High $T_m$ linear poly(L-lactide) s prepared via alcohol-initiated ROPs of L-lactide†

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Alcohol-initiated ROPs of L-lactide were performed in bulk at 160 °C for 72 h with variation of the catalyst or with variation of the initiator (aliphatic alcohols). Spontaneous crystallization was only observed when cyclic Sn(II) compounds were used as a catalyst. Regardless of initiator, high melting crystallites with melting temperatures ($T_m$) of 189–193 °C were obtained in almost all experiments with Sn(II) 2,2'-dioxybiphenyl (SnBiph) as catalyst, even when the time was shortened to 24 h. These HT$m$ poly(L-lactide)s represent the thermodynamically most stable form of poly(L-lactide). Regardless of the reaction conditions, such high melting crystallites were never obtained when Sn(II) 2-ethylhexanoate (SnOct2) was used as catalyst. SAXS measurements evidenced that formation of HT$m$ poly(L-lactide) involves growth of the crystallite thickness, but chemical modification of the crystallite surface (smoothing) seems to be of greater importance. A hypothesis, why the "surface smoothing" is more effective for crystallites of linear chains than for crystallites composed of cycles is discussed.

Introduction

Poly(L-lactide) is a technically produced biodegradable and biosourced engineering plastic, which is semicrystalline when optically pure.1-2 Poly(L-lactide) is known to have a melting temperature ($T_m$) in the range of 175–177 °C and after annealing in the absence of a catalyst or in the presence of a poisoned catalyst the $T_m$ may rise to 178–180 °C.1-7 Quite recently the authors have shown8 that cyclic poly(L-lactide), when prepared at 150–160 °C with a highly reactive catalyst, may form a high melting type of crystallite, so that the $T_m$ rises to 190–196 °C. However, only polymerizations obeying a ring-expansion polymerization mechanism or a ROPPOC mechanism (simultaneous ROP and polycondensation) were successful. In contrast, the standard catalyst used for the technical production of linear poly(L-lactide), namely tin(II) 2-ethylhexanoate (SnOct2) combined with an alcohol as initiator (cocatalyst), proved to be ineffective.8 Furthermore, it was found that the most reactive cyclic catalysts SnBiph (Scheme 1) and Sn-salicylate are capable of transforming the "low melting" (LT$m$) crystallites ($T_m < 180 °C$) into the high melting (HT$m$) counterparts. In a series of eight polymerization experiments involving alcohols as initiators not only SnOct2 failed to yield HT$m$ crystallites but also three cyclic tin catalysts were unsuccessful.8 Hence, despite numerous successful experiments with cyclic poly(L-lactide)s, direct syntheses of high $T_m$ linear poly(L-lactide)s are still unknown. Poly(L-lactide) having a $T_m$ around 193 °C was first reported by Pennings and co-workers who studied the isothermal crystallization of linear poly(L-lactide) at various temperatures.9,10 Those authors synthesized their poly(L-lactide) themselves using neat SnOct2 as catalyst and did not add a catalyst poison (rapid and homogeneous distribution of a catalyst poison is difficult to achieve in small scale experiments).

Scheme 1  Structures and labels of the catalysts used and/or discussed in this work.

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Quite recently, the authors have reported that neat SnOct₂ produces cyclic polylactides and not as believed for several decades' linear ones.¹¹ Hence, it is highly likely that the Pennings group had cyclic polylactide in hand and observed properties influenced by transesterification reactions catalyzed by SnOct₂.

In this context, it was the purpose of this work to find conditions allowing for the preparation of high Tₘ linear pol(l-lactide)s initiated by alcohols (or primary amines), and to find an explanation why alcohol-initiated ROPs and polymerization mechanisms yielding preferentially cyclic polylactides behave quite differently with regard to formation of HTₘ crystallites. Structures and labels of the catalysts used and/or discussed in this work were compiled in Scheme 1.

Experimental

Materials

l-Lactide, a product of PURAC, kindly supplied by Thysen-Uhde AG (Berlin, Germany) was recrystallized from “toluene 99.89% extra dry” purchased from ACROS Chem. (Geel, Belgium). 1-Lactylamide, ethyl l-lactate (EtLac), n-butanol, 10-undecenol (10-UND), benzyl alcohol (BnOH), benzylamine (BnNH₂), 2-hydroxymethyl naphthalene (2-HMN), 1,12-dodecanediol (DOD) and SnOct₂ were all purchased from Alfa Aesar (Karlsruhe, Germany) and used as received. The catalysts DSTL,¹² BuSnBuca,¹³ BuSnBiph,¹³ BuSnSal,¹⁴ SnSal,¹⁴ BuSnNaph,¹³ SnBiph¹² and SnNaph¹³ were those already used in the cited previous publications.

Polymerizations

General. In all polymerizations of this study conversions around 97% were reached when the polylactide remained in the molten state, because this conversion corresponds to the thermodynamic equilibrium. After complete crystallization the conversion increase above 99%, because most crystallized chains do not participate in the ring chain equilibrium.

(A) Ethyl l-lactate initiated polymerization catalyzed by various cyclic tin catalysts (Table 1). The catalyst (0.04 mmol) and the initiator (0.2 mmol) were weighed into a flame-dried 50 mL Erlenmeyer flask. A magnetic bar and 1-lactide were added under a blanket of argon. The reaction vessel was immersed into a preheated oil bath thermostated at 160 °C. Crystalline reaction products were isolated by destruction of the reaction vessel; viscous products were removed from the Erlenmeyer flask by means of a spatula.

(B) SnBiph-catalyzed polymerizations initiated with various alcohols (Tables 2 and 3). These polymerizations were performed with SnBiph as catalyst as described above.

(C) SnOct₂-catalyzed polymerizations initiated with various alcohols (Table 4). A 0.4 M solution of SnOct₂ in toluene (0.1 mL) and the initiator (0.2 mmol) were injected or weighed into a 50 mL flame-dried Erlenmeyer flask. A magnetic bar and l-lactide (40 mmol) were added under a blanket of argon. The reaction vessel was immersed into an oil bath thermostated at 160 °C.

(D) SnBiph or SnOct₂-catalyzed polymerizations with variation of the temperature (Table 5). These polymerizations were conducted in analogy to procedures (A) or (C) respectively.

Syntheses of linear poly(l-lactide)

H-PLA-Et. Ethyl acetate (1 mmol) was weighed into a 100 mL flame-dried Erlenmeyer flask and l-lactide (100 mmol) was added under a blanket of argon. A magnetic stirring bar was added and SnOct₂ (0.1 mL of a 1 M solution in toluene) was injected. This reaction mixture was allowed to polymerize for 4 h at 120 °C. The crystallized polylactide was dissolved in dichloromethane (100 mL) and precipitated into ligroin (1 L). The isolated polylactide was dried at 70 °C in vacuo. Yield 96%, Mₙ = 21 000; Mₘ = 43 000.

Ac-PLA-Et. H-PLA-Et was prepared as described above. Acetic anhydride (83 mL) and pyridine (81 mL) were added to the solution of the virgin H-PLA-Et in dichloromethane (10 mL) and allowed to stand at room temperature for 7 d. Afterwards it was precipitated into ligroin. Yield 95%; Mₙ = 22 000, Mₘ = 49 000.

Annealing experiments with preformed poly(l-lactide) ethyl esters (Table 6).

Synthesis of acetylated poly(l-lactide) ethyl ester. EtLac (1 mmol) and l-lactide (200 mmol) were weighed under a blanket of argon into a 100 mL flame-dried Erlenmeyer flask, a magnetic bar was added and finally 0.1 mL of a 0.5 M solution of SnOct₂ in toluene were injected. The reaction vessel was immersed into an oil bath thermostated at 130 °C. After 3 h, dry dichloromethane (80 mL) was added to the cooled reaction product and acetic anhydride (3 mL) and pyridine (1 mL) were added. After 3 d the resulting homogeneous solution was slowly poured with stirring into 1.2 L of ligroin. The fibrous precipitate was dried at 60 °C in a vacuum oven and divided into four portions of 5.76 g each plus a rest.

A portion of 5.76 g (80 mmol of lactyl units) was dissolved in dry dichloromethane (50 mL) and a catalyst (0.04 mmol of SnOct₂, DSTL or BuSnNaph) was added. The resulting solution was evaporated under normal pressure with slow heating up to 120 °C whereupon the polylactide crystallized.

Measurements

The MALDI TOF mass spectra were measured with Bruker AutoflexMax mass spectrometer. All spectra were recorded in the positive ion linear mode. The MALDI stainless steel sample targets were prepared from chloroform solutions of poly(l-lactide) or solutions of the stereocomplex in hexafluoropropanol (3–5 mg mL⁻¹) doped with potassium trifluoroacetate (2 mg mL⁻¹). Typically, 20 µL of sample solution, 2 µL of the potassium salt solution and 50 µL of a solution of trans-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidenedimalononitrile (DCTB, 20 mg mL⁻¹ in CHCl₃) serving as matrix were mixed in an Eppendorf vial. 1 µL of the corresponding solution was deposited on the MALDI target.

The GPC measurements were performed in a modular system kept at 40 °C consisting of an isocratic pump, 1 mL min⁻¹ and a refractive index detector (RI-501-Shodex). Samples were manually injected (100 µL, 2–4 mg mL⁻¹). For instrument control and data calculation Clarity software (GPC
extension, DataApex) was used. The calibration was performed using polystyrene standard sets (Polymer Standards Service – PSS, Mainz). All molecular weights listed in Tables 1–3 and 5 are uncorrected. They overestimate the real molecular weights by approximately 50% corresponding to a correction factor of 0.67 (±0.01).

The DSC heating traces were recorded on a (freshly with indium and zinc calibrated) Mettler-Toledo DSC-1 equipped with Stare Software-11 using a heating rate of 10 K min\(^{-1}\). Only the first heating traces were considered. The crystallinities were calculated with a maximum melting enthalpy of \(-106 \text{ J g}^{-1}\).

The SAXS measurements were performed using our in-house SAXS/WAXS apparatus equipped with an Incoatec™ X-ray source IµS and Quazar Montel optics. The wavelength of the X-ray beam was 0.154 nm and the focal spot size at the sample position was 0.6 mm\(^2\). The samples were measured in transmission geometry. The sample-detector distance for SAXS was 1.6 m. For WAXS, a distance of 0.1 m was used, allowing us to detect an angular range of 2\(\theta\) = 5°–33°. The patterns were recorded with a Rayonix™ SX165 CCD-Detector and the accumulation time per SAXS measurement was 1200 s and for WAXS 300 s.

DPDACK, a customizable software for reduction and analysis of X-ray scattering data sets was used for gathering 1D scattering curves.\(^a\) For the evaluation of the crystallinity of the samples the data were imported in Origin™ and analyzed with the curve fitting module. After subtracting of the instrumental background, the integral intensity of the crystalline reflections was divided by the overall integral intensity to determine the crystallinity \(x_c\).

### Results and discussion

**Ethyl \(\epsilon\)-lactate-initiated polymerizations with variation of cyclic tin catalysts**

A first series of polymerizations was conducted at 160 °C in bulk with EtLac as initiator and variation of the catalyst (Table 1) to elucidate the role of the catalyst. A first trend which was discovered, is the rather low tendency of dibutyltin \((\alpha)\) catalysts to yield crystalline polylactides. Only the most reactive member of this series, BuSnNaph, gave a low percentage of spherulites. The Sn(\(\alpha\))-based catalyst showed a better performance, but nearly complete crystallization of the reaction product was only observed for SnBiph-catalyzed polymerizations. Therefore, SnBiph was used for all further experiments with a cyclic tin catalyst. Nonetheless, all crystallites isolated from the polymerizations listed in Table 1 had \(T_m\)’s around 190 °C and thus, demonstrated that it is possible to obtain HT\(m\) polylactides via alcohol initiated ROPs. The reason why SnBiph turned out to be the most successful catalyst of this study seems to be its extraordinarily high activity as transesterification catalyst. This is also supported by the results of hundreds of ROPs of \(\epsilon\)-lactide

### Table 1

| Exp. no. | Catalyst       | Spherulites\(^a\) (%) | \(M_n\) | \(M_w\) | \(T_m\) (°C) | \(\Delta H_m\) (J g\(^{-1}\)) |
|----------|----------------|----------------------|--------|--------|-------------|------------------|
| 1        | DSTL           | 0                    | —      | —      | —           | —                |
| 2        | DSTD           | ~5–10                | —      | —      | —           | —                |
| 3        | BuSnBuca       | 0                    | —      | —      | —           | —                |
| 4        | BuSnCyca       | 0                    | —      | —      | —           | —                |
| 5        | BuSnBiph       | 0                    | —      | —      | —           | —                |
| 6        | BuSnNaph       | ~20–25               | —      | —      | —           | —                |
| 7        | SnBuca         | ~60–80               | —      | —      | —           | —                |
| 8        | SnBiph         | 80–95                | 18 500 | 40 000 | 193.0       | 87               |
| 9        | SnNaph\(^bc\)  | 80–95                | 16 000 | 38 000 | 178.0       | 65               |

\(^a\) Estimated volume fraction of the reaction mixture. \(^b\) Almost completely crystallized. \(^c\) With another batch of \(\epsilon\)-lactide only 50–60 vol% of the reaction mixture had crystallized.

### Table 2

| Exp. no. | Initiator | Lac/In | \(M_n\) | \(M_w\) | \(T_m\) (°C) | \(\Delta H_m\) (J g\(^{-1}\)) | Cryst. (%) | \(L\) (nm) | \(\ell\) (nm) |
|----------|-----------|--------|--------|--------|-------------|------------------|------------|---------|---------|
| 1\(^a\)  | EtLac     | 0      | 27 500 | 42 000 | 190.5       | 84.5             | 80         | 28      | 23      |
| 2        | EtLac     | 13 500 | 77 000 | 195.5  | 83.5        | 79               | 30         | 24      | —       |
| 3        | \(\beta\)-Butanol | 0      | 20 000 | 64 000 | 192.3       | 89.0             | 83         | 27      | 23      |
| 4        | 10-Und\(^d\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |
| 5        | 10-Und\(^d\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |
| 6        | 1-Hmn\(^e\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |
| 7        | 1-Hmn\(^e\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |
| 8        | 1,12-Dod\(^e\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |
| 9        | 1,12-Dod\(^e\) | 0      | 42 500 | 188.5  | 87.0        | 82               | 26         | 21      | —       |

\(^a\) Ethyl lactate was added as 2 M solution in toluene. \(^b\) Neat ethyl lactate was added. \(^c\) 10-Undecenol. \(^d\) 2-hydroxymethyl naphthalene. \(^e\) 1,12-Dodecanediol.
performed during the past five years, where SnBiph was found to be the most active polymerization catalyst.

On the basis of these results (Table 1), a series of ROPs was performed with SnBiph as catalyst and variation of the initiator (Table 2). This second series of polymerizations had the purpose to find out if and to what extent the initiator influences the formation of HTₘ crystallites. The steric demands of the initiator were varied over a broad range, but crystallization was observed for all initiators (Table 2) and all experiments yielded initiator were varied over a broad range, but crystallization was observed for all initiators (Table 2) and all experiments yielded poly(l-lactide) having Tₘ's > 189 °C. However, the first experiment with EtLac at a Lac/In ratio of 100/1 did not crystallize although the parallel experiment with a Lac/In ratio of 300/1 had crystallized (No. 2). For experiment 1A the EtLac was added in the form of a 2 M solution in toluene and when the experiment was repeated (No. 1B) with addition of neat EtLac complete crystallization was achieved. A similar observation was made for initiation with n-butanol. The first experiment failed to crystallize, whereas the second polymerization yielded a completely crystallized polylactide. These observations suggest that a lack of crystallization may in individual cases result from slow or hindered nucleation. Therefore, several experiments of Table 1 were repeated to check, if the failure of crystallization was reproducible and it was found to be reproducible. At this point, it should also be mentioned that the SEC data listed in Table 2 evidence a rough dependence of the molecular weights on the Lac/In ratio. A more precise control of the molecular weights may not be expected because of transesterification reactions including formation of cycles. In summary, the results obtained from the experiments of Table 2 underline the extraordinary usefulness of SnBiph and confirm that with an optimum catalyst linear HTₘ polylactides can be prepared via alcohol initiated ROPs. After this success, those experiments based on a Lac/In ratio of 200/1 were repeated with a time of 1 d for the following reasons:

1. A shorter time is more attractive from a preparative point of view and reduces the risk of partial racemization and other side reactions.

2. It should be found out, if the longer time of three days has a significant influence on Tₘ and ΔHₘ.

3. The results should be compared with those obtained from polymerizations catalyzed by SnOct₂ (see Table 4 below).

All polymerizations stopped after 1 d yielded crystalline polylactides but only in three experiments a Tₘ of 190 °C or higher was achieved, whereas in the case of n-butanol and 1,12-dodecanediol the Tₘ's were as low as 184.0 and 183.5 °C (Table 3). Hence, these experiments demonstrate that at the shorter time the initiator has indeed an influence on the perfection of the resulting crystallites. However, a straightforward explanation based on the steric demands of the initiator proved impossible, because the volume of 10-undecenol, which gave a high Tₘ was more than twice as high than that of n-butanol. These unexpected results like those of Table 1 justified, why it made sense to conduct numerous experiments with broad variation of all experimental parameters.

**Polymerizations catalyzed by SnOct₂**

SnOct₂ is an extraordinarily important catalyst, because it is used for all technical productions of poly(1-lactide), and thus, almost all studies of properties and applications of poly(1-lactide) are based on this catalyst.³⁻⁵⁻⁷⁻₈⁻₁₇⁻₂₀ Therefore, it was of high interest to find out, how this catalyst compares with the afore mentioned cyclic tin compounds under the given reaction conditions. In a previous publication³ three polymerizations using a monofunctional alcohol were performed in bulk at 160 °C with EtLac, n-butanol and 10-undecenol as initiators. Regardless of the initiator, HTₘ crystallites were not formed, although in the case of EtLac crystallinity of the reaction

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**Table 3** Alcohol-initiated ROPs of L-lactide catalyzed by SnBiph at 160 °C/1 d (Lac/Cat = 1 0000/1, Lac/In = 200/1) with variation of the initiator

| Exp. no. | Alcohol | Mₐ | Mₙ | Tₘ (°C) | ΔHₘ (J g⁻¹) | Crystal (%) |
|----------|---------|----|----|---------|-------------|-------------|
| 1        | EtLac   | 24 500 | 45 000 | 190.0 | 83.5 | 79 |
| 2        | n-BuOH | 20 000 | 43 000 | 184.0 | 75.0 | 71 |
| 3        | 10-Und  | 36 500 | 80 000 | 192.0 | 80.5 | 76 |
| 4        | 1-Hmn   | 34 500 | 71 000 | 190.5 | 79.0 | 75 |
| 5        | Dod     | 34 000 | 61 000 | 183.5 | 71.0 | 67 |

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**Table 4** SnOct₂-catalyzed polymerizations of L-lactide in bulk at 160 °C/3 d with variation of the initiator

| Exp. no. | Initiator | Lac/Cat | Lac/In | Spherulites (%) | Tₘ (°C) | ΔHₘ (J g⁻¹) |
|----------|-----------|---------|--------|----------------|---------|-------------|
| 1        | EtLac     | 100/1   | 1000/1 | 0              | —       | —           |
| 2        | EtLac     | 200/1   | 1000/1 | 0              | —       | —           |
| 3        | Lac. amide| 200/1   | 1000/1 | 0              | 20–30   | —           |
| 4        | n-Butanol | 100/1   | 1000/1 | 0              | —       | —           |
| 5        | n-Butanol | 200/1   | 1000/1 | 0              | —       | —           |
| 6        | 10-UND    | 100/1   | 1000/1 | 0              | —       | —           |
| 7        | 10-UND    | 200/1   | 1000/1 | c. 5           | —       | —           |
| 8        | 2-HMN     | 100/1   | 500/1  | c. 50          | 184.0   | 69.0        |
| 9        | 2-HMN     | 100/1   | 1000/1 | c. 60–70       | 187.5   | 79.5        |
| 10       | 2-HMN     | 200/1   | 500/1  | c. 15          | —       | —           |
| 11       | 2-HMN     | 200/1   | 1000/1 | c. 5           | —       | —           |
| 12       | BnOH      | 100/1   | 1000/1 | 0              | —       | —           |
| 13       | BnNH₂     | 100/1   | 1000/1 | 0              | —       | —           |

a Estimated vol% of the reaction mixture. b These experiments were repeated and the failure to crystallize was reproduced.
mixture took place. This was a first demonstration that SnOct₂ is a relatively unfavourable catalyst for the formation of HTₘ poly lactide. In this work twelve more experiments were conducted (Table 4). The variation of the initiator included two cases that yielded amide end groups (No. 3 and 13). Furthermore, the concentration of SnOct₂ was doubled in three experiments to enhance its effectiveness (Lac/Cat ratios = 100/1, No. 1, 3 and 5).

A first noteworthy result is the crystallization of the polylactides prepared with EtLac as initiator (No. 1 and 2, Table 3). Since Tₘ's < 180 °C were found, these results demonstrate the reproducibility of an experiment presented in ref. 8, which was conducted under exactly the same conditions as experiment No. 2 in Table 3 of this work. This point needs to be emphasized for two reasons. Firstly, it illustrates the conspicuous difference between the catalysts SnBiph and SnOct₂. Secondly, it demonstrates together with the other results compiled in Table 4, that in the case of SnOct₂ the initiator has a considerable influence on formation and perfection of the crystallites. With butanol and 10-undecenol no crystallization occurred, and this failure was reproducible. However, partial crystallization was again observable, when 2-hydroxymethyl naphthalene served as initiator and it was also found that a low Lac/In ratio was advantageous for the extent of crystallization. The most surprising result came up when the DSC measurements showed that Tₘ's of the polylactides from the 100/1 experiments (No. 6 and 7, Table 3) were as high as 184.0 and 187.5 °C. These Tₘ's were somewhere in between those of typical LTₘ and HTₘ crystallites and demonstrated for the first time that SnOct₂ may produce crystallites with higher perfection than the normal LTₘ species, but the results of experiments No. 6 and 7 were still far from the optimum which was achieved with SnBiph under the same conditions. Nonetheless, these unexpected results prompted the authors to study the effect of two other aromatic initiators and since the highest Tₘ was obtained with 2-HMN at a Lac/In ratio of 100/1, the additional experiments with benzyl alcohol and benzyl amine (No. 12 and 13) were performed with this Lac/In ratio, but no crystallization was observed.

To complete the comparison of SnOct₂ with SnBiph, two small series of polymerizations were performed with variation of the temperature (Table 5). All SnBiph-catalyzed polymerizations crystallized, but HTₘ crystallites with a Tₘ > 190 °C were only obtained at the highest temperature (160 °C). This result contrasts with SnBiph-catalyzed polymerization performed in the absence of an alcohol, because neat SnBiph yielded HTₘ poly lactide even at 120 °C. This comparison demonstrates again that alcohol initiated ROPs are unfavourable for the formation of HTₘ crystallites. With SnOct₂ no crystallization occurred at 160 °C and at lower polymerization temperatures the Tₘ's were all below 184 °C. In other words, the combination of SnOct₂ with alcohol proved again to be particularly unfavourable for the formation of HTₘ crystallites.

All the results reported above suggested that a larger number of OH end groups on the surface of the lamellar crystal is unfavourable for the formation of HTₘ poly(l-lactide). As a hypothetical explanation of these results, it may be concluded that the OH groups reduce the mobility of the catalyst either by donor-acceptor interaction (coordination) with the tin atoms or by temporarily (reversible) formation of covalent bonds. This assumption is supported by the well-known mechanism of SnOct₂/alcohol catalyzed polymerizations which includes as first step the reversible formation of Sn-alkoxide groups.

### Table 5  Ethyl lactate-initiated ROPs of l-lactide (Lac/In = 200/1) catalyzed by SiBiph or SnOct₂ (Lac/Cat = 1000/1) with variation of the temperature; time 1 d

| Exp. no. | Catalyst | Temp. (°C) | Spherulites (vol%) | Mₙ | Mₚ | Tₘ (°C) | ΔHₘ (J g⁻¹) | Cryst. | L (nm) | l_c |
|----------|----------|------------|-------------------|-----|-----|---------|------------|-------|-------|-----|
| 1        | SnBiph   | 160        | 90–100            | 30 000 | 51 000 | 191.5   | 84.0       | 79    | 28    | 22  |
| 2        | SnBiph   | 150        | 90–100            | 29 000 | 43 500 | 188.5   | 88.0       | 83    | 21    | 18  |
| 3        | SnBiph   | 140        | 90–100            | 29 000 | 39 000 | 187.0   | 87.0       | 82    | 20    | 16  |
| 4        | SnBiph   | 130        | 90–100            | 26 000 | 31 700 | 182.5   | 87.5       | 83    | 19    | 15/16 |
| 5        | SnOct₂   | 160        | —                 | —     | —     | —       | —          | —     | —     | —   |
| 6        | SnOct₂   | 150        | 30–40             | 19 500 | 44 700 | 183.5   | 80.5       | 76    | 18    | 14  |
| 7        | SnOct₂   | 140        | 90–100            | 22 000 | 35 700 | 183.5   | 79.0       | 75    | 19    | 14  |
| 8        | SnOct₂   | 130        | 90–100            | 21 000 | 28 300 | 179.5   | 78.5       | 74    | 17    | 12/13 |

![Scheme 2](image)  Simplified scheme of SnOct₂ + alcohol-catalyzed ROP of lactide.
(This hypothesis also explains why crystallites consisting of cyclic polylactides are more prone to modification by transesterification on their surface. Its surface is exclusively covered with loops and thus, their ester groups are easily accessible to the catalysts. Furthermore, the ester groups in the loops are slightly more reactive than those in linear chain segments, due to energetically less favourable conformations (cisoid versus transoid). In order to shed more light on this phenomenon, the annealing experiments summarized in Table 6 were conducted.

### Annealing experiments

These experiments were conducted in such a way that a linear poly(\(\varepsilon\)-lactide) was prepared with ethyl \(\varepsilon\)-lactate as initiator and a Lac/In ratio of 100/1, whereupon SnOct\(_2\) (Lac/Cat = 1000/1) served as catalyst (acronym: HO-PLA-Et, see Table 6). Part of this polylactide was modified by acetylation of the HO–CH end group with acetic anhydride. The resulting polylactide was named AcO-PLA-Et in Table 6. When HO-PLA-Et was heated with SnOct\(_2\) to 160 or 170 °C, \(T_m\)’s of 180.5 and 184.5 °C were reached (No. 1 and 2, Table 6). Analogous experiments with AcO-PLA-Et gave similar temperatures (No. 5 and 6). Almost the same temperatures were achieved with two cyclic catalysts (No. 7 and 8). In summary, these model experiments evidenced that higher \(T_m\)’s may be obtained in the presence of a catalyst, but they did not prove that OH end groups on the surface of the crystallites act as specific hindrance for the catalytic activity of SnOct\(_2\).

### DSC measurements

In this section characteristic features of the DSC measurements should be discussed. When the crystallization of the reaction mixture was almost complete as it was typical for SnBiph-catalyzed ROPs, the only feature observable in the DSC heating traces was a monomodal melting endotherm and a glass-transition was not detectable. A characteristic example of such DSC traces is presented in Fig. 1A, which represents most of the experiments performed with SnBiph (Tables 1, 2 and 5). A couple of exceptions are illustrated in Figure 1B, 2 and 3. Firstly, the small fraction of crystallites obtained with DSTD as catalyst is also shown.

| Exp. no. | Substrate         | Cat. used for annealing | \(T\) (°C) | \(t\) (h) | \(T_m\) (°C) | \(\Delta H_m\) (J g\(^{-1}\)) | Cryst. (%) |
|----------|-------------------|-------------------------|------------|-----------|-------------|-------------------------------|------------|
| 1        | HO-PLA-Et\(^a\)   | SnOct\(_2\)             | 160        | 48        | 180.5       | 92                           | 86         |
| 2        | HO-PLA-Et\(^a\)   | SnOct\(_2\)             | 170        | 24        | 184.0       | 77                           | 72         |
| 3        | AcO-PLA-Et\(^b\)  | —                       | 160        | 48        | 180.0       | 84                           | 79         |
| 4        | AcO-PLA-Et\(^b\)  | —                       | 170        | 24        | 180.5       | 80                           | 75         |
| 5        | AcO-PLA-Et\(^b\)  | SnOct\(_2\)             | 160        | 48        | 183.5       | 91                           | 86         |
| 6        | AcO-PLA-Et\(^b\)  | SnOct\(_2\)             | 170        | 24        | 184.5       | 87.5                         | 82         |
| 7        | AcO-PLA-Et\(^b\)  | DSTL                    | 170        | 24        | 182.5       | 90.5                         | 86         |
| 8        | AcO-PLA-Et\(^b\)  | BuSnNaph                | 179        | 24        | 184.5       | 89.0                         | 85         |

\(^a\) The EtLac-initiated, SnOct\(_2\)-catalyzed product of exp. no. 8, Table 5, was used as substrate. \(^b\) AA preformed poly(\(\varepsilon\)-lactide) prepared with EtLac as initiator (Lac/In = 200/1) and SnOct\(_2\) as catalyst (Lac/Cat = 1000/1) was acetylated with acetic anhydride plus pyridine and used as substrate.
(No. 2, Table 1) is worth mentioning. The crystalline phase was isolated after removal of the amorphous phase by careful washing with cold dichloromethane. In this case the DSC trace revealed two melting endotherms indicating simultaneous presence of \( \text{LT}_m \) and \( \text{HT}_m \) crystallites. A glass-transition was again not detectable (Fig. 1A).

When the sample picked up for the DSC measurements contained a large amount of amorphous phase, the glass-transition (around 50 °C) was clearly observable and followed by crystallization endotherm with a maximum around 105 °C (Fig. 2). The crystallites formed during this crystallization process had a low perfection and melted around 167 °C. The fourth feature was finally the melting endotherm of the \( \text{HT}_m \) crystallites formed during the polymerization. DSC heating traces with a similar structure were also obtained from poly(lactides) prepared with SnOct2 in the experiments of Table 5 (Fig. 3). Again, crystallization of the amorphous phase followed by a melting endotherm at low temperature (around 167 °C) can be seen. What is different from the DSC traces discussed before, is a strong endotherm at a temperature between 180 and 190 °C indicating a partial transformation of \( \text{LT}_m \) into \( \text{HT}_m \) crystallites.

**MALDI TOF mass spectrometry**

Alcohol-initiated catalyzed by SnOct2 or cyclic tin catalysts such as DSTL \(^{12}\) and BuSnBuca \(^{13}\) typically yield linear chains with considerable predominance of even-numbered species when performed at 130 °C or below and polymerization times limited to a few hours. Furthermore, cycles are not formed. Yet, at temperatures of 160 °C and higher in combination with a reaction time of 3 d considerable influence of transesterifications may be expected. To elucidate this aspect MALDI-TOF mass spectra of the crystalline sample listed in Tables 2 and 6 were recorded. These mass spectra indeed confirmed this expectation. A first important result are the equal intensities of even and odd chains, regardless if cyclics were present or not. This finding demonstrates that intensive interchain transesterification occurred at all temperatures studied in this work and that this equilibration does not depend on the existence of ring-chain equilibration \( \text{via} \) “back-biting”. This result is in perfect agreement with a previous study dealing with transesterification in SnOct\(_2\)-catalyzed and alcohol-initiated ROP of lactide.\(^{21}\) The intermolecular random transesterification between linear chains has a slightly higher rate than formation of cycles by back-biting. Mass spectra free of cyclics were typically obtained at temperatures below 160 °C as illustrated by Fig. 4A and B.

However, when UND was used as initiator with a Lac/In ratio of 100/1 cycles were also absent after 3 d at 160 °C (Fig. 5A). Yet, at Lac/In ratio of 200/1 small amounts of cycles were formed as demonstrated in Fig. 5B. This difference agrees with results of a previous study which showed that back-biting is favors by lower In/Cat ratios corresponding to higher Lac/In ratios at constant catalyst concentration. However, with other alcohols cycles were also formed at Lac/Cat ratios of 100/1 as demonstrated in Fig. S1A (see ESI).\(^{\dagger}\)
with $x = \text{degree of polymerization}, p = \text{conversion}, n_x = \text{number of chains having an identical degree of polymerization}$. For this MWD it is characteristic, that the first reaction product (the cyclic tetramer in the case of lactide) is the most abundant species and the number fraction of longer chains decreases exponentially. Fig. 6 illustrates such a distribution for polylactides prepared with $\text{Ph}_2\text{SnCl}_2$ (ref. 23) via ring-expansion polymerization combined with simultaneous polycondensation (ROPPOC, for definition and review s. ref. 24).

The most probable MWD results from an optimization of the entropy. Hence, it is obvious that the maxima observed in mass spectra of the semi-crystalline poly($\ell$-lactide)s result from a gain in enthalpy, and the only source of a negative enthalpy change is in this system formation of more and more perfect crystallites. In other words, these maxima of the MWD suggest that a certain chain length is for thermodynamic reasons particularly prone to crystallize. Their “extraction” from the amorphous phase into the crystallites has the consequence that such chains are regenerated from the pool of shorter and longer chains by transesterification. Such a scenario was also observed, when cyclic polylactides were annealed at $120 \, ^\circ\text{C}$ for $15 \, \text{d}$ with a large amount of DSTL ($\text{Lac}/\text{Cat} = 200/1$). It was concluded that enthalpy-driven formation of new maxima in the MWD is characteristic for cyclic polylactides. The results presented in this study clearly prove that not the topology, but the chain length is decisive. A more detailed study and explanation of this phenomenon was outside the scope of this work.

### WAXS and SAXS measurements

WAXS measurements of samples No. 1, 2, 7 and 8 of Table 5 were conducted, and in all four cases the typical WAXS patterns of the orthorhombic $\alpha$-modification, first described by DeSantis and Kovacs, were found (Fig. S3†). Numerous examples of such WAXS patterns were also presented in previous publications\(^{11,27}\). This result was predictable, because the $\alpha$-modification is thermodynamically most stable modification of poly($\ell$-lactide) and because the same result has been obtained in previous studies. In other words, the WAXS powder patterns do not contribute anything to a differentiation between LT$_m$ and HT$_m$ crystallites, but they reflect, as usual, variation of the crystallinity as illustrated by the two examples presented in Fig. S3.†

In the previous study\(^{27}\) dealing with HT$_m$ crystallites of predominantly cyclic poly($\ell$-lactide)s, it was found by means of SAXS measurements that the HT$_m$ polylactides possess lamellar crystallites with a greater thickness ($l_c$ values), than the standard LT$_m$ crystallites. Whereas $l_c$-values in the range of 25–35 nm were typical for HT$_m$ crystallites, $l_c$ values in the range of 8–11 nm were found for the LT$_m$ counterparts. Hence, it was of interest, if this trend could be confirmed by the alcohol-initiated polylactides prepared in this work. For the first SAXS measurements, samples listed in Table 2 were selected, because for these samples the highest degree of perfection was expected. The $l_c$-values listed in the last column of that table corresponded indeed to distances in the range of 21–25 nm (Fig. S4†), corresponding to a thickness growth by a factor of
2.0–2.2 relative to the usual thickness of LT \( m \) crystallites. However, a factor of 2.5–3.5 was found for most polymerization and annealing experiments in previous studies based on cyclic polyLAs.\(^{27}\)

Another series of experiments which was particularly interesting for SAXS measurements was the variation of the polymerization temperature illustrated in Table 5. As expected, from the relatively high \( T_m \), the \( l_c \)-value of 22 nm found for sample No. 1 (Fig. 7B) was in agreement with the formation of HT \( m \) crystallites. Furthermore, the other extreme, namely the LT \( m \) sample No. 8, prepared with SnOct2 at 130 °C was again in agreement with the expected trend: low \( T_m \) combined with a rather low \( l_c \)-value (12–13 nm; Fig. 7A). The other measurements listed in Table 5 gave \( T_m \) and \( l_c \) values in between these extremes.

In this connection, the most interesting result of this work is the finding that \( T_m \)'s > 191 °C were achieved with a rather moderate increase of the lamellar thickness when the crystallites are formed by linear chains compared with crystallites composed of cyclic polyLA. This means that another factor played an important role, namely a considerable reduction of the surface free energy \( \sigma_c \). According to the Gibbs–Thomson–

eqn (2), a high \( T_m \) may be a consequence of a low \( \sigma_c \) or a high \( l_c \) value. At identical \( T_m \) a lower crystal thickness as observed for the linear polyLAs of this work is therefore, correlated with a rather low surface free energy.

\[
T_m = T_{n0}[1 - (2\sigma_c/r \times \Delta H_{n0} \times l_c)]
\]  

(2)

Hence, the results of this work indicate that the alcohol-initiated linear chains are less favorable for the thickness growth of the crystallites than predominantly cyclic polylactides, but more favorable for a “smoothing” of the surface via transesterification. The transesterification reactions responsible for such a “smoothing” have been discussed in two previous publications, and thus should not be repeated here again. The demonstration that chemical “smoothing” of the crystallite surface plays an important role for the rise of \( T_m \) is remarkable for two reasons. First, to the best knowledge of the authors this phenomenon has never been documented before. Second, an explanation is required why the chemical smoothing is more effective when crystallites of linear chains are involved relative to crystallites composed of cyclic polyLAs. Illustrated in Fig. 8A, the surface of crystallites composed of cycles is exclusively covered by loops, which include energetically unfavorable conformations of the repeat units. Due to the steric demands of these loops, directly neighboring loops cannot have the same size. However, in the case of crystallites based on linear chains, loops may be neighbored by sterically less demanding and more flexible linear chain ends (Fig. 8B). Hence, smoothing by transesterification may create a more homogeneous surface with a smaller thickness of the rigid amorphous fraction (RAF), whereas the surface of crystals formed by cycles remains rougher and includes a higher level of conformational energy.
Finally, it should be mentioned that the SAXS patterns of all samples having \( T_m \)'s around 184 °C or higher show a second order reflection (Fig. 7 and S4†), which indicates a rather high 3-dimensional order of the crystallites in the spherulites. Fig. 9 presents a schematic summary and illustration of the consequences that transesterification reactions in the mobile and immobile disordered phase have on shape and 3-dimensional ordering of the crystallites.

Conclusions

The results of this work allow first of all for the conclusion that HT\textsubscript{m} polylactides can be prepared \textit{via} alcohol-initiated polymerizations. Yet, surprisingly, only cyclic tin(II) catalysts, such as SnBiph, gave satisfactory results regardless which alcohol served as initiator. Particularly remarkable is also the finding that none of the numerous experiments performed here and previously with SnOct\textsubscript{2} as catalyst and various alcohols as initiators yielded a HT\textsubscript{m} polylactide having a \( T_m > 190 \) °C. Since the technical production of polylactide is almost all studies of properties of polylactide(s) published over the past 50 years are based on ROPs catalyzed with SnOct\textsubscript{2} + alcohol, the present results explain why the HT\textsubscript{m} crystallites were not detected in experiments performed with this catalyst system. A third important result is the finding that the chemical modification of the crystallite surfaces by transesterification (smoothing) plays a key role for the formation of HT\textsubscript{m} crystallites based on linear chains. The smaller number of energetically unfavourable loops on their surface seems to be responsible for the greater effectiveness of chemical smoothing.

Author contributions

HK – conceptualization, supervision, syntheses, writing-original draft; SW – investigation, visualization, writing – review & editing; AM – SAXS measurements – review & editing.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

1 R. A. Auras, L.-T. Lim, S. E. Selke and H. Tsuji, \textit{Poly(lactic acid): synthesis, structures, properties, processing, and applications}, John Wiley & Sons, 2011.
2 M. L. Di Lorenzo and R. Androsch, \textit{Synthesis, Structure and Properties of Poly(lactic acid)}, Springer International Publishing, Cham, 2018.
3 D. Bigg, \textit{Technical papers of the annual technical conference-society of plastics engineers incorporated}, 1996, pp. 2028–2039.
4 M. L. Di Lorenzo, \textit{J. Appl. Polym. Sci.}, 2006, \textbf{100}, 3145–3151.
5 J. R. Dorgan, J. Janzen, M. P. Clayton, S. B. Hait and D. M. Knauss, \textit{J. Rheol.}, 2005, \textbf{49}, 607–619.
6 K. Jamshidi, S.-H. Hyon and Y. Ikada, \textit{Polymer}, 1988, \textbf{29}, 2229–2234.
7 J. J. Kolstad, \textit{J. Appl. Polym. Sci.}, 1996, \textbf{62}, 1079–1091.
8 H. R. Kricheldorf, S. M. Weidner and A. Meyer, \textit{Polyom. Chem.}, 2020, \textbf{11}, 2182–2193.
9 B. Kalb and A. J. Pennings, \textit{Polymer}, 1980, \textbf{21}, 607–612.
10 K. Kishore, R. Vasanthakumari and A. J. Pennings, \textit{J. Polym. Sci., Polym. Phys. Ed.}, 1984, \textbf{22}, 537–542.
11 H. R. Kricheldorf and S. M. Weidner, \textit{Polyom. Chem.}, 2020, \textbf{11}, 5249–5260.
12 H. R. Kricheldorf, S. M. Weidner and F. Schelia, \textit{Polym. Chem.}, 2017, \textbf{8}, 1589–1596.
13 H. R. Kricheldorf, S. M. Weidner and F. Schelia, \textit{Macromol. Chem. Phys.}, 2017, \textbf{218}, 1700274.
14 H. R. Kricheldorf and S. M. Weidner, \textit{Eur. Polym. J.}, 2018, \textbf{105}, 158–166.
15 H. R. Kricheldorf, S. M. Weidner and F. Schelia, \textit{Eur. Polym. J.}, 2019, \textbf{116}, 256–264.
16 G. Benecke, W. Wagermaier, C. Li, M. Schwartzkopf, G. Flucke, R. Hoerth, I. Zizak, M. Burghammer, E. Metwalli and P. Müller-Buschbaum, \textit{J. Appl. Crystalogr.}, 2014, \textbf{47}, 1797–1803.
17 G. Schwach, J. Coudane, R. Engel and M. Vert, \textit{Polym. Int.}, 1998, \textbf{46}, 177–182.
18 G. Kharas, F. Sanchez-Riera and D. Severson, \textit{Polymers of Lactic Acid in Plastics from Microbes}, ed. D. P. Mobley, Hanser Gardner Publications, Inc., 1994.
19 A. Södergård and M. Stolt, \textit{Industrial production of high molecular weight poly(lactic acid)}, Wiley & Sons, Hoboken, 2010.
20 J. A. Byers, A. B. Biernesser, K. R. Delle Chiaie, A. Kaur and J. A. Kehl, in \textit{Synthesis, Structure and Properties of Poly(lactic acid)}, ed. R. Di Lorenzo and R. Androsch, Springer, Cham, 2017, pp. 67–118.
21 S. M. Weidner and H. R. Kricheldorf, \textit{Macromol. Chem. Phys.}, 2017, \textbf{218}, 1600331.
22 P. J. Flory, \textit{Principles of polymer chemistry}, Cornell University Press, 1953.
23 H. R. Kricheldorf, S. M. Weidner and F. Schelia, \textit{J. Polym. Sci., Part A: Polym. Chem.}, 2019, \textbf{57}, 952–960.
24 H. R. Kricheldorf and S. M. Weidner, \textit{Macromol. Rapid Commun.}, 2020, 2000152.
25 S. M. Weidner and H. R. Kricheldorf, \textit{Macromol. Chem. Phys.}, 2017, \textbf{218}, 1700114.
26 P. DeSantis and A. J. Kovacs, \textit{Biopolymers}, 1968, \textbf{6}, 299–306.
27 H. Kricheldorf, S. Chatti, A. Meyer and S. Weidner, \textit{RSC Adv.}, 2021, \textbf{11}, 2872–2883.