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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(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.

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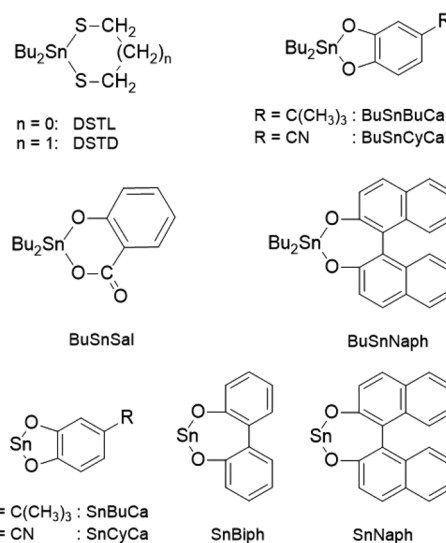
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Introduction

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)s, 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 poly lactides and not as believed for several decades' linear ones.¹¹ Hence, it is highly likely that the Pennings group had cyclic poly lactide 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 T_m linear poly(L-lactide)s initiated by alcohols (or primary amines), and to find an explanation why alcohol-initiated ROPs and polymerization mechanisms yielding preferentially cyclic poly lactides behave quite differently with regard to formation of HT_m 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 Thyssen-Uhde AG (Berlin, Germany) was recrystallized from "toluene 99.99% extra dry" purchased from ACROS Chem. (Geel, Belgium). L-Lactylamide, ethyl L-lactate (EtLac), *n*-butanol, 10-undecanol (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 SnBiph¹⁵ and SnNaph¹⁵ were those already used in the cited previous publications.

Polymerizations

General. In all polymerizations of this study conversions around 97% were reached when the poly lactide 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 equilibration.

(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 L-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)s

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 poly lactide was dissolved in dichloromethane (100 mL) and precipitated into ligroin (1 L). The isolated poly lactide was dried at 70 °C *in vacuo*. Yield 96%, $M_n = 21\ 000$; $M_w = 43\ 000$.

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%, $M_n = 22\ 000$, $M_w = 49\ 000$.

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 poly lactide 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 hexafluoroisopropanol (3–5 mg mL⁻¹) doped with potassium trifluoroacetate (2 mg mL⁻¹). Typically, 20 μL of sample the solution, 2 μL of the potassium salt solution and 50 μL of a solution of *trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenylidene]malononitrile (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



Table 1 Ethyl lactate-initiated ROPs of L-lactide catalyzed by various cyclic tin compounds (Lac/Cat = 1000/1, Lac/Cocat = 200/1, temp. 160 °C, time 72 h)

Exp. no.	Catalyst	Spherulites ^a (%)	M_n	M_w	T_m (°C)	ΔH_m (J g ⁻¹)
1	DSTL	0	—	—	—	—
2	DSTD	~5–10	—	—	—	—
3	BuSnBuca	0	—	—	—	—
4	BuSnCyca	0	—	—	—	—
5	BuSnBiph	0	—	—	—	—
6	BuSnNaph	~20–25	—	—	—	—
8	SnBuca	~60–80	—	—	—	—
10	SnBiph	80–95	18 500	40 000	193.0	87
11	SnNaph ^{b,c}	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 L-lactide only 50–60 vol% of the reaction mixture had crystallized.

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 J g⁻¹.

The SAXS measurements were performed using our in-house SAXS/WAXS apparatus equipped with an IncoatecTM X-ray source μ S 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 mm². 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 $2\theta = 5^\circ$ – 33° . The patterns were recorded with a RayonixTM SX165 CCD-Detector and the accumulation time per SAXS measurement was 1200 s and for WAXS 300 s.

DPDAK, a customizable software for reduction and analysis of X-ray scattering data sets was used for gathering 1D scattering curves.¹⁶ For the evaluation of the crystallinity of the samples the data were imported in OriginTM 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 L-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(IV) catalysts to yield crystalline poly(lactides). Only the most reactive member of this series, BuSnNaph, gave a low percentage of spherulites. The Sn(II)-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 poly(lactides) *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 L-lactide

Table 2 Alcohol-initiated ROPs of L-lactide catalyzed by SnBiph^a performed in bulk at 160 °C/3 d with variation of the initiator (Lac/Cat = 1000/1)

Exp. no.	Initiator	Lac/In	M_n	M_w	T_m (°C)	ΔH_m (J g ⁻¹)	Cryst. (%)	L (nm)	l_c (nm)
1A ^a	EtLac	100/1	No cryst.	—	—	—	—	—	—
1B ^b	EtLac	100/1	13 500	27 500	192.5	84.0	80	28	23
2	EtLac	300/1	37 500	77 000	195.5	83.5	79	30	24
3	<i>n</i> -Butanol	200/1	No cryst.	—	—	—	—	—	—
4	10-Und ^c	100/1	20 000	42 000	190.5	84.5	80	25	20
5	10-Und ^c	200/1	30 000	64 000	192.3	83.5	79	28	23
6	1-Hmn ^d	100/1	19 000	42 500	188.5	87.0	82	26	21
7	1-Hmn ^c	200/1	27 000	66 000	190.0	89.0	83	27	23
8	1,12-Dod ^e	200/1	29 500	68 500	190.2	84.0	77	30	23
9	1,12-Dod ^e	400/1	44 000	92 000	193.5	92.0	86	26	23

^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-Dodecane diol.



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	M_n	M_w	T_m	ΔH_m (J g ⁻¹)	Crystal (%)
1	EtLac	24 500	45 000	190.0	83.5	79
2	<i>n</i> -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

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 HT_m 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 polylactides having T_m '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 HT_m 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 reaction.

(2) It should be found out, if the longer time of three days has a significant influence on T_m and ΔH_m .

(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 T_m of 190 °C or higher was achieved, whereas in the case of *n*-butanol and 1,12-dodecanediol the T_m '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-undecanol, which gave a high T_m , is 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(L-lactide), and thus, almost all studies of properties and applications of poly(L-lactide) are based on this catalyst.^{1-3,5-7,9,17-20} 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 publication⁸ three polymerizations using a monofunctional alcohol were performed in bulk at 160 °C with EtLac, *n*-butanol and 10-undecanol as initiators. Regardless of the initiator, HT_m crystallites were not formed, although in the case of EtLac crystallization of the reaction

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 ^a (%)	T_m (°C)	ΔH_m (J g ⁻¹)
1	EtLac	100/1	1000/1	0	—	—
2 ^b	EtLac	200/1	1000/1	0	—	—
3	Lac. amide	200/1	1000/1	20–30	—	—
4	<i>n</i> -Butanol	100/1	1000/1	0	—	—
5 ^b	<i>n</i> -Butanol	200/1	1000/1	0	—	—
6	10-UND	100/1	1000/1	0	—	—
7 ^b	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	BnNH ₂	100/1	1000/1	0	—	—

^a Estimated vol% of the reaction mixture. ^b These experiments were repeated and the failure to crystallize was reproduced.



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%)	M_n	M_w	T_m (°C)	ΔH_m (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	SnOct ₂	160	—	—	—	—	—	—	—	—
6	SnOct ₂	150	30–40	19 500	44 700	183.5	80.5	76	18	14
7	SnOct ₂	140	90–100	22 000	35 700	183.5	79.0	75	19	14
8	SnOct ₂	130	90–100	21 000	28 300	179.5	78.5	74	17	12/13

mixture took place. This was a first demonstration that SnOct₂ is a relatively unfavourable catalyst for the formation of HT_m polylactide. 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 T_m '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 T_m '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 T_m 's were somewhere in between those of typical LT_m and HT_m crystallites and demonstrated for the first time that SnOct₂ may produce crystallites with higher perfection than the normal LT_m 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 T_m 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 HT_m crystallites with a T_m > 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 HT_m polylactide even at 120 °C.⁸ This comparison demonstrates again that alcohol initiated ROPs are unfavourable for the formation of HT_m crystallites. With SnOct₂ no crystallization occurred at 160 °C and at lower polymerization temperatures the T_m '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 HT_m 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 HT_m 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

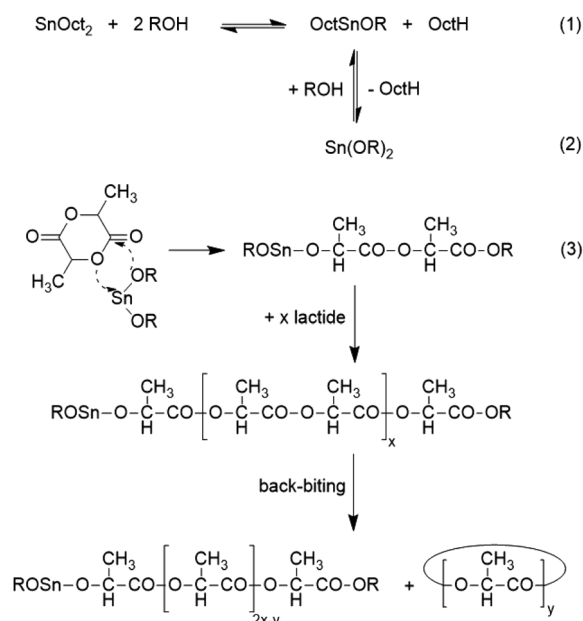
**Scheme 2** Simplified scheme of SnOct₂ + alcohol-catalyzed ROP of lactide.

Table 6 Annealing experiments with preformed acetylated poly(L-lactide) ethyl ester at 160 °C for 2 d or at 170 °C for 1 d (after annealing at 120 °C for 2 h)

Exp. no.	Substrate	Cat. used for annealing	T (°C)	t (h)	T_m (°C)	ΔH_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, SnOct₂-catalyzed product of exp. no. 8, Table 5, was used as substrate. ^b AA preformed poly(L-lactide) prepared with EtLac as initiator (Lac/In = 200/1) and SnOct₂ as catalyst (Lac/Cat = 1000/1) was acetylated with acetic anhydride plus pyridine and used as substrate.

(Scheme 2, eqn (1) and (2)). This hypothesis also explains why crystallites consisting of cyclic poly lactides 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(L-lactide) was prepared with ethyl L-lactate as initiator and a Lac/In ratio of 100/1, whereupon SnOct₂ (Lac/Cat = 1000/1) served as catalyst (acronym: HO-PLA-Et, see Table 6). Part of this poly lactide was modified by acetylation of the HO-CH end

group with acetic anhydride. The resulting poly lactide was named AcO-PLA-Et in Table 6. When HO-PLA-Et was heated with SnOct₂ 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 Ac-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 SnOct₂.

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

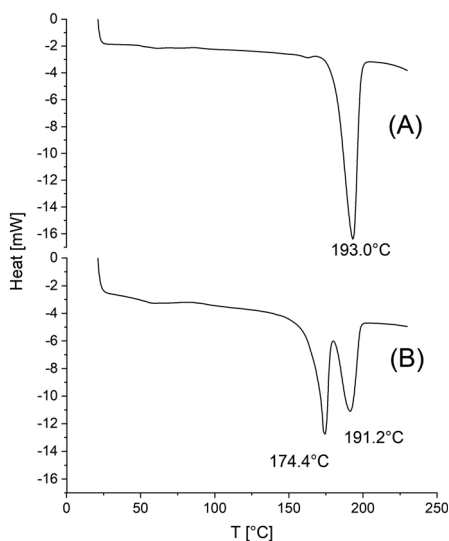


Fig. 1 DSC heating traces of poly lactides prepared by ethyl L-lactate-initiated ROPs in bulk at 160 °C/3 d: (A) with SnBiph (No. 10, Table 1), (B) with DSTD (No. 2, Table 1).

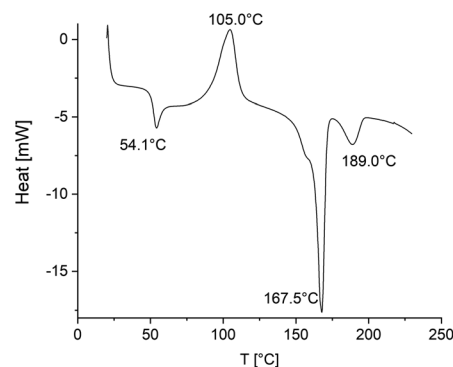


Fig. 2 DSC heating traces of a poly LA prepared with SnNaph as catalyst and ethyl L-lactate as initiator at 160 °C/3 d (No. 8, Table 1, see footnote c).



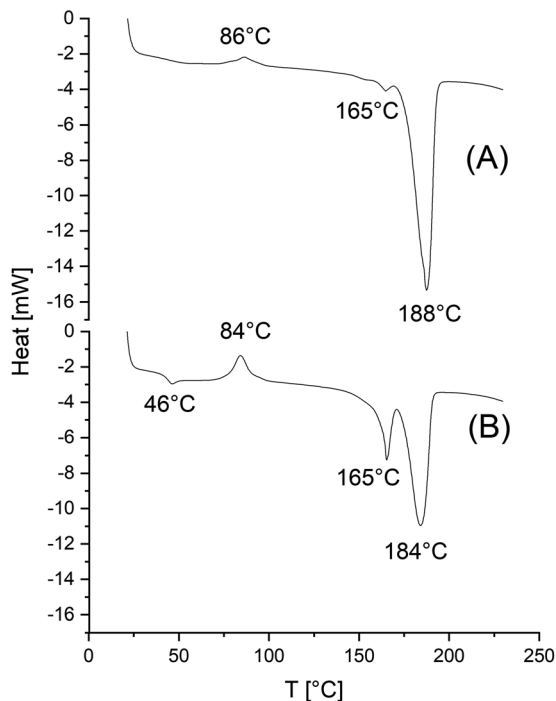


Fig. 3 DSC heating traces of polyLA prepared with SnOct_2 as catalyst and 1-HMN as initiator (LA/In = 100/1) at 160 °C, 3 d: (A) after 1 h (No. 9, Table 4), (B) after 0.5 h (No. 8, Table 4).

(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 LT_m and 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 HT_m crystallites formed during the polymerization. DSC heating traces with a similar structure were also obtained from polylactides prepared with SnOct_2 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 LT_m into HT_m crystallites.

MALDI TOF mass spectrometry

Alcohol-initiated catalyzed by SnOct_2 or cyclic tin catalysts such as DSTL¹² and BuSnBuca¹³ 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, cyclics are not formed. Yet, at temperatures of 160 °C and higher in combination with a reaction time of

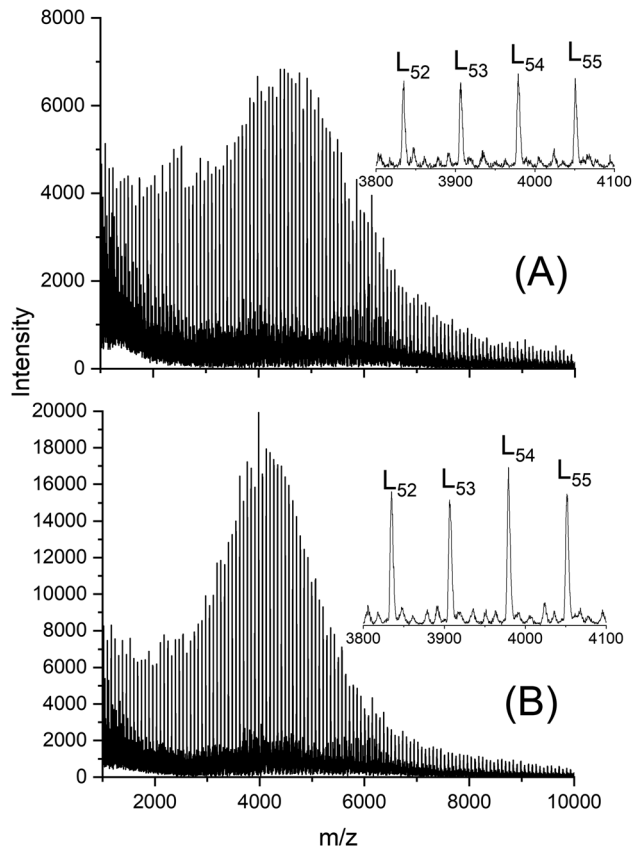


Fig. 4 MALDI TOF mass spectra of ethyl lactate-initiated polylactides polymerized with (A) SnBiph at 150 °C/1 d (No. 2, Table 5), (B) SnOct_2 at 140 °C/1 d (No. 7, Table 5). L = linear chains having ethyl ester end groups.

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 *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 cyclics were also absent after 3 d at 160 °C (Fig. 5A). Yet, at Lac/In ratio of 200/1 small amounts of cyclics were formed as demonstrated in Fig. 5B. This difference agrees with results of a previous study which showed that back-biting is favored by lower In/Cat ratios corresponding to higher Lac/In ratios at constant catalyst concentration. However, with other alcohols cyclics were also formed at Lac/Cat ratios of 100/1 as demonstrated in Fig. S1A (see ESI).†



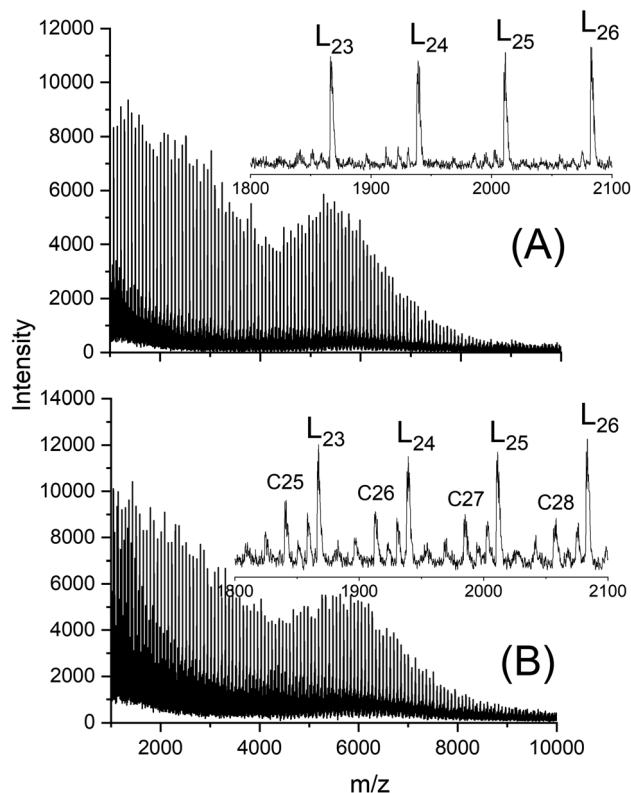


Fig. 5 MALDI TOF mass spectra of polylactides initiated with 11-undecenol and catalyzed with SnBiph at 160 °C: (A) LA/In = 100/1, No. 4 Table 2, (B) LA/In = 200/1, No. 5, Table 2. L = linear chains having undecenyl ester end groups.

The most interesting and somewhat surprising result was the existence of a maximum in the molecular weight distribution (MWD) between m/z 5000 and 6000, whenever semi-crystalline polylactides were measured (Fig. 4, 5, S1 and S2†). In principle, one may expect that a fully equilibrated polymer possesses a “most probable” distribution according to eqn (1) as first demonstrated by Flory for irreversible and reversible polycondensations.²²

$$n_x = p^{(x-1)}(1 - p) \quad (1)$$

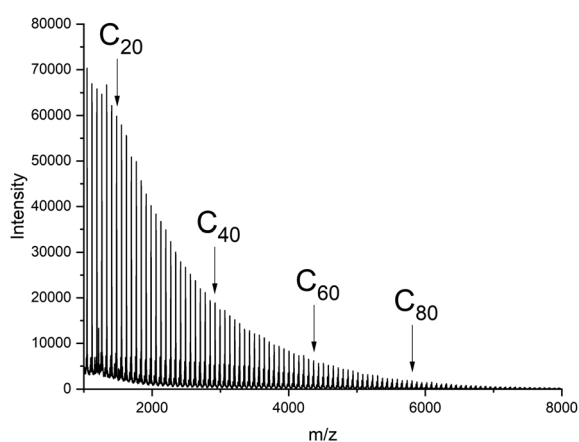


Fig. 6 MALDI TOF mass spectrum of a polylactides prepared with Ph_2SnCl_2 as catalyst in bulk at 160 °C/1 h (reproduced from ref. 23).

with x = degree of polymerization, p = conversion, n_x = 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 Ph_2SnCl_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(L-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 °C for 15 d with a large amount of DSTL (Lac/Cat = 200/1).²⁵ 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 α -modification, first described by DeSantis and Kovacs,²⁶ were found (Fig. S3;† numerous examples of such WAXS patterns were also presented in previous publications^{11,27}). This result was predictable, because the α -modification is thermodynamically most stable modification of poly(L-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 study²⁷ dealing with HT_m crystallites of predominantly cyclic poly(L-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



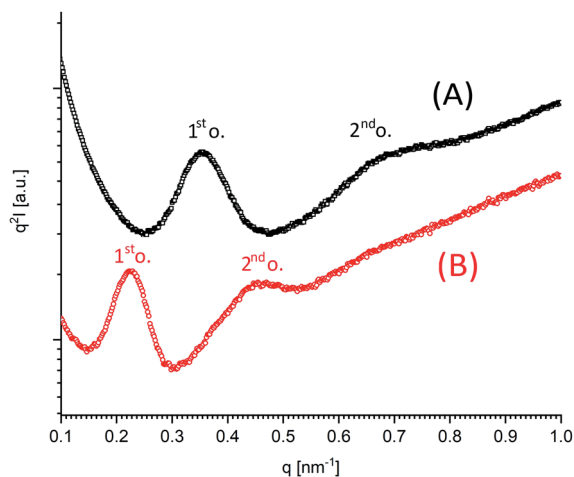


Fig. 7 SAXS Kratky plots of poly(lactides) prepared with ethyl lactate as initiator and with: (A) SnOct₂ as catalyst at 130 °C (No. 8, Table 5), (B) SnBiph as catalyst at 160 °C (No. 1, Table 5), 1st o. = reflection of first order of lamellar long period *L*.

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 σ_e . According to the Gibbs–Thomson –

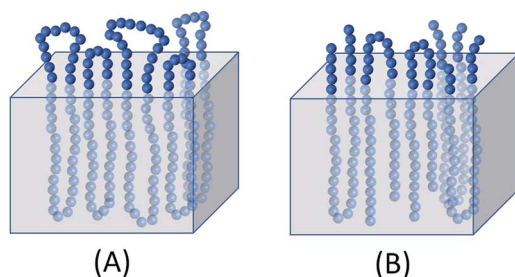


Fig. 8 Hypothetical illustration of the smoothed surface of crystallites consisting of cyclic polyLA (A) or of linear polyLA (B).

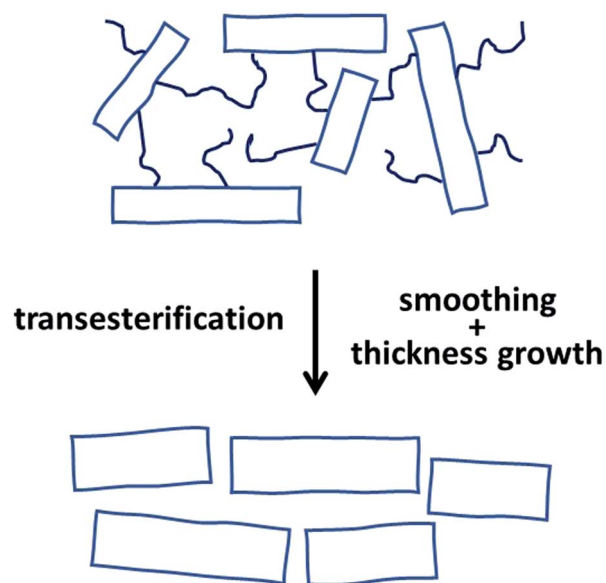


Fig. 9 Schematic illustration of the morphological change caused by transesterification reactions across the rigid amorphous phase on the large surfaces of the lamellar crystallites.

eqn (2), a high *T_m* may be a consequence of a low σ_e 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.

$$T_m = T_{m0} [1 - (2\sigma_e/r \times \Delta H_{m0} \times l_c)] \quad (2)$$

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 poly(lactides), 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_m polyactides can be prepared *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 SnOct₂ as catalyst and various alcohols as initiators yielded a HT_m polyactide having a $T_m > 190$ °C. Since the technical production of poly(L-lactide) and almost all studies of properties of poly(L-lactide)s published over the past 50 years are based on ROPs catalyzed with SnOct₂ + alcohol, the present results explain why the HT_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_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, *Poly(lactic acid): synthesis, structures, properties, processing, and applications*, John Wiley & Sons, 2011.
- 2 M. L. Di Lorenzo and R. Androsch, *Synthesis, Structure and Properties of Poly(lactic acid)*, Springer International Publishing, Cham, 2018.
- 3 D. Bigg, *Technical papers of the annual technical conference-society of plastics engineers incorporated*, 1996, pp. 2028–2039.
- 4 M. L. Di Lorenzo, *J. Appl. Polym. Sci.*, 2006, **100**, 3145–3151.
- 5 J. R. Dorgan, J. Janzen, M. P. Clayton, S. B. Hait and D. M. Knauss, *J. Rheol.*, 2005, **49**, 607–619.
- 6 K. Jamshidi, S.-H. Hyon and Y. Ikada, *Polymer*, 1988, **29**, 2229–2234.
- 7 J. J. Kolstad, *J. Appl. Polym. Sci.*, 1996, **62**, 1079–1091.
- 8 H. R. Kricheldorf, S. M. Weidner and A. Meyer, *Polym. Chem.*, 2020, **11**, 2182–2193.
- 9 B. Kalb and A. J. Pennings, *Polymer*, 1980, **21**, 607–612.
- 10 K. Kishore, R. Vasanthakumari and A. J. Pennings, *J. Polym. Sci., Polym. Phys. Ed.*, 1984, **22**, 537–542.
- 11 H. R. Kricheldorf and S. M. Weidner, *Polym. Chem.*, 2020, **11**, 5249–5260.
- 12 H. R. Kricheldorf, S. M. Weidner and F. Scheliga, *Polym. Chem.*, 2017, **8**, 1589–1596.
- 13 H. R. Kricheldorf, S. M. Weidner and F. Scheliga, *Macromol. Chem. Phys.*, 2017, **218**, 1700274.
- 14 H. R. Kricheldorf and S. M. Weidner, *Eur. Polym. J.*, 2018, **105**, 158–166.
- 15 H. R. Kricheldorf, S. M. Weidner and F. Scheliga, *Eur. Polym. J.*, 2019, **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, *J. Appl. Crystallogr.*, 2014, **47**, 1797–1803.
- 17 G. Schwach, J. Coudane, R. Engel and M. Vert, *Polym. Int.*, 1998, **46**, 177–182.
- 18 G. Kharas, F. Sanchez-Riera and D. Severson, *Polymers of Lactic Acid in Plastics from Microbes*, ed. D. P. Mobley, Hanser Gardner Publications, Inc., 1994.
- 19 A. Södergård and M. Stolt, *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 *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, *Macromol. Chem. Phys.*, 2017, **218**, 1600331.
- 22 P. J. Flory, *Principles of polymer chemistry*, Cornell University Press, 1953.
- 23 H. R. Kricheldorf, S. M. Weidner and F. Scheliga, *J. Polym. Sci., Part A: Polym. Chem.*, 2019, **57**, 952–960.
- 24 H. R. Kricheldorf and S. M. Weidner, *Macromol. Rapid Commun.*, 2020, 2000152.
- 25 S. M. Weidner and H. R. Kricheldorf, *Macromol. Chem. Phys.*, 2017, **218**, 1700114.
- 26 P. DeSantis and A. J. Kovacs, *Biopolymers*, 1968, **6**, 299–306.
- 27 H. Kricheldorf, S. Chatti, A. Meyer and S. Weidner, *RSC Adv.*, 2021, **11**, 2872–2883.

