

SnOct₂-Catalyzed and Alcohol-Initiated ROPS of L-Lactide—Control of the Molecular Weight and the Role of Cyclization

Hans R. Kricheldorf,* Steffen M. Weidner, and Felix Scheliga

Ring-opening polymerizations (ROP) of L-lactide (LA) are conducted in bulk at 130, 160, or 180 °C and are initiated with two different alcohols at 160 °C. The lactide/initiator ratio (LA/In) is varied from 50/1 (20/1 at 180 °C) to 900/1 and the lactide/catalyst ratio (LA/Cat) between 2000/1 and 8000/1. At all temperatures a nearly perfect control of number average molecular weight (M_n) via the LA/In ratio is feasible up to LA/In = 200/1, but at higher ratios the M_n value lags behind the theoretical values and the discrepancy increases with higher LA/Cat ratios. Variation of the LA/Cat ratio influences the formation of cycles but does not significantly influence M_n , when the LA/In ratio is kept constant. The formation of cycles is favored by lower In/Cat ratios and is the main reason for the unsatisfactory control of M_n at high LA/In ratios. The results also suggest that the cycles are mainly or exclusively formed by end-to-end cyclization and not, as believed previously, by back-biting.

concerning its mechanism. A first simplified formulation of the polymerization mechanism widely accepted today was published by Zhang et al. in 1994.^[6] Those authors observed that the molecular weight depends roughly on the LA/initiator (LA/In) ratio (only two different ratios were compared) and postulated that the alcohol reacts with SnOct₂ in a reversible exchange reaction ((a) in Scheme 1). The intermediately formed tin alkoxide species was assumed to be the real initiator which reacts with LA according to the coordination-insertion mechanism outlined before by Kricheldorf et al. for ROPs initiated by dibutyltin alkoxides ((b) and (c) Scheme 1).^[7] Confirmation of this mechanism derived from ROPs in bulk was reported a few years later.^[8]


More experimental evidence and detailed kinetic measurements were contributed at the same time by the Penczek group.^[9,10]

The formation of alkyl ester and Sn–O–CH end groups was demonstrated by spectroscopic methods and it was found that the ROP obeys the principle of a living polymerization yielding low dispersities. Furthermore, it was shown that SnOct₂ alone was inactive, and addition of *n*-Butanol was required to start the ROP. However, all those features were only elaborated for polymerizations in THF at 80 °C. These conditions that are far from those of the technical production of PLA, which is performed by polymerization in bulk at temperatures in the range of 130–180 °C. Neither the McAulley^[6] nor the Penczek group^[9,10] studied systematically, how the LA/In ratio influences the number average molecular weight (M_n). A detailed study with this regard was later published by Prud'Homme and coworkers.^[11] This group performed ROPs in toluene at 70 °C and varied the LA/In ratio from 10/1 up to 320/1 at constant LA/Cat ratio. A satisfactory proportionality between LA/In and M_n was found up to a LA/In around 110/1, along with a narrow molecular weight distribution. At higher LA/In ratios the experimental M_n 's fell below the theoretical values. However, technical applications of PLA require at least (uncorrected) M_n 's around or above 50 000 and weight average molecular weights (M_w 's) above 100 000 for application as engineering plastic, e.g. for injection molding.^[12] Even higher molecular weights are needed for extrusion of films, for bottle blowing or fiber spinning. In summary, the authors have not found any study describing a control of M_n for LA/In ratios above 100/1 in ROPs conducted in bulk at temperatures between

1. Introduction

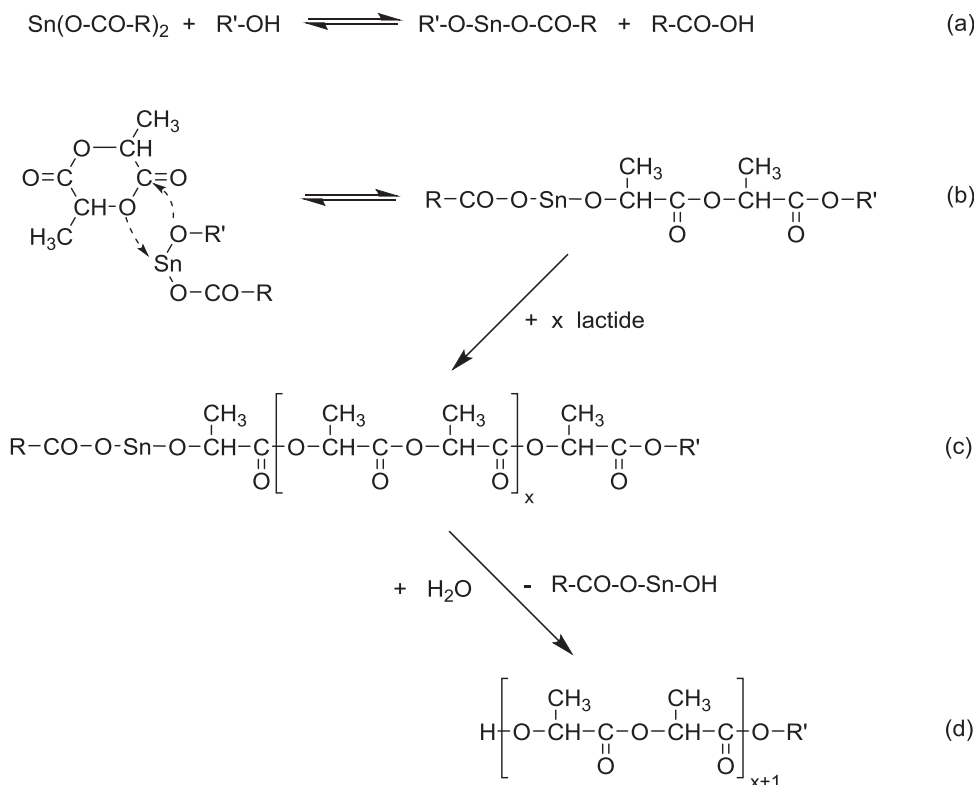
In addition to derivatives of cellulose, polylactide (PLA) have become the most important biosourced and biodegradable material with numerous applications, for example in agriculture (plastic sheets), medicine (implants and sutures) or pharmacy (drug delivery systems).^[1–4] Its technical production is based on the ring-opening polymerization (ROP) of L-lactide (LA) initiated by an aliphatic alcohol and catalyzed by tin(II) 2-ethyl hexanoate (SnOct₂).^[5] This kind of ROP has found numerous preparative applications and has attracted numerous research activities

H. R. Kricheldorf, F. Scheliga
 Universität Hamburg
 Institut für Technische und Makromolekulare Chemie
 Bundesstr. 45, Hamburg D-20146, Germany
 E-mail: hrkricheldorf@aol.de
 S. M. Weidner
 BAM – Bundesanstalt für Materialforschung und -prüfung
 Richard-Willstätter-Str. 11, Berlin D-12489, Germany

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/macp.202100464>

© 2022 The Authors. Macromolecular Chemistry and Physics published by Wiley-VCH GmbH. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

DOI: 10.1002/macp.202100464



Scheme 1. Simplified scheme of the alcohol-initiated and SnOct₂-catalyzed ROP of lactide.

130 and 180 °C, conditions, which are typical for the technical production of PLAs.

In two recent studies the authors have demonstrated that several transesterification mechanisms occur at 130 °C or above including formation of cyclics.^[13,14] Hence, a clean living polymerization as described by the Penczek group for THF solutions at 80 °C or by Prud'Homme in toluene may not be expected for ROPs in bulk at 130–180 °C. Therefore, it was the purpose of this work to elucidate to what extent M_n can be controlled via the LA/In ratio when the polymerizations are performed in bulk at 130–180 °C. Furthermore, more light should be shed on the origin and influence of cyclization reactions. Inspired by the work of Jacobson and Stockmayer^[15,16] it was believed for several decades that the cycles formed at higher temperatures (e.g., >130 °C) result from reversible back-biting of the Sn–O–CH chain end. However, recent studies of the authors^[17] have shown that neat SnOct₂ catalyzes the formation of cyclic PLAs via the ROP-POC mechanism (ROP + simultaneous polycondensation).^[18] This mechanism produces cycles via end-to-end (ete) cyclization (**Scheme 2**, route (a)). The competing reaction pathway (b) is much slower and above LA/Cat ratios of 400/1 the resulting PLA almost completely consists of cycles. Furthermore, recent experiments indicated that the cycles produced by ROPPOC catalysts (incl. SnOct₂) at 130 or 160 °C and short reaction times (<4 h) almost exclusively result from ete-cyclization in combination with intermolecular transesterification experiments.^[19] In other words, it seems that the work of Jacobson and Stockmayer (and the dogma of Flory^[20] that ete-cyclization is absolutely unlikely for higher oligomers and polymers) has resulted in enor-

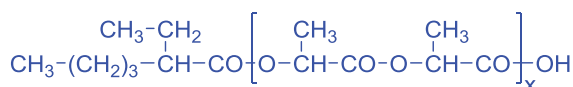
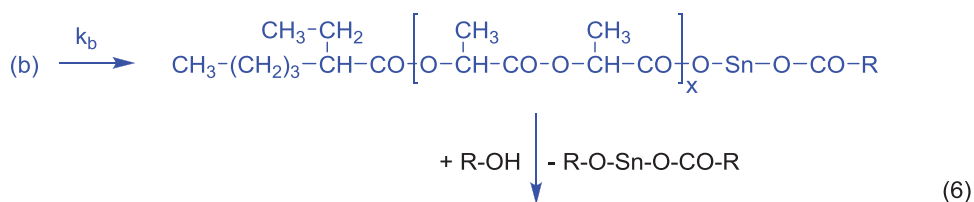
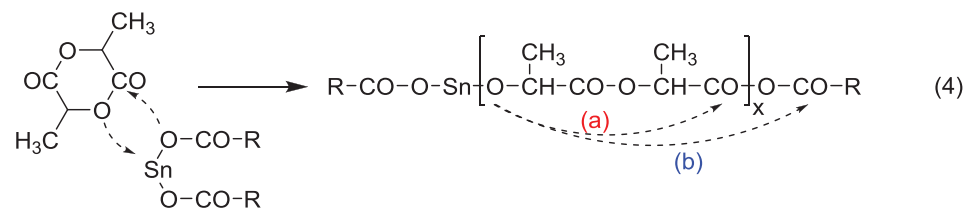
mous overestimation of the role of back-biting. The present study had also the purpose to elaborate more information about this problem and the influence of cyclization reactions on the control of M_n .

2. Results and Discussion

2.1. Polymerizations at 130 °C

The first series of polymerizations was performed at 130 °C, because this is usually the lowest temperature used for the technical production of polyLA and because several research groups used this temperature for fundamental research.^[5,21–23] As demonstrated by the experiments listed in **Table 1**, the LA/initiator ratio was varied between 50/1 and 600/1 at a LA/cat ratio fixed at 2000/1. HMN was used as initiator, because it is a non-hygroscopic solid alcohol, which is easy to dry and to handle in small quantities, and because the end group is easy to identify in the ¹H NMR spectra. A successful ROP with this initiator performed at a LA/In ratio of 50/1 and a time of 1 h has already been published recently along with an interesting MALDI TOF mass spectrum which will be discussed below.^[24]

Since SnOct₂ is known to catalyze rapid degradation of polyLA,^[25] and since homogeneous and complete poisoning of the catalyst at the end of the ROP is difficult to achieve in small-scale experiments, two different reaction times were used to elucidate to what extent the molecular weights (number average, M_n , and weight average, M_w) were influenced by degradation reactions. A comparison of 2 and 4 h revealed indeed that despite



Scheme 2. Formation of cyclic polyLAs via the SnOct₂-catalyzed ROPPOC mechanism.

Table 1. ROPs at 130°C in bulk initiated with HMN and catalyzed by SnOct₂ (LA/Cat = 2000/1) with variation of the LA/In ratio.

Exp.No	LA/In	Time[h]	M_n^a [theor]	M_n^b [corr.]	M_n [meas.]	M_w [meas.]	\bar{D}
1A	50/1	2	7380	7300–9300	10 600–13 300	14 400–15 000	1.1–1.2
1B	50/1	4	–	7400–9000	10 700–13 100	14 000–14 500	1.1–1.2
2A	100/1	2	14 600	15 300–17 000	22 000–25 000	26 800–27 500	1.1–1.2
2B	100/1	4	–	14 700–16 000	21 500–23 500	26 300–26 900	1.1–1.2
3A	150/1	2	21 700	21 200	31 000	37 300	1.2
3B	150/1	4	–	–	29 000	33 800	1.2
4A	200/1	2	28 900	26 000	38 500	49 500	1.3
4B	200/1	4	–	–	37 500	47 000	1.3
5A	400/1	2	57 500	39 000	55 000	77 000	1.4
5B	400/1	4	–	–	47 500	68 500	1.5
6A	600/1	2	86 500	55 000	83 000	141 000	1.7
6B	600/1	4	–	–	64 000	109 000	1.7
7A	900/1	2	127 500	68 000	100 500	168 000	1.7
7B	900/1	4	–	–	81 000	130 000	1.6

^{a)} Calculated for a conversion of 100% plus end group; ^{b)} Calculated with a correction factor 0.68.

the low temperature the molecular weights were lower at the longer time indicating beginning degradation (Table 1). Since it is well known that polystyrene-calibrated GPC measurements overestimate the real M_n 's of aliphatic polyester at least by 50%, due to a lower hydrodynamic volume of polystyrene, only a comparison of corrected M_n 's with calculated theoretical values makes sense. A correction factor of 0.68 was used in this work, which has been determined by the Penczek group for CH₂Cl₂ solutions of polylactide.^[25,26] With this factor reasonable M_n values were obtained in previous studies and also in this work.

The comparison of corrected and theoretical M_n 's indicates a slight overestimation of the M_n 's at the lowest LA/Cat ratios, and satisfactory agreement at LA/Cat at 200/1. Yet, at LA/Cat ratios of 400/1 and 600/1 the corrected M_n 's fall significantly below the theoretical values. The dispersities are as low as 1.15±0.05 for the lowest LA/In ratio and increase up to values of 1.7–1.8 with higher LA/In ratios. An interpretation of these results is given in the last section.

The MALDI TOF mass spectra revealed the following facts. First, regardless of the LA/In ratio the even/ odd equilibration

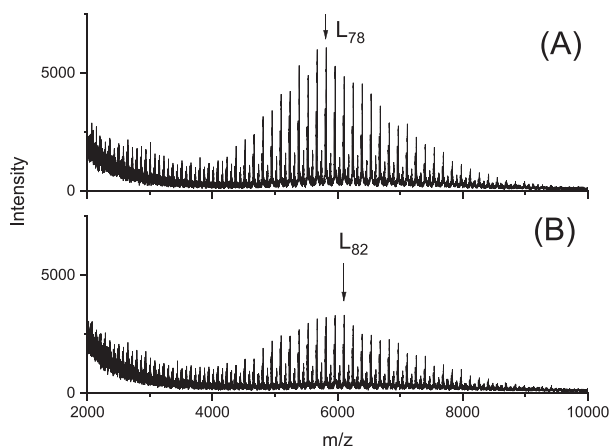


Figure 1. MALDI-TOF mass spectra of polyLAs prepared with HMN at 130 °C using a LA/In ratio of 50/1 (Table 1): A) after 2 h (No. 1A), B) after 4 h (No. 1B).

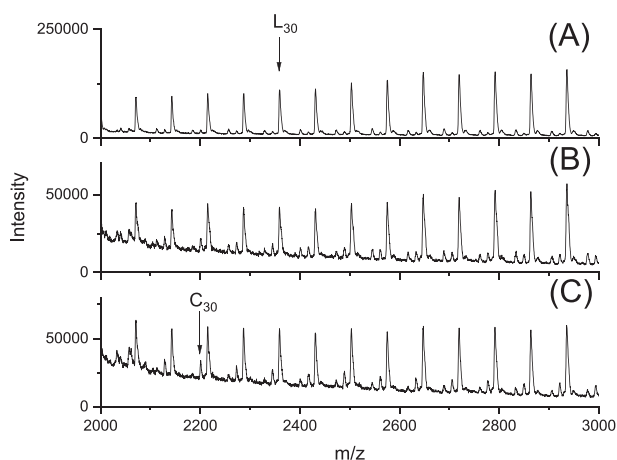


Figure 2. Low molar mass segments of MALDI TOF mass spectra of polyLAS initiated with HMN at 130 °C for 4 h (Table 1): A) LA/In 50/1 (No. 1B), B) LA/In 100/1 (No. 2B), C) LA/In 200/1 (No. 3B).

was far from complete after 2 or 4 h (**Figure 1**) but reached completion after 24 h. Second, no peaks of cycles were detectable in the polyLAs prepared with LA/In 50/1 after 1 h, in agreement with previous experiments conducted under identical conditions.

Yet after 4 h tiny peaks of cycles were observable (**Figure 2A**). Third, the fraction of cycles increased with higher LA/In ratios as demonstrated in **Figure 2**. Increasing LA/In ratio means decreasing In/Cat ratio. The formation of more cycles at lower In/Cat ratios is a trend, which was already discovered on the small basis of three experiments conducted under somewhat different conditions in another previous publication.^[13] The explanation given in that previous publication is difficult to prove or disprove. Now, a more straightforward explanation can be offered, due to the recent detection that neat SnOct₂ catalyzes a so-called ROPPOC mechanism, meaning ring-opening polymerization combined with simultaneous polycondensation (Scheme 1).^[18] This mechanism yields cyclic polyLAs and at high LA/Cat ratios (>400/1) a negligible fraction of COOH-terminated linear chains. The equilibrium between SnOct₂ and alcohol ((a) in Scheme 1) favors the left side of the reaction, because the Sn-alkoxide bond is weaker

than the Sn-carboxylate bond. Decreasing initiator concentration, therefore, means larger fraction of SnOct₂ and thus, favors formation of cyclic polyLAs. In other words, lower In/Cat ratios favor the competition of ROPPOC mechanism (Scheme 2(a)) at the expense of the normal ROP mechanism (Scheme 1).

2.2. Polymerizations at 160 °C

At 160 °C the same La/Cat and LA/In ratios were used as before to enable a straightforward comparison with the ROPs conducted at 130 °C, but in addition to reaction times of 2 and 4 h all ROPs were also stopped at 1 h to reduce the influence of degradation reactions (see **Table 2**). The following similarities were found. Surprisingly, a significant influence of the time was not found. In analogy to the 130 °C experiments, the M_n data show again a slight overestimation of the real M_n at LA/In of 50/1. A satisfactory agreement between theoretical and corrected M_n 's was found for LA/In 100/1 and 200/1. The dispersities increase with the LA/In ratio, but regardless of the LA/In ratio the dispersities are considerably higher at 160 °C. This finding indicates a stronger influence of transesterification reactions two of which are outlined in **Schemes 3** and **4**.

The MALDI TOF mass spectra gave the following results. First, regardless of the LS/In ratio the even/odd-equilibration was complete (**Figures 1, 3, and 4**). Second, the peaks of cycles dramatically increased with the LA/In ratio. **Figure 3** displays a comparison of LA/In 50/1 with LA/In 100/1 and **Figure 4a** comparison of LA/In 200/1 with LA/In 400/1. At 200/1 the cycles have become the predominant species below 1500 Da (**Figure 4A**) and at 400/1 the cycles were the prevailing species up to 4000 Da (**Figure 4B**). This trend continuous up to LA/In 900/1, the highest LA/In ratio studied in this work, where the peaks of cycles are the predominant species up to ≈ 8000 Da (**Figure 5B**).

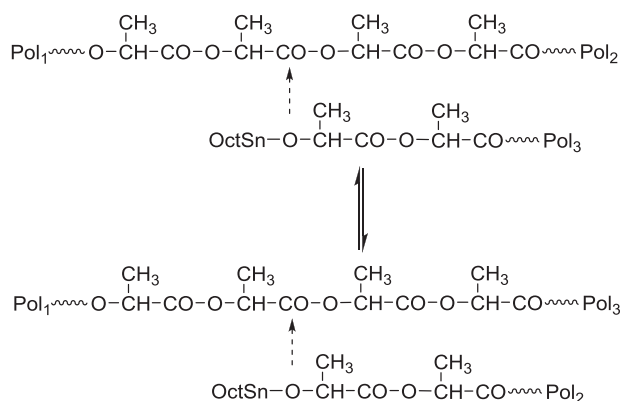
By these MALDI TOF mass spectra nothing can be concluded about the topology of polyLA chains above m/z 10 000. To shed more light on this aspect, the intrinsic viscosities of the samples No. 5B and 6B (**Table 2**) were compared with that of a commercial mainly linear polyLA (Purapol L105). This method allows for a semiquantitative interpretation of the Mark–Houwink–Sakurada (MHS) plots, because the hydrodynamic volume and thus, the intrinsic viscosity of cyclic polymers typically amounts to 66–67% of the viscosity of the corresponding linear species. The MHS plot presented in **Figure 6** demonstrates that the viscosities of No. 5B and even more of 6B deviate from that of the linear standard toward lower values. With increasing molecular weight this difference vanishes suggesting that the weight fraction of cycles tends toward zero. Hence, this MHS plot perfectly agrees with the above interpretation of the mass spectra.

In order to find out, if the fraction of cycles decreases when the concentration of SnOct₂ decreases, several ROPs were conducted with a LA/Cat ratio of 8000/1 (**Table 3**). The MALDI TOF mass spectra suggest indeed that the fraction of cycles was slightly lower than in analogous experiments of **Table 2**. Presumably a consequence of these results were higher M_n values of the experiments performed with LA/In ratios around or above 200/1. In this way M_n 's up to 110 000 can be achieved (No. 4A, **Table 3**). LA/Cat ratios in the range of 5000/1 up to 10 000/1 are characteristic for the technical production of polyLAs and the results found

Table 2. ROPs at 160 °C in bulk initiated with HMN and catalyzed by SnOct₂ (LA/Cat = 2000/1) with variation of time and LA/In.

Exp.No	LA/In	Time[h]	M_n^a [theor]	M_n^b [corr.]	M_n [meas.]	M_w [meas.]	\bar{D}
1A	50/1	1	7200	7200–8400	10 600–12 600	18 300–19 000	1.6–1.7
1B	50/1	2	7200	7500–8500	11 000–12 700	19 300–20 000	1.5–1.7
1C	50/1	4	7200	7300–8500	10 800–12 700	19 400–20 100	1.6–1.7
2A	100/1	1	14 600	14 250	20 800	30 800	1.5
2B	100/1	2	14 600	14 000	20 700	34 000	1.6
2C	100/1	4	14 600	14 300	20 900	34 400	1.6
3A	200/1	1	28 900	25 000	37 000	77 500	2.1
3B	200/1	2	28 900	24 000	36 500	75 500	2.1
3C	200/1	4	28 900	23 000	35 500	73 000	2.1
4A	400/1	1	57 500	43 000	61 500	121 000	2.0
4B	400/1	2	57 500	43 000	61 000	123 000	2.0
4C	400/1	4	57 500	43 000	61 500	127 000	2.1
5A	600/1	1	57 500	46 000	66 000	156 000	2.4
5B	600/1	2	86 900	51 000	75 000	175 000	2.1
5C	600/1	4	86 900	48 000	69 500	161 000	2.3
6A	900/1	1	127 500	49 000	71 500	170 000	2.4
6B	900/1	2	127 500	59 000	87 000	200 000	2.3

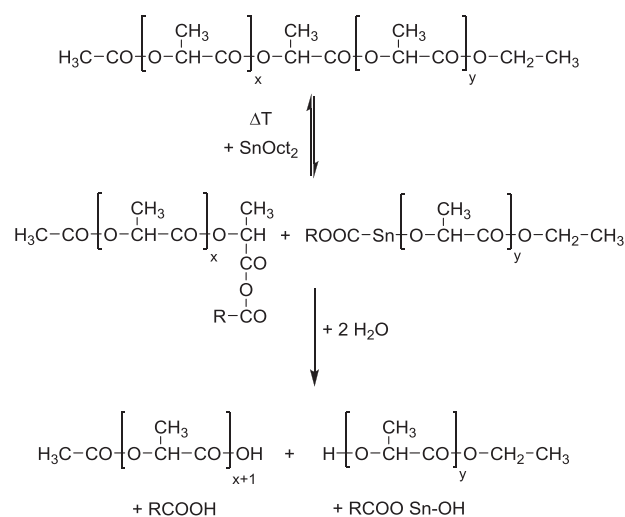
^a) Calculated for a conversion of 97% plus end group; ^b) Calculated with correction factor 0.68.



Scheme 3. Intermolecular transesterification via nucleophilic attack of the active chain end onto another polyLA chain.

here suggest that such high LA/Cat ratios combine four advantages: lower costs, lower toxicity per weight of polyLA, higher M_n values and a lower content of cyclics.

A third series of ROPs was conducted at 160 °C with 11-undecenol as initiator (Table 4). The purpose of these ROPs was to demonstrate, that HMN is a quite normal initiator, so that the results obtained with HMN are reproducible with an aliphatic alcohol. The results summarized in Table 4 confirm this expectation. At LA/Cat ratios of 200/1 the measured and corrected M_n 's are as high or slightly higher than the theoretical M_n 's but fall below the theoretical values at higher LA/Cat ratios. Furthermore, the dispersities increase with higher LA/Cat ratios and the mass spectra revealed that the fraction of cycles increased with higher LA/In ratios corresponding to lower In/Cat ratios. Finally, it should be mentioned that the ROPs performed with LA/In ratios of 400/1–900/1 were twice repeated with different batches of



Scheme 4. Intermolecular transesterification via cleavage of a polyLA chain by SnOct₂.

L-lactide that differed slightly by the rate of cooling during recrystallization. The M_n and M_w data scattered within the margin of error of $\pm 5\%$. The highest values were listed in Tables 1–3. In two previous papers it was demonstrated that when the first recrystallization of the PURC L-lactide used for this and previous studies is optimized, the second recrystallization does not enhance the molecular weights.^[27,28]

2.3. Polymerizations at 180 °C

The polymerizations conducted at 180 °C were focused on two questions. First, is the formation of cycles via “back-biting” as

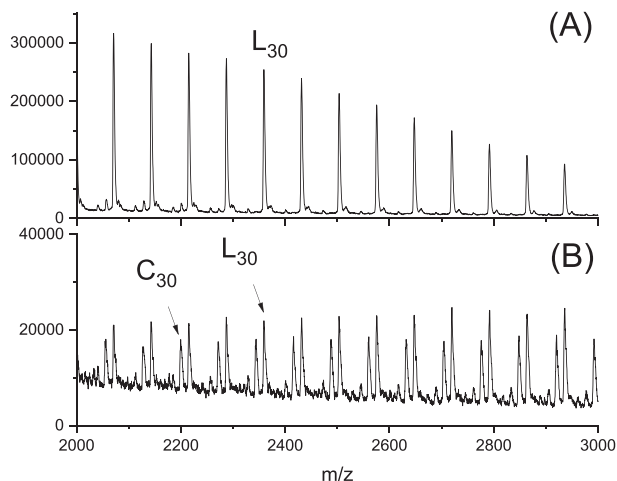


Figure 3. MALDI TOF mass spectra of polyLAs prepared with HMN at 160 °C/4 h (Table 2): A) LA/In 50/1 (No. 1C), B) LA/In 100/1 (No. 2C).

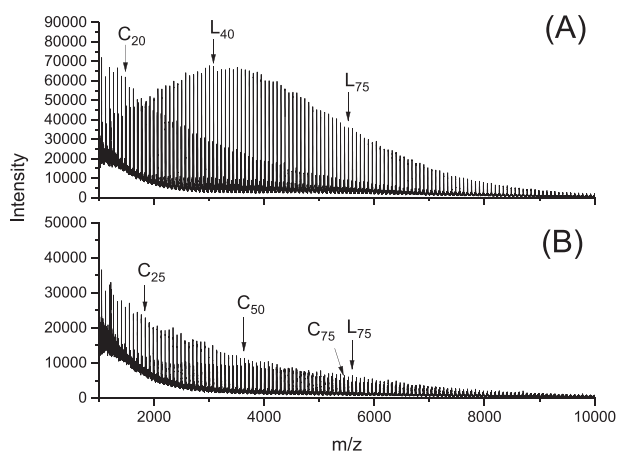


Figure 4. MALDI TOF mass spectra of polyLAs prepared with HMN at 160 °C/4 h (Table 2): A) LA/In 200/1 No. 3C, B) LA/In 400/1 (No. 4C).

rapid as believed by the authors and other researchers influenced by the work of Jacobson and Stockmayer^[15,16] and their followers.^[29–35] Second, is the formation of cycles reduced and M_n enhanced, when the LA/In ratio is reduced from 2000/1 to 8000/1 a ratio typical for the technical production. A first series of ROPs was performed with the low LA/In ratio of 20/1 corresponding to an In/Cat ratio of 100, when the LA/Cat ratio remains fixed at 2000/1 (Nos. 1–4, Table 5). Thereby, time was varied, and careful examination of the MALDI mass spectra revealed that no cycles were detectable up to 1 h. After 2 h only traces of cycles appeared (Figure 7). In an analogous series of ROPs conducted with a LA/In ratio of 100/1 corresponding to a In/Cat ratio of 20/1 small peaks of cycles became detectable after the shortest time of 0.5 h. These findings demonstrate again that even at this high temperature the efficiency of back-biting is low and depends on the In/Cat ratio. Since it was recently demonstrated that ethyl lactate undergoes slow polycondensation, when heated with SnOct₂ or another tin catalyst to 130 or 160 °C,^[19] it is highly probable that the cycles formed at 180 °C at least partially result from end-to-end cyclization. Three more ROPs were per-

formed again with a LA/In ratio of 100/1, but with a higher LA/Cat ratio of 8000/1 (Nos. 3A–C, Table 5). As expected for the higher In/Cat ratio the MALDI mass spectra indicate smaller fractions of cycles, when compared with LA/Cat 2000/1 experiments, whereas the GPC measurements did not reveal a significant difference. At a LA/In ratio of 100/1, both LA/Cat ratios gave a satisfactory agreement of measured and corrected M_n values, on the one hand, and theoretical M_n , on the other. Finally, increasing dispersities with longer polymerization times are worth noting. They are mainly based on decreasing M_n 's.

2.4. Discussion of GPC Measurements

Two trends of the GPC measurements need discussion, namely the overestimation of M_n observed for low LA/In ratios and the significant under-estimation found for LA/In ratios > 200/1. The first trend is certainly an artefact of the GPC measurements. The ¹H NMR spectra proved the complete incorporation of the initiator into the polyLAs and thus, the degrees of polymerizations (DP; and the correlated M_n 's) taken from experiments cannot be higher than the LA/In ratios. The overestimation of M_n results from the fitting of the baseline to the elution curve via the automated process given by the software. The fraction of low oligomers (<1000 Da) increases with decreasing M_n and when the fitting of the baseline prevents that all these oligomers were included in the calculation of M_n , an overestimation of 10–20% is a logical consequence. This effect vanishes at higher M_n 's. Two typical GPC elution curves are presented in Figure 8.

The underrating of the theoretical M_n 's by the measured (and corrected values) is primarily a consequence of cycles, the fraction of which increases with the LA/In ratio (Figure 2). Since the vast majority of the cycles has molecular weights below 5000, they have a considerable influence on M_n of high molar mass polyLAs. In addition to the direct effect the low molar mass cycles have on the calculation of M_n , there is also an indirect effect concerning the correction factor. Cyclic polylactides (and other aliphatic polyesters) have a hydrodynamic volume which is almost identical with that of polystyrene. Hence, the correction factor is around unity (or in other words it vanishes). This means in turn, that the correction factor of 0.68 increases toward 1.0 with increasing fraction of cycles. Since the MALDI mass spectra and the intrinsic viscosities suggest that the fraction of cycles increases toward 20–25% for LA/Cat ratios of 400/1–900/1 a correction factor around 0.75 may be more adequate at least for LA/Cat ratios of 600/1 and 900/1. This means that the deviation of the corrected M_n 's from the theoretical M_n 's decreases from 35–40% to 25–30%. Furthermore, it should be considered that the polymerization times used in this work do not necessarily represent the optimum, so that a further narrowing of the difference between theoretical and corrected M_n 's should be considered. However, even an optimization of the polymerization time will not eliminate the trend and its explanation discussed in this work. Furthermore, cleavage of ester groups via β -elimination or transesterification with 2-ethylhexanoic acid (the only impurity of the SnOct₂ used in this work) might also contribute to the lower experimental M_n and M_w values. However, it was demonstrated previously that polymerization with neat SnOct₂ yields higher molecular weights (M_w 275 000–315 000) than the ROPs described above,^[18] and thus, such side reactions cannot play a significant role.

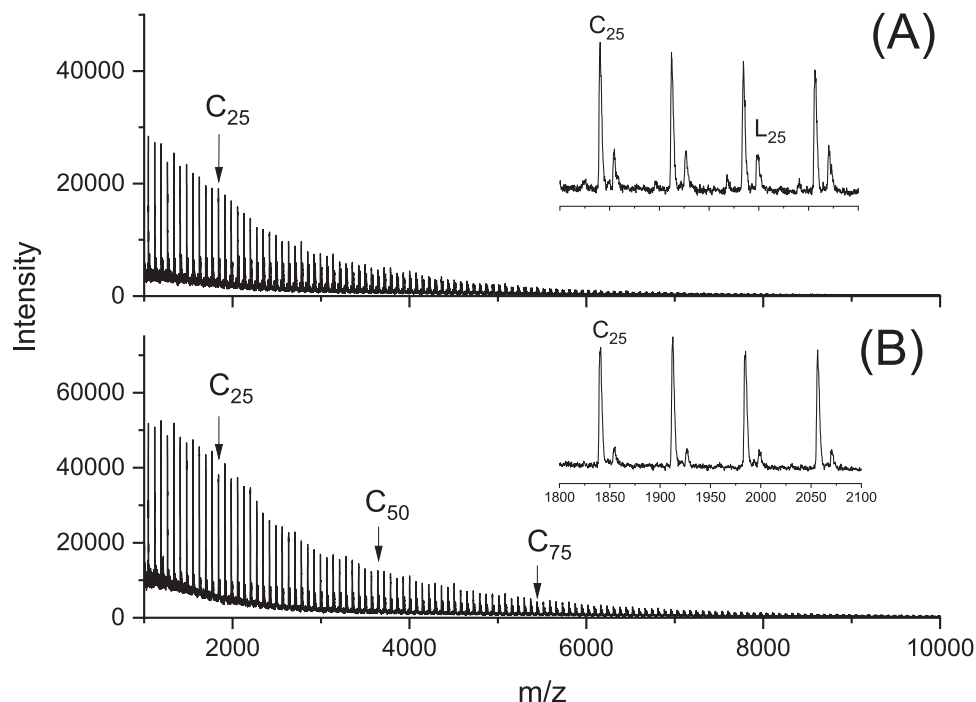


Figure 5. MALDI TOF mass spectra of polyLAs prepared with HMN at 160 °C/4 h: A) LA/IN 600/1, B) LA/IN 900/1.

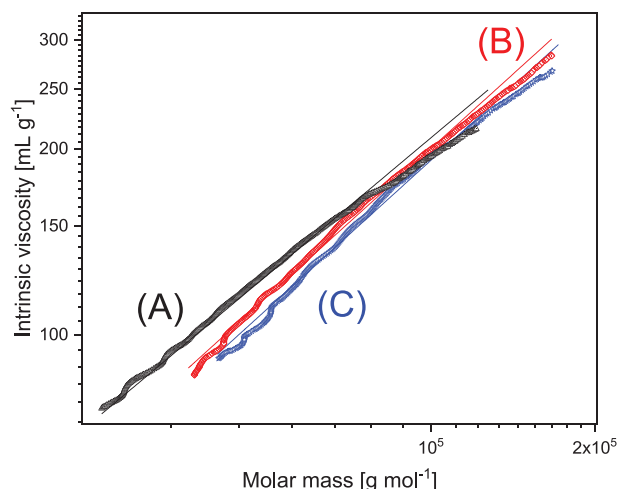


Figure 6. Mark-Houwink-Sakurada (MHS) plot of A) linear polyLA (Pu-rapol) compared to polyLAs prepared with HMN at 160 °C/4 h: B) LA/IN 600/1 (No. 5B, Table 2), C) LA/IN 900/1 (No. 6B, Table 2).

Increasing dispersities with longer times is also a consequence of a larger fraction of low molar mass cycles. This effect is particularly pronounced at 180 °C and illustrated by two mass spectra in Figure 3. However, the higher dispersities observed at 160 and 180 °C do not only result from formation of cycles they are also a consequence of intermolecular transesterification reactions. Two of these transesterification mechanisms, identified in a previous study, are outlined in Schemes 3 and 4. In contrast to the formation of small cycles these transesterifications do not reduce the average molecular weights. However, they broaden the MWD,

which initially is narrow, when the kinetically controlled ROP is not affected by thermodynamically driven equilibration reactions. At this point it is worth noting, that high dispersities (>2.0) are desirable for any technical application requiring processing from the melt, such as injection molding, extrusion, bottle blowing or fiber spinning, because polymers with high dispersities show a better balance between moderate melt viscosity and good mechanical properties such as elongation at break. The narrow dispersities hailed in many papers dealing with polymerizations in solution are not only obsolete, but they are also a serious disadvantage for any application based on thermal processing.

3. Conclusions

There are three major conclusions which can be drawn from this work. First, a proper control of the molecular weight via the LA/In ratio is not feasible for SnOct₂-catalyzed ROPs conducted in bulk at temperatures xxx of 130–180 °C, when the LA/In ratios exceed 200/1 what is typical for the technical production of poly(L-lactide). The formation of cycles is the main reason, why the molecular weights lag behind those expected from the LA/In ratio and conversions around 97%. Since the formation of cycles is favored by low In/Cat ratios, not only low initiator concentrations but also low catalyst concentrations (corresponding to LA/Cat ratios of 6000/1–10 000/1) are favorable for high molecular weights (M_n 's around or above 100 000). Second, the formation of odd and even-numbered cycles is mainly the result of ete-cyclization resulting from the ROPPOC mechanism catalyzed by neat SnOct₂. Intermolecular transesterification reactions are responsible for the odd/even- equilibration. Third, cyclization via back-biting of the nucleophilic chain end (Sn–O–CH) does not play any role at short reaction times (<4 h) regardless of the temperature. Hence,

Table 3. ROPs at 160 °C in bulk initiated with HMN and catalyzed by SnOct₂ (LA/Cat = 8000/1).

Exp.No	LA/In	Time[h]	M_n^a [theor]	M_n^b [corr.]	M_n [meas.]	M_w [meas.]	\bar{D}
1A	200/1	2	28 900	29 000	43 500	70 000	1.6
1B	200/1	4	28 900	30 000	45 000	73 000	1.6
2A	400/1	2	57 500	41 000	62 500	121 000	1.9
2B	400/1	4	57 000	42 000	64 000	124 000	1.9
3A	600/1	2	86 900	58 000	84 000	178 000	2.1
3B	600/1	4	86 900	56 000	81 500	169 000	2.1
4A	900/1	2	127 500	73 000	109 000	211 000	2.0
4B	900/1	5	127 500	70 000	102 500	203 000	2.0

^{a)} Calculated for a conversion of 97% plus end group; ^{b)} Calculated with correction factor 0.68.

Table 4. ROPs at 160 °C in bulk initiated with 11-undecenol and catalyzed by SnOct₂ (LA/Cat = 2000/1) with variation of time and LA/In ratio.

Exp.No	LA/In	Time[h]	M_n^a [theor]	M_n^b [corr.]	M_n [meas.]	M_w [meas.]	\bar{D}
1A	50	1	7380	10 000	14 400	21 100	1.5
1B	50	2	7380	9800	14 300	22 400	1.6
2A	100	1	14 500	14 800	21 500	39 100	1.8
2B	100	2	14 500	13 800	20 000	37 500	1.9
3A	200	1	28 900	29 500	43 000	76 000	1.8
3B	200	2	28 900	28 000	41 700	76 000	1.8
4A	400	1	57 500	40 000	59 500	121 000	2.0
4B	400	2	57 500	42 000	62 000	127 000	2.0

^{a)} Calculated from the LA/In ratio with 100%; ^{b)} Calculated from styrene-calibrated SEC measurements by multiplication with the correction factor 0.68.

these results combined with those of a previous study^[36] indicate that the role of back-biting in the chemistry of polyesters, first postulated by Jacobson and Stockmayer in 1950, was and is overestimated, whereas the role of ete-cyclization has been heavily underrated.

4. Experimental Section

Materials: L-Lactide (LA), a product of Corbion Purac was kindly supplied by Thyssen-Uhde AG and recrystallized from "Toluene 99.89% extra dry" purchased from Fischer ACROS Chemicals (Geel Belgium). The re-

crystallization was performed with 160 g of L-lactide dissolved in 700 mL of toluene. Crystallization was initiated by cooling the neck of the rotating 1 L round bottom flask. Afterward the toluene solution was allowed to cool slowly down to ≈ 20 °C without additional cooling. After 20 h the lactide was isolated by filtration under a blanket of argon.

1-Hydroxymethyl naphthalene (HMN) and 11-undecenol (UND) were purchased from ALFA Aesar (Kandel, Germany). HMN was dried at 50 °C in vacuo. Tin(II) 2-ethylhexanoate (purity >96%) was also purchased from ALFA Aesar and used as received. It certainly contained a small amount of 2-ethyl hexanoic acid, but as it was demonstrated previously, polymerizations performed with neat SnOct₂ gave higher molecular weights (with almost complete cyclization) than those reported below and distillation of SnOct₂ did not yield better results.^[18]

Table 5. ROPs at 180 °C in bulk initiated with HMN and catalyzed by SnOct₂.

Exp. No.	La/In	LA/Cat	Time [h]	Cycles	M_n^a [theor]	M_n^b [corr.]	M_n [meas.]	M_w [meas.]	\bar{D}
1A	20/1	2000/1	0.5	–	–	–	–	–	–
1B	20/1	2000/1	1.0	–	2900	(2600)	(3600)	(6000)	1.6
1C	20/1	2000/1	2.0	–	2900	(2300)	(3300)	(7000)	2.1
1D	20/1	2000/1	4.0	Traces	2900	(2100)	(3000)	(6900)	2.3
2A	100/1	2000/1	0.5	+	14 400	14 000	20 500	39 000	1.9
2B	100/1	2000/1	1.0	+	14 400	15 400	22 300	43 000	2.0
2C	100/1	2000/1	2.0	+	14 400	14 000	20 500	40 500	2.0
2D	100/1	2000/1	4.0	++	14 400	11 000	16 000	37 000	2.3
3A	100/1	8000/1	1.0	+	14 400	15 500	22 500	39 500	1.8
3B	100/1	8000/1	2.0	+	14 400	14 400	22 000	42 000	1.9
3C	100/1	8000/1	4.0	++	14 400	14 300	21 000	44 000	2.1

^{a)} Calculated with a conversion of 97% plus end group; ^{b)} Calculated with correction factor 0.68.

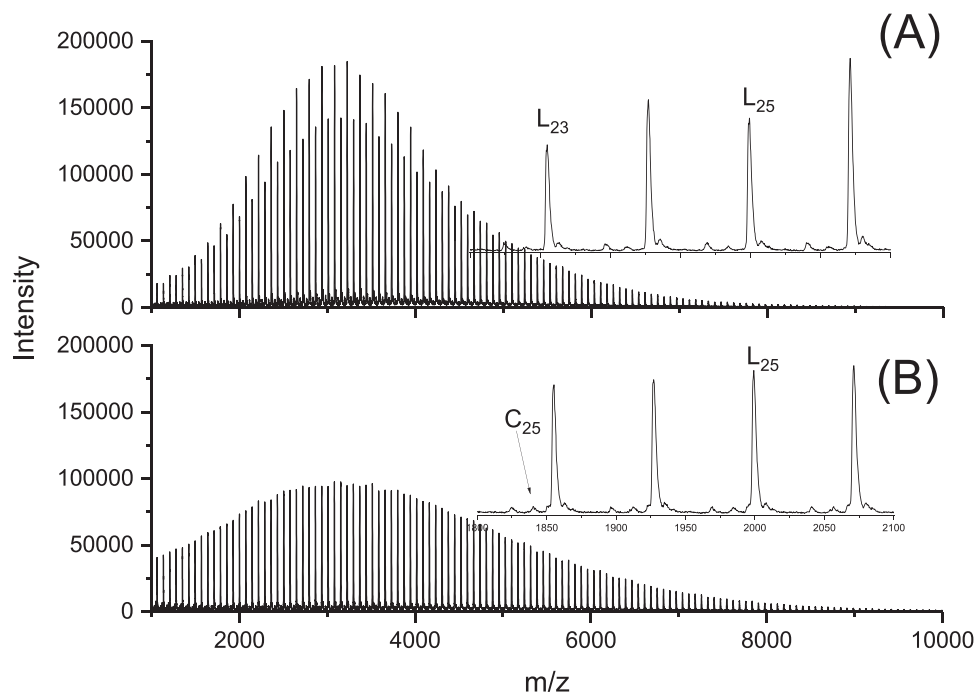


Figure 7. MALDI TOF mass spectra of polyLA prepared at 180 °C with LA/In = 20/1: A) after 0.5 h (No. 1, Table 5), B) after 2 h (No. 3, Table 5).

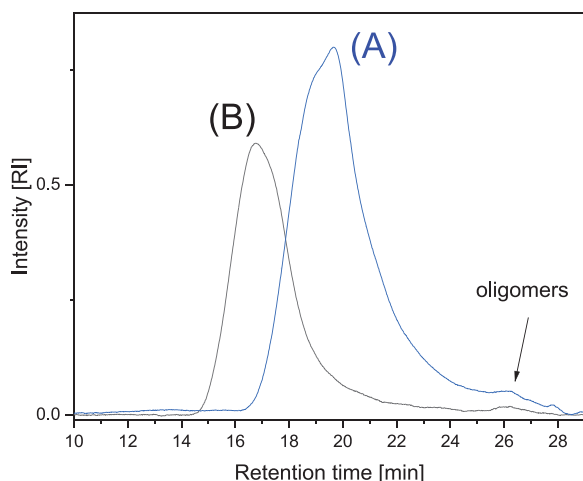


Figure 8. Typical GPC elution curves showing A) polyLA No. 2B, Table 2 and B) No. 5B, Table 2.

Polymerizations at 130 °C (No. 2, Table 1): HMN (0.4 mmol) was weighed into a flame-dried 50 mL Erlenmeyer flask and LA (40 mmol) and a magnetic bar were added under a blanket of argon. Afterwards, 0.1 mL of a 0.4 M solution of SnOct₂ in toluene was injected. The reaction vessel was placed into an oil bath thermostated at 130 °C. After 1 or 2 h the reaction vessel was opened and a sample of ≈1 g was removed with a spatula under a blanket of argon. Afterward, the reaction vessel was again placed into the oil bath and a second sample was taken when the polymerization was stopped. The polymerizations at 160 °C (Table 2) were conducted analogously.

Polymerizations at 160 °C (No. 2, Table 3): HMN (0.4 mmol) was weighed into a 50 mL Erlenmeyer flask and LA (80 mmol) and a magnetic bar were added under a blanket of argon. Afterward, 0.1 mL of a 1 M solu-

tion of SnOct₂ in toluene was injected. The reaction vessel was immersed into an oil bath thermostated at 160 °C.

Polymerizations with 11-Undecenol (No. 2, Table 4): UND (0.4 mmol) was weighed by means of a syringe into a flamed dried 50 mL Erlenmeyer flask and LA (40 mmol) and a magnetic bar were added under a blanket of argon. After injection of 0.1 mL of a 0.4 M solution of SnOct₂ in toluene the reaction vessel was immersed into an oil bath thermostated at 160 °C. In the case of experiments No. 4, 0.1 mL of a 1 M solution of UND in toluene was added.

Polymerizations at 180 °C (No. 1, Table 5): HMN (2 mmol) was weighed into a 40 mL Erlenmeyer flask. LA (40 mmol) and a magnetic bar were added under a blanket of argon. SnOct₂ (0.1 mL) was injected in the form of a 0.4 M solution in toluene. The reaction vessel was immersed into an oil bath thermostated at 180 °C.

Measurements: All samples were characterized in the virgin state.

The 400 MHz ¹H NMR spectra were recorded with a Bruker Avance 400 in 5 mm sample tubes. CDCl₃ containing TMS served as solvent and shift reference.

The DSC measurements were conducted with a heating rate of 10 K min⁻¹ on a Mettler-Toledo DSC-1 equipped with Stare Software version 11.00. Only the first heating was evaluated.

MALDI TOF mass spectrometry was performed using an Autoflex max (Bruker Daltonik GmbH, Bremen) in the linear positive mode using trans-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidene] malononitrile (DCTB) dissolved in chloroform (20 mg mL⁻¹) as matrix. The solution was doped with potassium trifluoroacetate to enable selective potassium adduct ion formation. The matrix solution was premixed with the analyte solution (chloroform, 4 mg mL⁻¹) in a ratio of 5/2 (v/v). 1 μL of the resulting solution was deposited on the sample target. Typically, 8000 single spectra recorded at 4 different positions within one spot were accumulated. The instrument was previously calibrated with PEO standards.

For the GPC experiments a modular system kept at 40 °C (isocratic pump, 1 mL min⁻¹, refractive index detector, RI-501—Shodex) was applied. Samples dissolved in chloroform were manually injected (100 μL, 2–4 mg mL⁻¹). For instrument control and data calculation Astra 6.1 software (Wyatt Technology Europe GmbH, Dernbach) was used. The

calibration was performed using polystyrene standard sets (Polymer Standards Service—PSS, Mainz, Germany).

For the determination of the Mark–Houwink–Sakurada (MHS) relationship a viscometer (Viscostar, Wyatt) and a multiangle laser light scattering (MALS) detector (Dawn EOS, Wyatt,) were used. Astra 6.1 software (Wyatt) also served for calculating the MHS curves.

Acknowledgements

The authors wish to thank BAM for technical support and Dipl. Ing. A. Myxa for the GPC measurements. Furthermore, the authors thank Dr. U. Mühlbauer (Thyssen-Uhde) for kindly supplying the lactide and Prof. G. Luinstra (TMC, Univ. of Hamburg) for financial support.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

cyclization, MALDI TOF mass spectrometry, polylactide, ring-opening polymerization, transesterification

Received: December 1, 2021

Revised: January 5, 2022

Published online:

- [1] R. A. Auras, L.-T. Lim, S. E. Selke, H. Tsuji, *Poly (Lactic Acid): Synthesis, Structures, Properties, Processing, and Applications*, John Wiley & Sons, Hoboken, New York **2011**.
- [2] J. Ahmed, S. K. Varshney, *Int. J. Food Prop.* **2011**, *14*, 37.
- [3] R. P. Pawar, S. U. Tekale, S. U. Shisodia, J. T. Totre, A. J. Domb, *Recent Pat. Regener. Med.* **2014**, *4*, 40.
- [4] M. L. Di Lorenzo, R. Androsch, *Industrial Applications of Poly (Lactic Acid)*, Vol. 282, Springer, Cham, Switzerland **2018**.
- [5] M. L. Di Lorenzo, R. Androsch, *Synthesis, Structure and Properties of Poly (Lactic Acid)*, Vol. 279, Springer, Cham, Switzerland **2018**.
- [6] X. Zhang, D. A. Macdonald, M. F. A. Goosen, K. B. Mcauley, *J. Polym. Sci. Part A: Polym. Chem.* **1994**, *32*, 2965.
- [7] H. R. Kricheldorf, M. Berl, N. Scharnagl, *Macromolecules* **1988**, *21*, 286.
- [8] H. R. Kricheldorf, I. Kreiser-Saunders, A. Stricker, *Macromolecules* **2000**, *33*, 702.
- [9] A. Kowalski, A. Duda, S. Penczek, *Macromolecules* **2000**, *33*, 7359.
- [10] A. Kowalski, J. Libiszowski, A. Duda, S. Penczek, *Macromolecules* **2000**, *33*, 1964.
- [11] M. Jalabert, C. Fraschini, R. E. Prud'homme, *J. Polym. Sci., Part A: Polym. Chem.* **2007**, *45*, 1944.
- [12] L.-T. Lim, R. Auras, M. Rubino, *Prog. Polym. Sci.* **2008**, *33*, 820.
- [13] S. M. Weidner, H. R. Kricheldorf, *Macromol. Chem. Phys.* **2017**, *218*, 1600331.
- [14] S. M. Weidner, H. R. Kricheldorf, *Macromol. Chem. Phys.* **2018**, 219.
- [15] H. Jacobson, C. O. Beckmann, W. H. Stockmayer, *J. Chem. Phys.* **1950**, *18*, 1607.
- [16] H. Jacobson, W. H. Stockmayer, *J. Chem. Phys.* **1950**, *18*, 1600.
- [17] H. R. Kricheldorf, S. M. Weidner, *Polym. Chem.* **2020**, *11*, 5249.
- [18] H. R. Kricheldorf, S. M. Weidner, *Macromol. Rapid Commun.* **2020**, *41*, 2000152.
- [19] H. R. Kricheldorf, S. M. Weidner, J. Falkenhagen, *Polym. Chem.* **2021**, *12*, 5003.
- [20] P. J. Flory, *Principles of Polymer Chemistry*, Cornell University Press, Ithaca, New York **1953**.
- [21] J. R. Dorgan, J. Janzen, M. P. Clayton, S. B. Hait, D. M. Knauss, *J. Rheol.* **2005**, *49*, 607.
- [22] Y. Yu, G. Storti, M. Morbidelli, *Ind. Eng. Chem. Res.* **2011**, *50*, 7927.
- [23] Y. Yu, E. J. Fischer, G. Storti, M. Morbidelli, *Ind. Eng. Chem. Res.* **2014**, *53*, 7333.
- [24] S. M. Weidner, A. Meyer, J. Falkenhagen, H. R. Kricheldorf, *Eur. Polym. J.* **2021**, *153*, 110508.
- [25] K. Jamshidi, S.-H. Hyon, Y. Ikada, *Polymer* **1988**, *29*, 2229.
- [26] A. Kowalski, A. Duda, S. Penczek, *Macromolecules* **1998**, *31*, 2114.
- [27] H. R. Kricheldorf, S. M. Weidner, F. Scheliga, *Eur. Polym. J.* **2019**, *116*, 256.
- [28] H. R. Kricheldorf, S. M. Weidner, A. Meyer, *Mater. Adv.* **2022**, *3*, 1007.
- [29] J. F. Brown, G. M. J. Slusarczyk, *J. Am. Chem. Soc.* **1965**, *87*, 931.
- [30] J. B. Carmichael, D. J. Gordon, F. J. Isackson, *J. Phys. Chem.* **1967**, *71*, 2011.
- [31] J. B. Carmichael, J. B. Kinsinger, *Can. J. Chem.* **1964**, *42*, 1996.
- [32] S. J. Clarson, in *Cyclic Polymers*, 2nd ed., (Ed: J. A. Semlyen), Kluwer Academic Publ, Dordrecht, **2000**.
- [33] J. Roovers, *Macromolecules* **1988**, *21*, 1517.
- [34] J. A. Semlyen, in *Large Ring Molecules* (Ed: J. A. Semlyen), J. Wiley & Sons, Chichester, p. 1996.
- [35] J. A. Semlyen, in *Cyclic Polymers*, Springer, **2000**, p. 1.
- [36] H. R. Kricheldorf, S. M. Weidner, F. Scheliga, *Polym. Chem.* **2020**, *11*, 2595.