with a H502 viscometer detector (Viscotek Corp.) for absolute molecular weight determinations. Polymers were dissolved in chloroform (1.0 wt.-%) and elution was performed at 25 °C at a flow rate of 1.5 mL/min using chloroform as eluent.

Results and discussion

In recent publications, it has been demonstrated that yttrium isopropoxide is a highly effective initiator for the polymerization of isocyanates[18], ethylene oxide[19], lactones and lactides[20–23]. In this paper, the ring-opening polymerization of ω-pentadecalactone, a monomer considered to have a low polymerizability when non-enzymatic methods are used, has been explored.

The results of the ring-opening polymerization of ω-pentadecalactone performed in the bulk using different reaction conditions are summarized in Tab. 1. From the data obtained, it was observed that all polymerizations proceeded very fast. Within the temperature range studied (60~100 °C), the polymerization rate increased with increasing temperature. On the other hand, when the

Tab. 1. Ring-opening bulk polymerization of ω-pentadecalactone by yttrium isopropoxide

Entry	[M]/[I] in mol/mol	Temp. in °C	Time in min	Conv.[a] in %	$\bar{M}_n \times 10^{-4}$			$\bar{M}_w/\bar{M}_n$[d]
					Calc[b]	^{1}H NMR[c]	GPC[d]	
1	13	60	10	100	0.12	0.16	n.d.[e]	n.d.[e]
2	26	60	10	100	0.24	0.25	n.d.[e]	n.d.[e]
3	39	60	10	100	0.36	0.39	n.d.[e]	n.d.[e]
4	52	60	10	100	0.48	0.49	n.d.[e]	n.d.[e]
5	65	60	10	100	0.60	0.64	n.d.[e]	n.d.[e]
6	150	60	30	100	1.4	1.3	1.6	1.6
7	200	60	30	93.5	1.7	1.7	1.7	1.8
8	200	80	30	100	1.8	1.7	1.5	2.1
9	200	100	5	94.5	1.7	1.3	1.6	1.6
10	400	60	60	61.6	2.3	2.1	2.9	1.6
11	400	80	30	94.0	3.4	2.6	3.2	1.6
12	400	100	5	70.0	2.6	1.7	2.5	1.5

[a] Calculated from ^{1}H NMR spectra of the crude polymerization mixtures.
[b] Calculated based on the following formula: $\bar{M}_n, calc = (240 \times [M]/[I] \times conversion)/2.6$.
[c] Experimental values obtained from ^{1}H NMR end group analysis.
[d] Determined by GPC analysis.
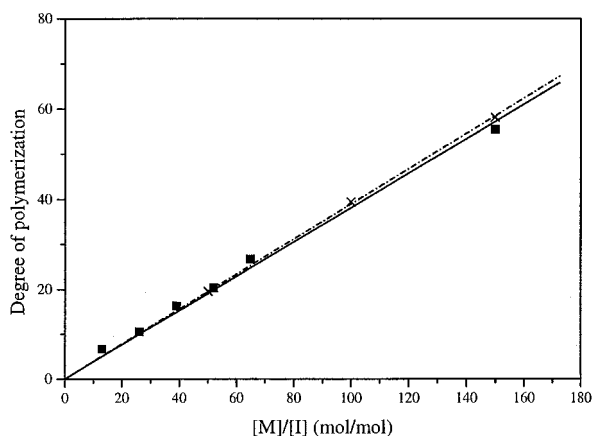[e] Not determined. Lose accuracy in this molecular weight range.

Fig. 1.　Degree of polymerization (DP) of ω-pentadecalactone as a function of monomer/initiator ratio. Yttrium isopropoxide was used as the initiator. (■) Bulk polymerization at 60 °C, (×) solution polymerization (in toluene) at 80 °C
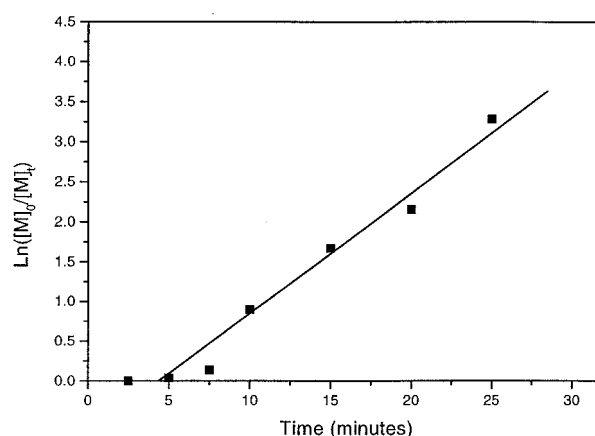

Fig. 2.　A plot of Ln ($[M]_0/[M]_t$) versus time for the bulk polymerization of ω-pentadecalactone initiated by yttrium isopropoxide at 60 °C with [M]/[I] = 150 (mol/mol)

polymerization temperature was fixed, a longer polymerization time was necessary to reach good conversion with increasing monomer/initiator ratios. Absolute molecular weights determined from GPC were in good agreement with experimental values calculated from ^{1}H NMR end-group analysis when the molecular weight is not too high, and are close to the theoretical values (entry 6–10, Tab. 1). At high DP, no accurate values could be determined from ^{1}H NMR because the signals of the end-group become too small. However, the calculated values correlated well with those determined by GPC. The molecular weight distributions were around 1.6 (with the exception of entry 8).

The dependencies of the degree of polymerization (DP) of ω-pentadecalactone on monomer/initiator ratios initiated by yttrium isopropoxide conducted both in the bulk at 60 °C and in solution at 80 °C are shown in Fig. 1. The DPs of the obtained polymers were calculated from integral ratios of signals at δ = 4.05 (—C$\underline{H}_2$—OC(O)—) and 3.63 (terminal methylene (—C$\underline{H}_2$—OH) protons). The resulting degrees of polymerization (DP) of the polymers correlated very well with the monomer/initiator ratios. The lines through the origin had slopes of 0.38 for bulk polymerization and 0.39 for solution polymerization, respectively, both very close to the theoretical value (5/13). It could be concluded that all isopropoxide groups were active and brought about the polymerization of ω-pentadecalactone. The polymerization proceeded in a controlled manner, analogous to the ring-opening polymerization of ε-caprolactone and lactides[23].

The conversion of ω-pentadecalactone as a function of polymerization time at a reaction temperature of 60 °C was determined by manual sampling followed by ^{1}H NMR analyses. The monomer has a characteristic signal at δ = 4.15 (—(O)CO—C$\underline{H}_2$—), while these protons in the polymer chains are found at δ = 4.05. The conversions

were calculated from the peak integrals (Fig. 2). An induction period was observed, which was also reported for the ring-opening polymerization of ε-caprolactone by aluminum alkoxide[24] or yttrium isopropoxide[21]. This induction period has been related to structural rearrangement processes of the initiator to form the actual active sites. The rather slow initiation compared to propagation might explain the slightly broad molecular weight distributions of the resulting polymers.

The polymers were analyzed by proton NMR and typical spectra are given in Fig. 3. The signals at δ = 5.06 and 3.63 were assigned to the methine protons of the isopropoxycarbonyl end group and α-methylene protons of the alcohol end group and have integral ratios close to 1 : 2 within the limits of the NMR experimental errors, which agrees with their theoretical ratio. In order to confirm the chemical shift of the terminal hydroxyl end group, a ^{1}H NMR spectrum was recorded after reacting the polymer with trifluoroacetic anhydride (Fig. 3B). Comparing these two spectra, it was found (Fig. 3B) that the original signal at δ = 3.63 (triplet) completely disappeared, and a new peak with equivalent intensity at δ = 4.30 (triplet) appeared. The downfield shift of the α-methylene protons, owing to the formation of the trifluoroacetic ester end group, fully demonstrated the presence of the hydroxyl end groups. The isopropoxycarbonyl group at one end and the hydroxyl group at the other end of the polymer chains revealed that the polymerization took place via acyl-oxygen bond cleavage of ω-pentadecalactone (Scheme 1).

The molecular weights and molecular weight distributions of the resulting polymers were measured by gel permeation chromatography (GPC). A typical GPC chromatogram is shown in Fig. 4. Unlike the results reported previously[13], the GPC chromatogram of poly(ω-pentadecalactone) displayed a unimodal and symmetric peak, with

$(CH_3)_2-CH-O-[\overset{\overset{O}{\parallel}}{C}-CH_2-CH_2-(CH_2)_{10}CH_2-CH_2-O]_m-\overset{\overset{O}{\parallel}}{C}-CH_2-CH_2-(CH_2)_{10}CH_2-CH_2-OH$

a   b   c d   e f g   h

Fig. 3. 300 MHz ^{1}H NMR spectra of poly(ω-pentadecalactone) before (A) and after (B) addition of excess trifluoroacetic anhydride

Fig. 4. Typical GPC profile of poly(ω-pentadecalactone) (entry 11 of Tab. 1)

Scheme 1:

no low molecular weight fraction detected. These results confirmed that all the isopropoxide groups of the initiator had a similar reactivity in the ring-opening polymerization of ω-pentadecalactone.

The thermal properties of poly(ω-pentadecalactone) were studied by differential scanning calorimeter (DSC). For all samples, no obvious glass transition was detected

Fig. 5. DSC curves of poly(ω-pentadecalactone)

within the temperature range studied (from -100 to $130\,°C$), even after rapid quenching from the melt. In order to get some qualitative information on the crystallization rate, DSC measurements with various cooling rates were performed. The results (Fig. 5) displayed a large crystallization enthalpy in the cooling traces and only little difference between the melting temperature (T_m) and the crystallization temperature (T_c) [(T_m-T_c) $<$ $30\,°C$], indicating that poly(ω-pentadecalactone) has a high crystallization rate. The equilibrium melting temperature and enthalpy of non-defective poly(ω-pentadecalactone) crystals were reported as $97.35 \pm 1\,°C$ and 232.95 J/g, respec-

tively[9]. Here, an enthalpy between 118.4 and 178.5 J/g at a melting temperature range of 95 and 106 °C was found. Poly(ω-pentadecalactone)s obtained in this study had a degree of crystallinity in between 50.8 and 76.6%.

Conclusions

Using ω-pentadecalactone as a model monomer, we studied the ring-opening polymerization behavior of large-membered lactones with yttrium isopropoxide conducted both in bulk and in solution. Polymerization reactions proceeded quickly and in a controlled manner. The molecular weight of the resulting polymers could be controlled by varying the monomer/initiator ratio.

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