



High T_m Poly(L-lactide)s by Means of Bismuth Catalysts?

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One series of BiSub-catalyzed ring-opening polymerizations (ROPs) is performed at 160 °C for 3 days with addition of difunctional cocatalysts to find out, if poly(L-lactide) crystallizes directly from the reaction mixture. An analogous series is performed with monofunctional cocatalysts. High T_m crystallites ($T_m > 190$ °C) are obtained from all bifunctional cocatalysts, but not from all monofunctional ones. It is shown by means of SAXS measurements that the high T_m values are mainly a consequence of a transesterification–homogenization process across the lamellar surfaces resulting in thickness and smoothing of the surfaces. An unusual enthalpy-driven modification of the molecular weight distribution is found for samples that have crystallized during the polymerization. A third series of ROPs is performed at 170 °C for 2 h followed by annealing at 120 °C (2 h) to induce crystallization. Complete transformation of the resulting low T_m crystallites ($T_m < 180$ °C) into the high T_m crystallites by annealing at 170 °C for 1 d is not achieved, despite variation of the cocatalyst.

and reduction of environmental pollution, even when this substitution cannot reach the level of 100%. In addition to the substitution of fuel-based, plastics homo- and copolymers of lactic acid have found numerous applications in medicine and pharmacy.^[6–8] This situation justifies to explore new methods and catalysts useful for the preparation of high molecular poly(lactides) (poly-LAs) and to explore their chemical and physical properties in more detail.

In contrast to the classical polymer chemistry mainly based on polymers of α -olefins and vinyl monomers, the production of biodegradable environmentally friendly polymers makes only sense, when the catalysts used for their production possess a low toxicity. The commercial polylactides are all produced by ring-opening polymerization (ROP) of L-lactide

(sometimes containing also D-units) by means of tin(II) 2-ethylhexanoate (SnOct_2) as catalyst in combination with an alcohol as initiator. This tin(II)salt, like any other tin compound, possess a considerable broad cytotoxicity, which concerns almost all microorganisms. Since its toxicity for humans is rather low, SnOct_2 has been accepted by the U. S. Food and Drug Administration (FDA) as antifouling food additive. Nonetheless, for medical and pharmaceutical applications any contamination of polylactides by tin compounds is unwanted and substitution by a less toxic catalyst is desirable.

Over the past 20 years an increasing number of research groups has focused its work on ROPs of L- or D,L-lactide catalyzed by metal-free organocatalysts claiming that they are less toxic than metal-based catalyst.^[9–11] However, those authors have rarely published toxicity data of their catalysts and in cases where such data are available (e.g., *N,N*-dimethyl-4-aminopyridine) its toxicity is significantly higher than that of SnOct_2 . The most promising alternative of tin is bismuth, first, because its toxicity is extremely low^[12–14] (even lower than that of zinc^[13]) and second, because its tendency to racemize L-lactide at high reaction temperatures is as low or lower than that of tin salts.^[14] It has been demonstrated (and reviewed) that various bismuth(III) salts combined with alcohols enable syntheses of linear homo and copolymers of lactide and glycolide.^[15,16] Furthermore, the authors have reported that the combination of BiSub and salicylic acid also allows for a racemization-free synthesis of cyclic poly(L-lactide) under optimized reaction conditions.^[17]

In addition to the exploration of preparative methods, studies of physical properties of polylactides are of interest. Regardless of the thermal history, optically pure, commercial poly(L-lactide)

1. Introduction

In addition to certain derivatives of starch or cellulose, polylactides are the most widely used and produced biosourced and biodegradable polymer.^[1–5] Since the pollution of nature with “immortal” fuel-based plastics rapidly increases, their substitution by biosourced, hydrolytically degradable polymers is an important contribution to the stabilization of climate

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typically has melting temperatures (T_m) below 180 °C.^[18–21] These low T_m values (called LT_m in the following text) are characteristic for poly(L-lactide)s free of catalyst or containing a poisoned catalyst. However, quite recently the authors have shown that high-melting (HT_m) poly(L-lactide)s having T_m 's around 193–196 °C (called HT_m in the following text) can be obtained via ring-expansion (REP) or ROP combined with polycondensation using tin catalysts,^[22] whereas the technically used catalyst system, SnOct₂ + alcohol, does not yield HT_m polylactides. It was found that thickness growth of the lamellar crystals supported by a “smoothing” of the crystal surfaces via transesterification is responsible for the formation of HT_m crystals.

In this context, the present work served several purposes. First, it should be found out, to what extent BiSub-based catalysts modified by variation of the cocatalyst are capable to yield HT_m poly(L-lactide) by direct polymerization. Second, it should be studied, if BiSub-based catalysts are reactive enough to transform LT_m crystallites in solid polylactides into HT_m crystallites. Third, it should be confirmed that HT_m variant of poly(L-lactide) is the thermodynamically most stable morphology of this polymer regardless of catalyst and not confined to tin chemistry. In this way it should also be clarified, if and to what extent tin catalysts can be substituted by a nontoxic Bi-based catalyst for the preparation of HT_m poly(L-lactide)s.

2. Experimental Section

L-lactide, a product of Corbion Purac was kindly supplied by Thyssen-Uhde AG (Berlin). It was recrystallized from “Toluene 99.89% extra dry” (AGROs Chem. Geel, Belgium). Bismuth subsalicylate (BiSub) was purchased from Sigma-Aldrich (Taufkirchen, Germany) and used as received. Salicylic acid, 2-hydroxyphenylacetic acid, 2-hydroxyphenoxyacetic acid, 2,2'-dihydroxybiphenyl, 4-tert-butylcatechol, 4-cyanoacatechol, 2-ethylhexanoic acid, phthalic acid, and 4-hydroxybenzotrile, ethyl L-lactate and 1-hydroxymethyl naphthalene were all purchased from Alfa Aesar (Karlsruhe, Germany) and used as received.

2.1. Polymerizations

2.1.1. At 160 °C/3 days (Tables 1 and 2)

BiSub (0.04 mmol), the cocatalyst (0.04 mmol) and L-lactide (40 mmol) were weighed into a flame-dried 50 mL Erlenmeyer flask under a blanket of argon. A magnetic bar was added, and the reaction vessel was immersed into an oil bath thermostated at 160 °C. When the polylactide was partially or completely crystallized, the reaction vessel was destroyed after cooling and the crude reaction product was characterized.

2.1.2. At 170 °C/2 h (Table 3)

BiSub (0.05 mmol), the cocatalyst (0.05 mmol), and L-lactide (50 mmol) were weighed into a flame-dried 50 mL Erlenmeyer flask under a blanket of argon, and a magnet bar was added.

The reaction vessel was immersed into an oil bath preheated to 170 °C. After 2 h the reaction vessel was cooled with cold water down to a temperature below 120 °C and then transferred into an oil bath thermostated at 120 °C for 2 h. After cooling the reaction vessel was destroyed, the isolated disk of crystalline poly(L-lactide) was broken into pieces and part of the product was annealed at 170 °C for 1 d.

2.2. Measurements

The matrix-assisted laser desorption/ionization time-of-flight (MALDI TOF) mass spectra were recorded with an Autoflex Max mass spectrometer Bruker Daltonik, Bremen, Germany). All spectra were measured in the linear positive ion mode. 8000 single spectra recorded at four different, randomly chosen positions of the sample spot were accumulated for one spectrum. The MALDI targets were prepared from chloroform (CHCl₃) solutions of PL 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, CHCl₃) serving as matrix were mixed in an Eppendorf vial. 1 µL of this 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). The number average (M_n 's) and weight average molecular weights (M_w 's) listed in **Table 1** are not corrected to ease comparison with uncorrected data in the literature. Corrected values may be obtained by multiplication with a correction factor of 0.68.^[23]

The DSC heating traces were recorded on a (with indium and zinc freshly 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 listed in the tables were calculated with a $\Delta H_{m\max}$ of 106 J g⁻¹.^[24,25]

The WAXS and SAXS measurements were performed using the 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 mm². The samples were measured in transmission geometry and were recorded with a Rayonix SX165 CCD-Detector. For the WAXS measurements the sample–detector distance was 0.1 m, allowing to detect an angular range of $2\theta = 5^\circ\text{--}33^\circ$. The recording time for each WAXS pattern was 300 s. The SAXS measurements were performed at sample–detector distance of 1.6 m and the accumulation was 1200 s. DPDAK, a customizable software for reduction and analysis of X-ray scattering data sets was used for gathering 1D scattering curves.^[26] 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

Table 1. BiSub-catalyzed polymerizations of L-lactide in bulk at 160 °C/3 days with bifunctional cocatalysts (Lac/Cat = 1000/1).

Exp. no.	Cocatalyst	M_n	M_w	T_m [°C]	ΔH_m [J g ⁻¹]	Cryst. [%]	L [nm]	l_c
1	–	14000	26000	191.0	93.0	88	24	21
2A ^{a)}	Salicylic acid	37000	78000	–	–	–	–	–
2B	Salicylic acid	15500	40000	192.0	88.5	83	26 (15–17)	22
3	2-Hydroxyphenyl-acetic acid	21000	52000	193.0	97.5	92	28–32	25–28
4A ^{a)}	2-Hydroxyphenoxy-acetic acid	38500	79000	–	–	–	–	–
4B	2-Hydroxyphenoxy-acetic acid	18500	44000	191.0	95.0	90	24–26	19–23
5	4-tert-Butylcatechol	12000	28500	– ^{b)}	– ^{b)}	– ^{b)}	– ^{b)}	–
6	4-Cyanocatechol	23000	65000	191.5	91.5	87	26–27	22–23
7A	2,2'-Dihydroxybiphenyl	31000	69000	192.5	91.0	86	28	24
7B ^{c)}	2,2'-Dihydroxybiphenyl	–	–	194.0	92.5	87	(17)	–
8	2,2'-Dihydroxynaphthalene	13500	50000	–	–	–	–	–
9	Phthalic acid	Black	Tar	–	–	–	–	–

^{a)}Polymerization time 2 h; ^{b)}Only 5–10% of the reaction mixture had crystallized; ^{c)}Repetition with another batch of L-lactide.

the instrumental background, the integral intensity of the crystalline reflections was divided by the overall integral intensity to determine the crystallinity X_c . The SAXS curves were converted into Kratky plots. The long periods of the lamellar domains were determined by the q values of the reflection maxima.

3. Results and Discussion

3.1. Crystallization by Polymerization

A first series of polymerizations was performed with addition of difunctional cocatalysts, such as diphenols, aromatic ortho hydroxy acids or phthalic acid. A temperature of 160 °C and a time of 3 days were selected as standard reaction conditions, and the Lac/Cat ratio was fixed at 1000/1. These reaction conditions were selected, because it was found in a previous study dealing with tin catalysts, that these conditions are particularly favorable for crystallization of poly(L-lactide) from the reaction mixture.^[22] This spontaneous crystallization from the reaction mixture had the consequence that poly(L-lactide)s having T_m values >190 °C were formed (HT_m crystallites) when neat tin catalysts were used. By contrast, only melting temperatures <180 °C were obtained (LT_m crystallites), when samples free of catalyst or containing a catalyst poison were annealed.

The experiments listed in Table 1 yielded relatively low molecular weights with weight average molecular weights <70000 g mol⁻¹, due to thermal degradation. This interpretation was supported by comparison of experiments 2A with 2b and 4A with 4B. After 2 h the weight average molecular weights (M_w 's) were more than 50% higher than those obtained after 3 days. Largely complete crystallization was achieved in most experiments with bifunctional cocatalysts (Table 1), and most of these polymerizations yielded HT_m crystallites. Formation of dark-colored spherulites having diameters up to 5 mm was observed in the surrounding yellowish or brownish melt (see next section).

In a second series of experiments same reaction conditions were used, but monofunctional cocatalysts were added (Table 2). In this series three trends were observable. First, T_m

values above 190 °C were only obtained when the quantity of cocatalyst was small, corresponding to a Lac/Cat ratio of 1000/1 in analogy to the experiments with diphenols listed in Table 1. The experiment with 1,12.dococene diol (No. 9) is an exception from this rule. Second, when the amount of monofunctional additives was enhanced to a Lac/Cat ratio of 200/1, so that most chains were initiated by the alcohol, the formation of HT_m crystallites was impaired. This trend fits in with previous results obtained with various tin catalyst in polymerization experiments performed at 160 °C/2 d in bulk.^[22,27] Addition of alcohols at a Lac/Cat ratio of 200/1 suppressed crystallization almost completely. A satisfactory explanation has not been found yet, but it is now clear from the experiments compiled in Table 2, that this phenomenon is not limited to tin catalysts.

The MALDI TOF mass spectra revealed two noteworthy trends. First, the predominance of cycles in the mass range below m/z 8000 Da and mainly below m/z 6000, which is typical for polymerizations performed with relatively short times (experiments in Table 1 and ref. [22]), has vanished, seemingly because of thermal degradation. Even when chain cleavage is a rare event at 160 °C, one must consider that the polymerization time of 3 days is long and one chain scission per cycle suffices to change the topology from cyclic to linear. A more surprising effect is the appearance of a maximum in the molecular weight distribution curve around m/z 5000–6000 as illustrated in Figure 1A,B and in Figure S1A,B (Supporting Information). Exactly this type of maxima was also observed in several polymerization and annealing experiments catalyzed by various tin catalysts.^[27,28]

This phenomenon is, therefore, not characteristic for the BiSub-catalyzed experiments presented in this work. The formation of these maxima must be dictated by a gain of enthalpy. This could be, e.g., the formation of crystals with a thermodynamically favorable thickness and surface, because in the entropy driven “most probable distribution” the first reaction product (dimer, trimer or tetramer) represents the maximum followed by an exponential decay of the molar fraction of the higher oligomers and polymers.^[29] A segment of such a distribution, which is typical for the polylactides of this

Table 2. BiSub-catalyzed polymerizations of L-lactide in bulk at 160 °C/3 days with monofunctional cocatalysts and 1,12-dodecanediol (Lac/Cat = 1000/1).

Exp. no.	Cocatalyst	Lac/Coc	Spherul. ^{a)} [%]	M _n	M _w	T _m [°C]	ΔH _m [J g ⁻¹]	Cryst. [%]
1	2-Ethylhexanoic acid ^{b)}	1000/1	70–80	25000	73 500	190.0	85	80
2	4-Hydroxybenzo-nitrile ^{c)}	1000/1	80–90	21000	56 500	192.5	99.6	94
3	4-Hydroxybenzo-nitrile	200/1	60–70	25000	57000	171.5	70.0	66
4	Hydroxymethyl -benzodioxane	1000/1	10–15	14000	53000	170.8 183.5	61.0 both peaks	57
5	Hydroxymethyl-benzodioxane	200	5–10	11500	30000	171.0 188.0	72.5 both peaks	68
6	Ethyl acetate	200/1	≈10	14500	52000	186.5	86.0	81
7	<i>n</i> -Butanol	1000/1	50–60	15000	51000	194.5	92.5	87
8	<i>n</i> -Butanol	200/1	35–45	11500	35000	187.0	89.0	84
9	1,12-Dodecanediol	1000/1	60–70	15500	57000	185.5	87.5	83
10	1,12-Dodecanediol	200/1	5–10	14000	51000	167.0 183.0	52.5 both peaks	48
11	1-Hydroxymethyl-naphtahalene	200/1	30–40	13000	53000	167.5 189.0	(56.5)	52

^{a)}Estimated vol% of the reaction mixture; ^{b)}L = 17–21 nm yellow fraction; ^{c)}L = 24–25 nm (spherulites).

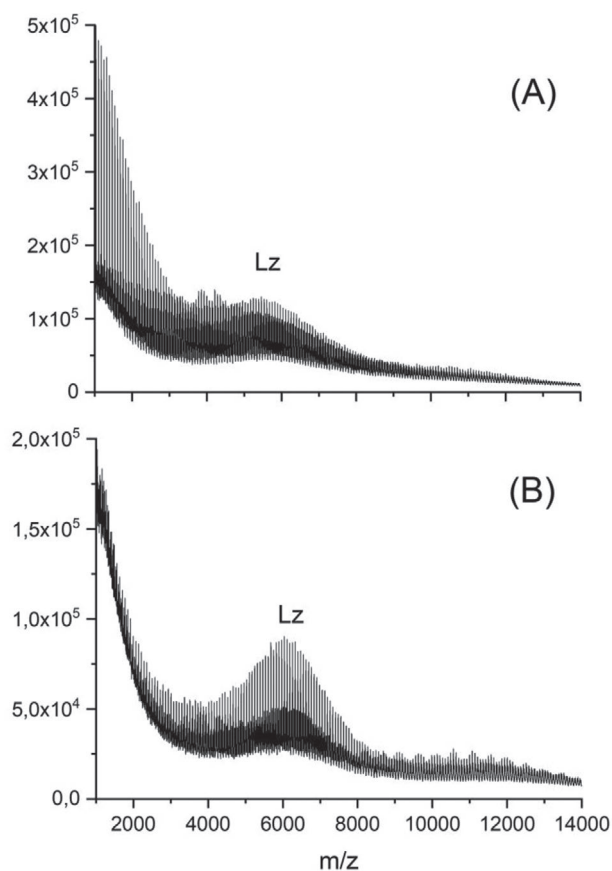
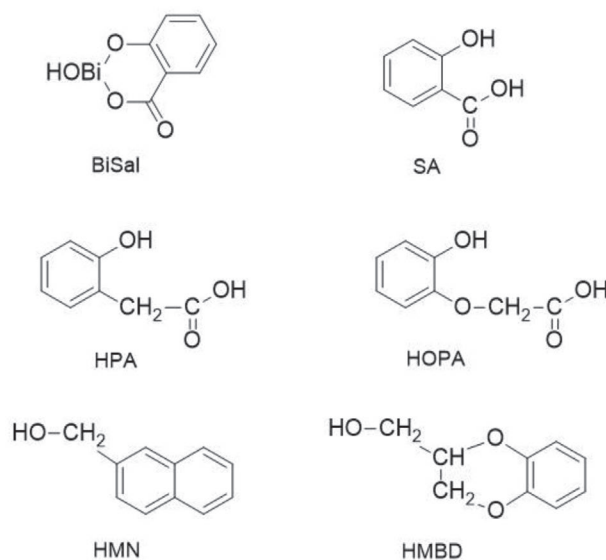


Figure 1. MALDI-TOF mass spectra of poly(L-lactide)s polymerized at 160 °C/3 days with A) salicylic acid (No. 2A, Table 1) and B) 2-hydroxyphenyl acetic acid (No. 3, Table 1).

work when the crystallites were not modified by transesterification, is presented and discussed in the last section of this text (Figure 9A).

Particular conspicuous is a second, flat maximum around m/z 11000 in the spectra of Figure 1A,B in as much, as this broad maximum displays a characteristic fine structure. Exactly this type of maximum has also been found in mass spectra of poly(L-lactide)s, when LT_m crystals were annealed with the SnBiph catalyst (Scheme 1) at 170 °C.^[27] A reasonable explanation of this phenomenon cannot be forwarded at this time.



Scheme 1. Structures of BiSub and selected cocatalysts with their symbols.

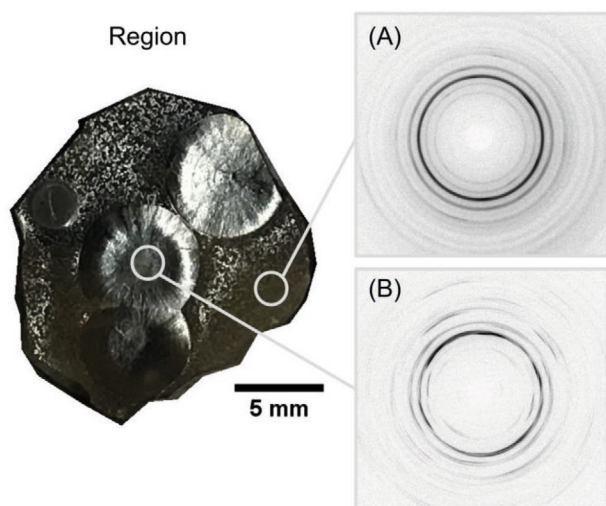


Figure 2. Optical image of spherulites prepared at 160 °C/3 days with BiSub and salicylic acid (No. 2A, Table 1).

3.2. WAXS and SAXS Measurements

In previous studies concerning the formation of HT_m poly(L-lactide)s based on tin catalysts it was found that all the WAXS measurements yielded the pattern characteristic for the α -modification first described by DeSantis and Kovacs.^[30] This orthorhombic crystal lattice which is based on an antiparallel alignment of 3/1 helical polylactide chains is the thermodynamically most stable modification of poly(L-lactide), and thus its formation at reaction temperature of 160 °C is quite normal and predictable, when mechanical stress is absent.^[30] In agreement with these facts the WAXS measurements of spherulites picked up from several experiments of Tables 1 and 2 displayed the pattern typical for the α -modification (Figures 2 and 3A). As already reported for experiments with tin catalysts the WAXS patterns do not differentiate between LT_m and HT_m crystallites.^[22]

The SAXS measurements of the spherulites revealed *L*-spacings in the range of 24–28 nm (Figure 3B; Figure S3, Supporting Information). However, with regard to Figure S3 of the Supporting Information it should be added, that the intensity of the SAXS flections of most samples was weak, obviously due to an extremely high degree of crystallinity (87–94%). These *L*-values are in between the values typical for LT_m crystallites, which fall into the range of 16–22 nm and *L*-values of 28–34 nm obtained by polymerization with cyclic tin catalysts under identical conditions.^[22] Since the *L*-spacings include both crystalline and amorphous phases, more precise information about the crystal thickness is obtained by the *l_c* values calculated by multiplication of *L*-spacing and crystallinity. These *l_c*-values fall into the range of 19–25 nm (Table 1) whereas the *l_c*-values of LT_m crystallites measured previously are in the range of 8–11 nm. Hence, the *l_c*-values obtained in this work indicate a thickness growth of the crystallites by a factor 2.0–2.5. For polymerizations with tin catalysts a slightly higher increase of layer thickness (factor 2.1–2.8) was found. These results, therefore, prove that formation of HT_m poly-LA is mainly a result of the considerable thickness growth resulting from

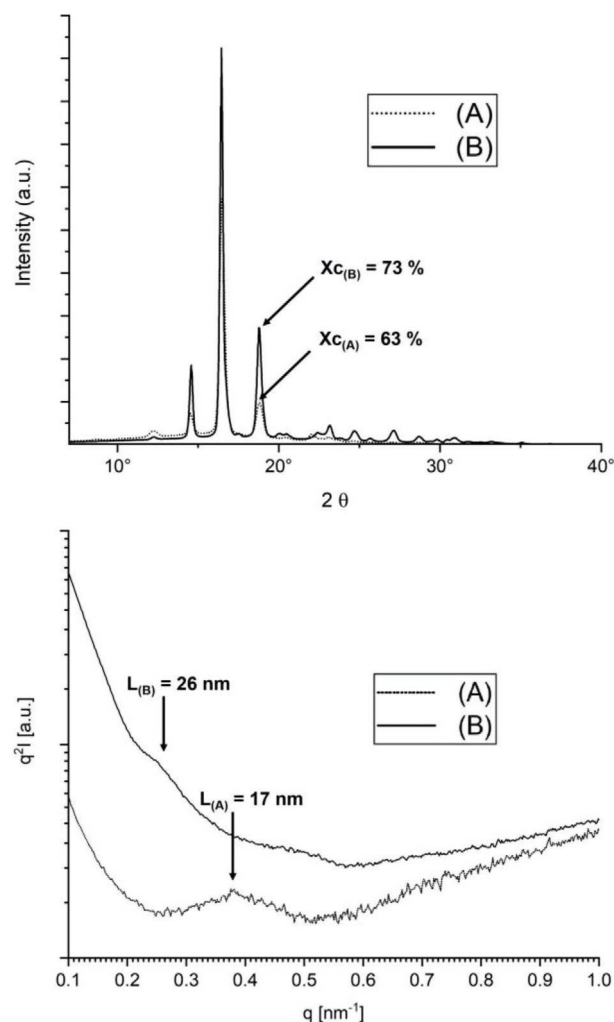
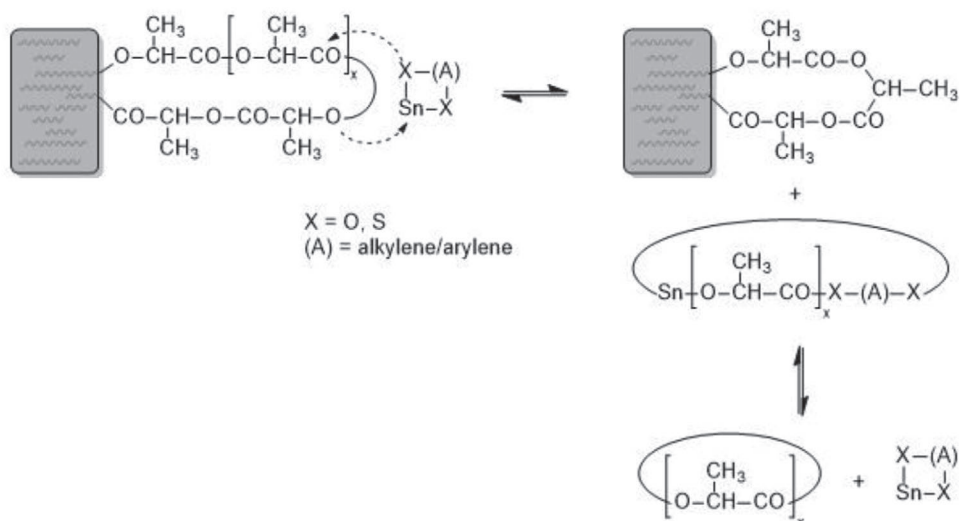


Figure 3. WAXS curves (top) and SAXS curves (bottom) of the crystallites displayed in Figure 2A. The labels (A) and (B) correspond to the labels used in Figure 2.

transesterification on across the large surface of the lamellar crystallites. Examples of such transesterification reactions based on the coordination insertion mechanism are formulated in Schemes 2–4 and the result illustrated in Figure 4. The existence of transesterification reactions along the surface of poly-LA crystallites without involving ester bonds inside the crystallites has recently been demonstrated by the authors.^[22,27,31]

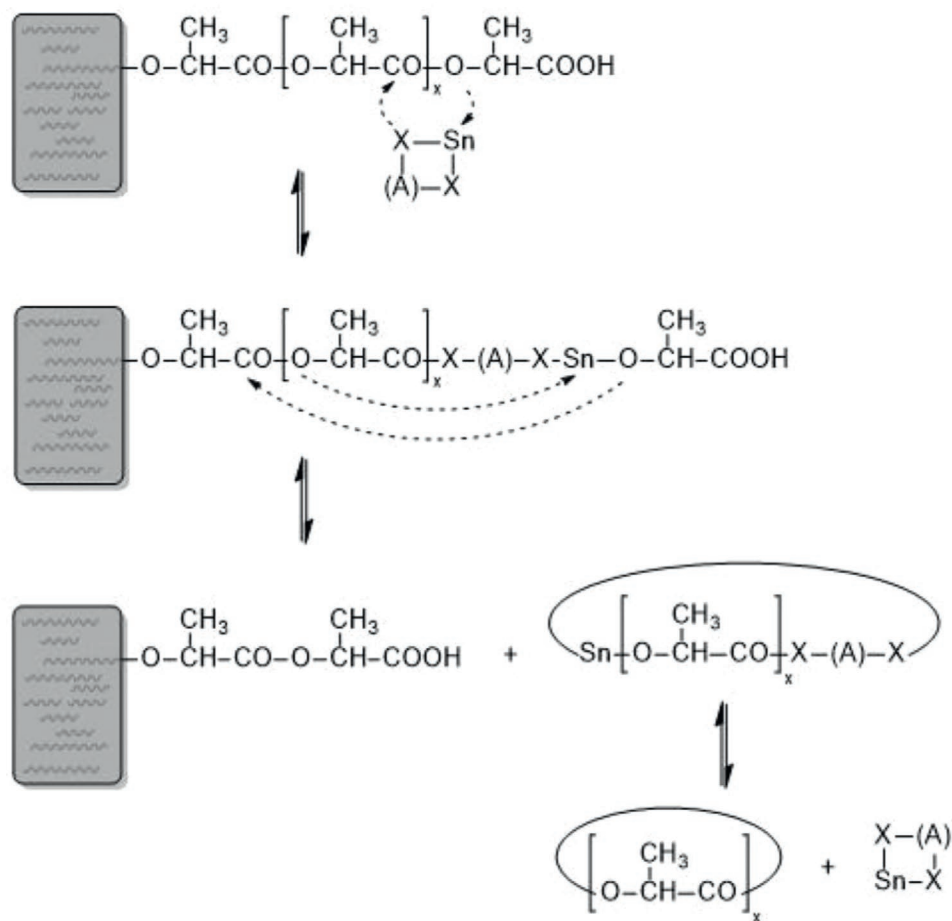
As illustrated in Figure 4, transesterification and thickness growth most likely also involves a smoothing of the crystal surfaces. This “smoothing” is based on a homogenization of loops and loose chain ends in combination with a removal of tie molecules. Three observations support this hypothesis. In the previous experiments with tin catalysts no parallel between *L*-spacings and *T_m* was found. Second, a second order reflection in the SAXS curves (Figure 3A), which is absent in the scattering curves of the LT_m crystallites, indicates a more perfect 3 days-ordering in the arms of the spherulites, a consequence which is not automatically correlated with a greater crystal thickness. A more perfect 3 days-packing of crystallites based on smoother surfaces also provides a reasonable explanation



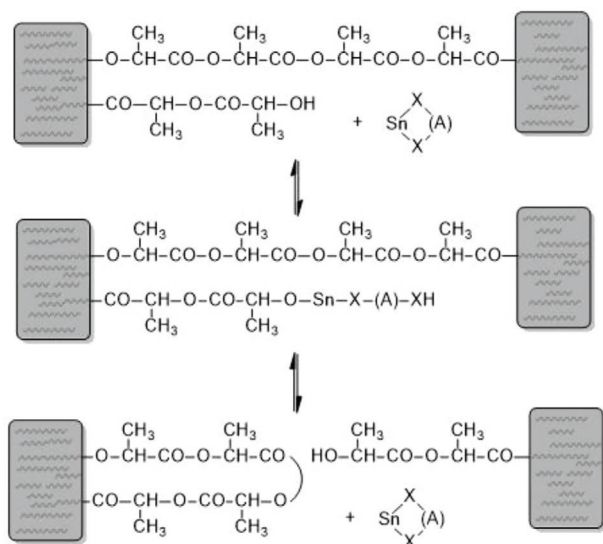
Scheme 2. Transesterification resulting in shortening or growing of loops on a crystal surface.

of the extremely high degrees of crystallinity (Table 1). Furthermore, a smoothing of the surfaces also favors formation of higher T_m values, because it reduces the surface free energy

(σ_e). The correlation between T_m and σ_e is given by the Gibbs-Thomson equation (1), which demonstrates that a lower surface free energy results in a higher T_m



Scheme 3. Transesterification resulting in shortening or growing of linear chains sticking out from the surface of a crystallite.



Scheme 4. Transesterification resulting in formation of a loop and cleavage of a tie molecule.

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

with T_{m0} as the melting temperatures of a large ideal crystal, ρ as density of the crystalline phase, l_c as lamellar thickness, and σ_e as the “fold surface free energy.”

A correlation between a low surface free energy and a smooth surface was also postulated by Sugai et al. who studied low molar mass ($M_n < 3000$) cyclic poly(L- and D-lactide)s having a low dispersity.^[32] However, those polylactides had the structure of guest–host copolymers and their melting temperatures and melting enthalpies were much lower than those of the poly(L-lactide)s listed in Tables 1 and 2 or described previously due to the influence of the guest comonomer.

For three reasons a more detailed study and discussion of the various chemical and physical processes going on in solid poly-LA in the presence of catalysts was not intended in this work. First, it was the purpose of this work to clarify, if BiSub-based catalysts can generate HT_m poly-LA and which reaction conditions favor their formation, Second, the poly-LA samples

listed in Tables 1 and 2 possess a broad dispersity. Third, the polymerization products showed an enormous physical heterogeneity as discussed in the next section.

3.3. Heterogeneity of the Reaction Products

All experiments of this work were performed with quantities of 5.76 g (40 mmol) of L-lactide in 50 mL Erlenmeyer flasks, and thus disks having a diameter around 5 cm and a thickness of 2.5–3.0 mm were obtained. The late onset of nucleation (typically after 24 h) and the slow growth of the spherulites had the consequence, that the disks were neither completely nor homogeneously filled with spherulites. Due to a dark color, these spherulites were distinguishable from the surrounding ochre or brownish melt which turned into a mainly transparent amorphous phase upon rapid cooling. However, in several samples (e.g., No. 2B, Table 1 and No. 1 Table 2) randomly dispersed and oriented small spherulites surrounded the spherulites. This scenario is illustrated by WAXS surface scanning (Figure 2; Figure S4, Supporting Information). These tiny spherulites are not observable by the naked eye with two consequences. First, not all areas of the transparent phase are completely amorphous. Second, the volume fraction of the reaction product filled with spherulites only concerns visible large spherulites and is not directly correlated to the degree of crystallinity of the entire sample.

The heterogeneity inside the disks had, therefore, the consequence, that the shape of the DSC curves depended on the location of the probe taken from the disks. When the probe almost completely consisted of large spherulites, only one melting endotherm appeared in the first heating trace and a glass transition step was not observable (Figure 5A). By contrast, the DSC trace of a completely amorphous area displays a distinct glass-transition step followed by a crystallization exotherm with a maximum around 110 °C (Figure 5B). Finally, a melting endotherm of the freshly crystallized phase appears around 169–171 °C originating from rather imperfect LT_m crystals.

When the probe contains more or less perfect HT_m crystallites together with amorphous polylactide, DSC traces presented in Figure 6A,B were obtained. These DSC traces show all the features typical for an amorphous polylactide, but in addition to

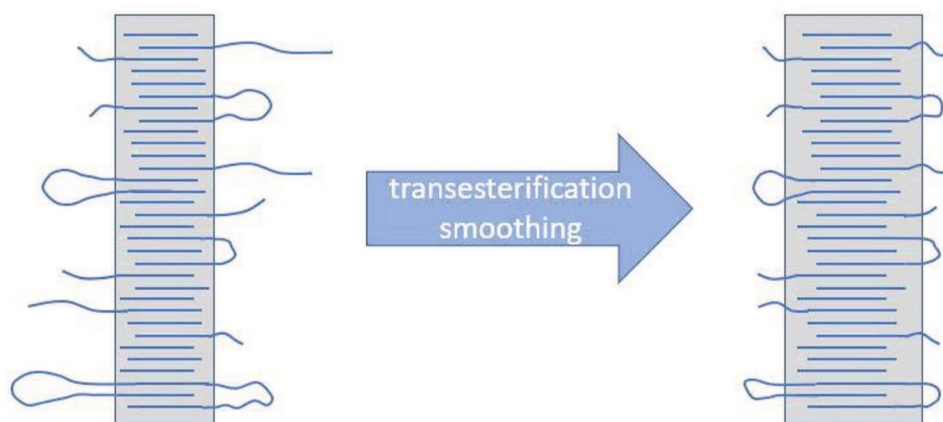


Figure 4. Illustration of crystal growth and “smoothing” of LT_m crystallites.

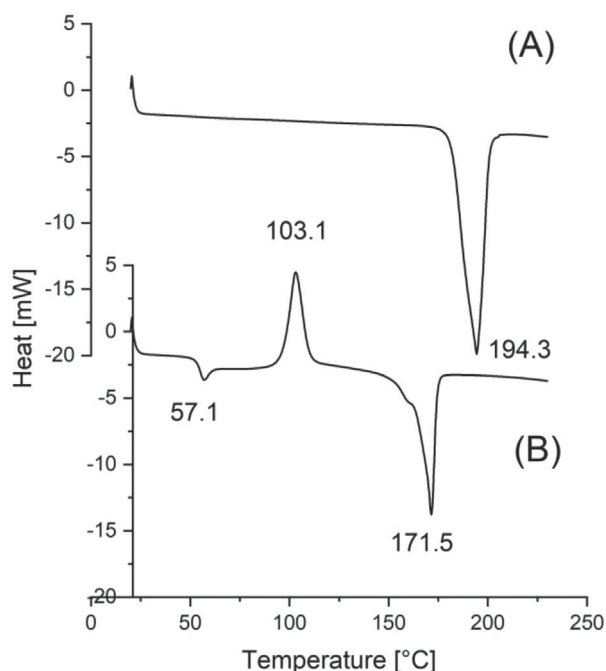


Figure 5. DSC heating traces of poly(L-lactide)s polymerized at 160 °C/3 days with A) 2,2'-dihydroxabiphenyl (No. 2B, Table 1) spherulites and B) HOPA (No. 4A, Table 1), amorphous phase.

the T_m of the LT_m crystals around 167 °C, a second endotherm >185 °C became observable, the intensity of which depended on the reactivity of the catalyst and depended, as illustrated in

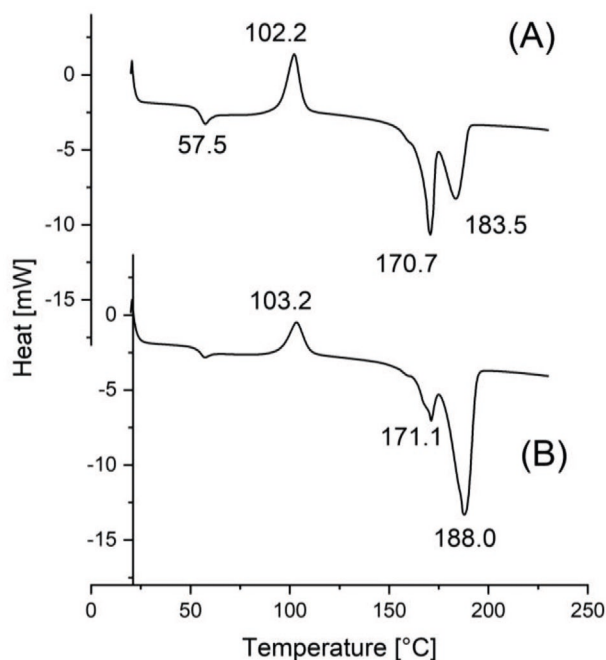


Figure 6. DSC heating traces of poly(L-lactide)s polymerized at 160 °C/3 days with A) HMBD, 1000/1 (No. 4, Table 2) combination of amorphous and crystalline phase and B) HMBD, 200/1 (No. 5, Table 2), combination of amorphous and crystalline phase.

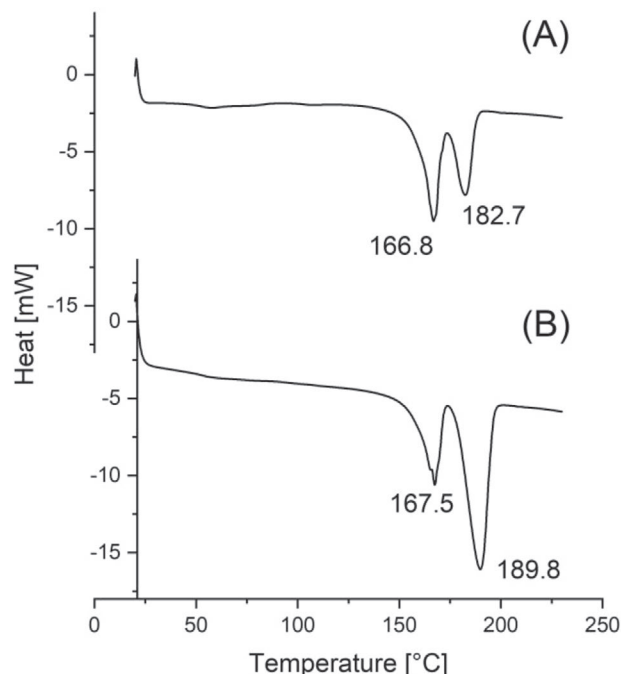


Figure 7. DSC heating traces of poly(L-lactide)s polymerized with A) DOD, 2001 (No. 10, Table 2) and B) HMN, 200/1 (No. 11, Table 2).

Figure 6, on the quantity of the catalyst. In a couple of experiments a third type of DSC traces was found illustrated in **Figure 7**. Glass-transition step and recrystallization exotherm are barely detectable, but two rather strong melting endotherms are evident, one peak in the range of 167–169 °C and a second one above 182 °C. It seems that in these cases most or all of the LT_m crystallites were formed during the polymerization process along with imperfect HT_m crystallites. For two of these samples (No. 2B, Table 1 and No. 1, Table 2) two SAXS reflections were observed with an L -spacing of <21 nm in the ochre phase and $L > 24$ nm for the spherulites. These results make clear, why it is impossible to calculate degrees of crystallinity for the entire polymerization product (disk). Hence, the crystallinity data listed in Tables 1 and 2 exclusively concern the samples used for DSC measurements.

Finally, it should be mentioned that in all samples where the relatively large, dark spherulites were formed, these spherulites surrounded the magnetic bar. Apparently, the mechanical stress caused by the motion of the bar during the last minutes before it was stopped, favored nucleation.

3.4. Annealing Experiments

Annealing experiments were performed to explore, if BiSub-based catalysts are capable of transforming LT_m crystallites into HT_m crystallites by annealing of solid polylactides. These experiments summarized in **Table 3** were performed in three steps. At first, polylactides were prepared by polymerization at 170 for 2 h. The same cocatalysts as those listed in Table 1 for the 160 °C experiments were used. The samples were rapidly cooled to a temperature below 100 °C, so that crystallization

Table 3. Experiments concerning the transformation of LT_m crystallites into HT_m crystallites (Lac/Cat = 1000/1, Cocat/Cat = 1/1).

Exp. no.	Cocatalyst	Temp. [°C]	Time [h]	M_n	M_w	T_m [°C]	ΔH_m [J g ⁻¹]	Cryst. [%]
1A	–	120	2	20 000	57 000	155.5	62.0	58
1B	–	170	24	17 000	54 000	156.5, 186.5	20.0	61.6
2A	Salicylic acid	120	2	22 000	54 000	161.0	59.5	55
2B	Salicylic acid	170	24	8 000	32 000	164.0, 186.0	71.0	66
3A	2-Hydroxyphenyl- acetic acid	120	2	35 500	75 000	176.5	61.5	57
3B	2-Hydroxyphenyl- acetic acid	170	24	20 000	57 000	186.0	87.0	82
4A	2-Hydroxyphenoxy- acetic acid	120	2	18 500	60 000	162.5	70.0	66
4B	2-Hydroxyphenoxy- acetic acid	170	24	18 000	58 000	187.5	84.5	80
5A	4-Cyanoatechol	120	2	28 000	89 000	168.3	63.5	59
5B	4-Cyanoatechol	170	24	18 000	55 000	189.0	100.5	95
6A	2,2'-Dihydroxybi- phenyl	120	2	31 500	99 000	175.0	55.5	51
6B	2,2'-Dihydroxybi- phenyl	170	24	16 000	54 000	184.5	90.5	85
7A	4-Hydroxy benzotrile	120	2	27 000	64 000	167.0	65.5	61
7B	4-Hydroxy benzotrile	170	24	9 000	20 000	171.0	70.5	66

was suppressed. Second, amorphous samples were annealed at 120 °C for 2 h, whereby crystallization with formation of rather imperfect LT_m crystallites was achieved in all cases, as indicated by the T_m 's below 165 °C listed in Table 3 and illustrated in Figure 8A and Figure S4A (Supporting Information). The third step consisted of annealing at 170 °C for 1 d. Exactly the same procedure has recently been applied to poly(L-lactide)s prepared with five different cyclic tin catalysts.^[31] It was found that complete transformation of LT_m into HT_m crystallites was feasible with tin(II)-based catalysts at 170 °C after 8 h or 24 h depending on the reactivity of the catalyst. The experiments compiled in Table 3 show that all experiments failed

to yield complete transformation into poly(L-lactide)s having a $T_m > 190$ °C. However, with exception of experiment No. 7 based on addition of 4-hydroxy benzonitrile, at least partial transformation was achieved (Figure 8B; Figure S4B, Supporting Information). It is in good agreement with the results presented in Tables 1 and 2 that the only total failure resulted from an experiment conducted with a monofunctional cocatalyst. The best result was obtained with 4-cyanoatechol as cocatalyst (No. 5, Table 3), because here at least a T_m of 189 °C was achieved. From a preparative point of view, it may be concluded that direct polymerization with BiSub-based catalysts is more successful for a preparation of HT_m crystallites than a transformation of preformed LT_m crystallites, and certain tin(II) based catalysts are more effective than the BiSub-based catalysts studied in this work.

Another unexpected result was discovered by MALDI TOF mass spectra of the annealed samples. In most annealing experiments a new maximum of the molecular weight distribution was formed between m/z 5500 and 6000 in analogy to the ROP experiments of Tables 1 and 2. Figure 9 provides an exemplary illustration of this phenomenon. Furthermore, this figure also demonstrates that the initial predominance of cyclic poly-lactides almost completely vanishes. This change can be found less pronounced in all other experiments of Table 3. It indicates that heating to 170 °C for many hours causes chains scission, which in the case of cyclic species is automatically combined with a change of the topology. Analogous results were obtained with tin catalysts.^[31]

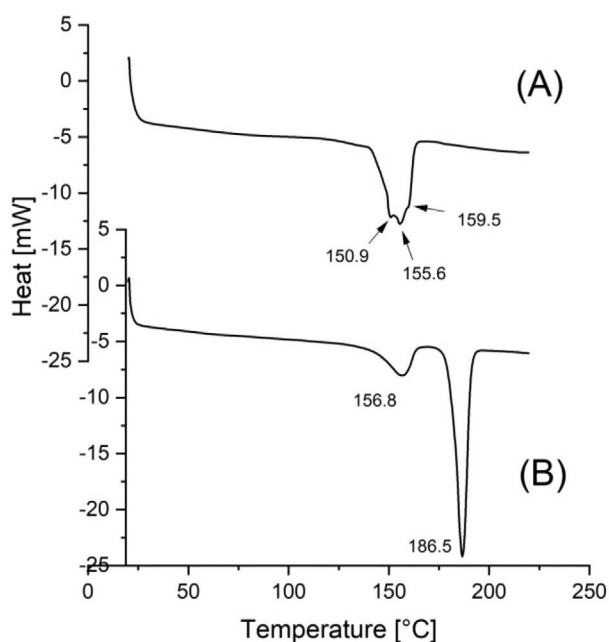


Figure 8. DSC heating traces of poly(L-lactide)s polymerized with neat BiSub A) annealed at 120 °C/2 h (No. 1A, Table 3) and B) annealed at 170 °C/1 d (No. 1B, Table 3).

4. Conclusions

The experiments performed in this work allow for several interesting and unpredictable conclusions. First, HT_m poly(L-lactide)s having T_m values >190 °C can be prepared by direct ROP with BiSub, when certain diphenols (e.g., catechols), or aromatic ortho-hydroxy acids are used as cocatalysts. However, the addition of monofunctional alcohols was less successful. Second, SAXS measurements prove that the thickness growth

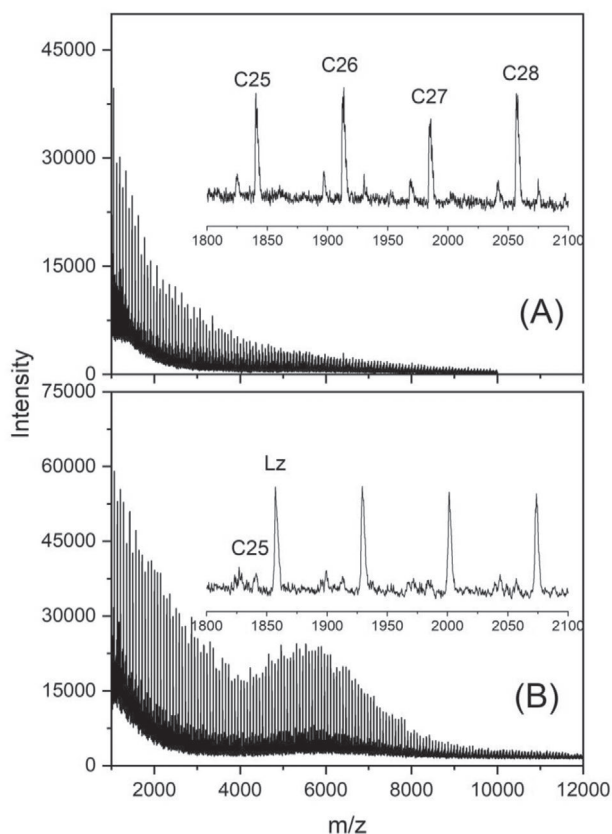


Figure 9. MALDI TOF mass spectra of poly(L-lactide)s polymerized with 2,2'-dihydroxybiphenyl A) annealed at 120 °C/2 h (No. 6A, Table 3) and B) annealed at 170 °C/1 d (No. 6B, Table 3).

of crystallites is the main reason for the increase of T_m . Third, annealing of LI_m poly(L-lactide)s in the presence of BiSub-based catalysts does not yield a perfect transformation into HI_m poly(L-lactide), in contrast to several tin catalysts studied recently. Fourth, these experiments confirm that the T_m of thermodynamically optimized pol(L-lactide) is in the range of 193–196 °C and not below 180 °C. T_m values below 180 °C are either a result of kinetically controlled morphologies^[2,18–21] or a result of structural defects such as D-units^[33] or guest comonomers.^[32,34] Fifth, a few cocatalysts stimulate an enthalpy-driven alteration of the molecular weight distribution possibly via formation of crystallites with a certain thermodynamically favorable size and lamellar thickness.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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