

## Preparation of PLLA/PDLA Stereocomplexes Using a Novel Initiator Based on Mg(II) and Ti(IV) Alkoxides

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**ABSTRACT:** Herein we describe the obtention of polylactide stereocomplexes using a novel initiator system comprising Mg(II) and Ti(IV) centers. The stereocomplexes were successfully prepared using two different routes: by PDLA and PLLA co-precipitation from chloroform solutions and two-step diblock copolymerization. For the PDLA/PLLA mixing procedure, individual homochiral polymers were prepared in solution at different monomer/initiator ratios; whereas, the PLA stereoblock was prepared employing one-pot sequential polymerization of both chiral monomers. The products analyzed by WAXD showed the characteristic stereocrystal reflections while the high melting temperatures found in the DSC runs confirmed the formation of PLA stereocomplexes in both cases. Surprisingly, one of the stereocomplexes showed a second endothermic event at 250.1°C and to our knowledge this is the highest melting temperature reported for PLA stereocomplexes till date. These results point to the discovery of an effective initiator based on low toxicity metals for the preparation of biodegradable materials with interesting thermal properties. © 2014 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2014**, *131*, 40771.

**KEYWORDS:** Biopolymers & renewable polymers; polyesters; ring-opening polymerization

Received 29 November 2013; accepted 27 March 2014

DOI: 10.1002/app.40771

### INTRODUCTION

Poly(lactide) (PLA) is an aliphatic polyester obtained from renewable resources well known for its biodegradability and biocompatibility that finds many applications in medicine, fiber technology and packing. It has been reported in the literature that when two PLA with different structural configurations, poly(L-lactide) and poly(D-lactide) are mixed, a new material with different properties can be obtained, a complex with higher melting temperature than the homochiral polymers.<sup>1</sup> Therefore, this material, called stereocomplex, has received large attention due to its enhanced properties.<sup>2-5</sup> The studies on PLA stereocomplexes (sc-PLA) afforded important insights into the nature of the polymer interactions in solid state and a compilation of crucial conditions to prepare these materials with high level of efficiency.<sup>6</sup> The reported data on the subject suggest that conditions such as the molecular weight, the mixing ratio, whether the process is in solution or in bulk and the optical purity of the two isomeric polymers are important parameters in PLA stereocomplexation. Taking into account these many factors, sometimes is difficulty to achieve high level of aggregation in these polymers. In fact, one of the main drawbacks concerning the preparation of stereocomplexes from poly(D-lactide) (PDLA) and poly(L-lactide) (PLLA) mixing is the difficult to

obtain pure stereocrystals, once the homopolymers crystallization is favored when high molecular polymers are employed.<sup>7</sup> An alternative procedure to overcome this limitation is the block copolymerization of the two chiral monomers (L-lactide and D-lactide) to form a material called stereoblock (PLLA-*b*-PDLA). The great advantage of the stereoblock approach is the extremely effective interaction between the polymer blocks of opposite configurations, avoiding co-precipitation of PLA homocrystals. In an attempt to develop an optimum process to prepare PLA stereoblocks, some reports have investigated the formation of PDLA-*b*-PLLA via aluminum or tin-assisted ring opening polymerization (ROP) of lactide.<sup>8-12</sup> However, the removal of the metal fragments from the bulk of the final material is impossible in many cases. The safety of long-term use of metals like aluminum or tin in medical devices or food packages is still under debate.<sup>13,14</sup> These limitations have encouraged several research groups to explore the activity of many catalysts and initiators based on nontoxic metals, such as Zn, Fe, Ca, and Mg on the polymerization and copolymerization of cyclic esters.<sup>15-17</sup> Due to the low cytotoxicity and well established activity of titanium and magnesium compounds in a large number of ROP reactions we have decided to explore the reactivity of a novel initiator based on mixed Mg/Ti alkoxides in

lactide homopolymerization and also verify their usefulness as initiator system for L- and D-lactide one-pot sequential copolymerization in solution. Catylen<sup>®</sup> S200 is a non-toxic hydrocarbon soluble bimetallic complex comprising Mg(II) and Ti(IV) designed for Ziegler-Natta-type olefin polymerization that, to the best of our knowledge, was never tested in lactide polymerizations. Herein we wish to report our first results on the activity studies of Catylen<sup>®</sup> S200 on lactide polymerizations and discuss the use of the resulting polymers to produce PLA stereocomplexes.

## EXPERIMENTAL

### Materials

All experiments were carried out under purified nitrogen using standard Schlenk techniques or in a glove-bag. Toluene was distilled from Na/benzophenone under nitrogen. Chloroform and ethanol were obtained from Vetec<sup>®</sup> Brazil and used as received. The L-lactide ((S,S)-3,6-Dimethyl-1,4-dioxane-2,5-dione) and D-lactide ((R,R)-3,6-Dimethyl-1,4-dioxane-2,5-dione) were purchased from Purac<sup>®</sup> and recrystallized from dry toluene before use. The final free acid content measured by potentiometric titration was 3.14 and 4.61 meq/kg for D-lactide and L-lactide respectively. The Mg/Ti initiator (Catylen<sup>®</sup> S200) was supplied by Evonik Industries and was used as received.

### Measurements

The WAXD analyses were performed in a Rigaku Miniflex (model DMAX 2200) X-ray diffractometer (generator of 3kW, a graphite monochromator, CuK<sub>α</sub> radiation (wavelength,  $\lambda = 0.154$  nm)], operated at 30 kV/15mA. The samples were scanned with a counting time of 1 s under a diffraction angle of  $2\theta$  in the range of 2.0–40.0°. Number-average ( $M_n$ ) and weight-average ( $M_w$ ) molecular weight of PLAs were determined by means of Gel Permeation Chromatography in an Agilent 1200 Series GPC-SEC Analysis System, Agilent Technologies, (Santa Clara, CA) fitted with PLgel 5  $\mu$ m MIXED-C Columns (Agilent Technologies) using polystyrene standards for the calibration and chloroform (CHCl<sub>3</sub>) as the solvent at 30°C with a flow rate of 1.0 mL/min. The glass transition ( $T_g$ ), the crystallization temperature ( $T_c$ ), and the melting ( $T_m$ ) temperatures of the samples were determined using a DSC-7 calorimeter (Perkin Elmer Inc., Wellesley, MA). The polylactide samples were analyzed from 25 to 190°C. The stereocomplexes obtained from co-precipitation and the stereoblock were analyzed from –20 to 260°C. All the DSC scans were performed under nitrogen flow with heating and cooling ramps of 10°C/min. The PLLA and PDLA

crystallinities were calculated from the DSC melting enthalpies, using a melting enthalpy value of 106 J/g for 100% crystalline PLLA or PDLA.<sup>18</sup> The <sup>1</sup>H and <sup>13</sup>C-NMR spectra were recorded at room temperature with a Varian Mercury VX-300FT-NMR spectrometer operating at 300 MHz (<sup>1</sup>H) or 75 MHz (<sup>13</sup>C) using tetramethylsilane (TMS) as an internal reference. Polymers were analyzed in CDCl<sub>3</sub> solution. Chemical shifts ( $\delta$ ) were given in ppm.

## PROCEDURES

### Homopolymerizations

In a typical polymerization procedure a Schlenk flask previously dried in oven at 100°C for 24 hours was charged with 10.0 g of monomer (L-lactide or D-lactide) and 40 mL of toluene. The Schlenk flask was then immersed in oil bath at 70°C. After the complete dissolution of the monomer the desired amount of initiator was added and the polymerization was carried out for 3 hours. The polymer was immediately precipitated in an excess of cold ethanol, filtered and dried in oven at 50°C for 24 hours.

### PLLA/PDLA Stereocomplexation

Polylactide stereocomplexes were obtained by mixing saturated solutions of PLLA and PDLA in chloroform and stirring at 200 rpm for 20 minutes at 25°C. The stereocomplex was then precipitated in excess of cold ethanol filtered and dried in oven at 50°C for 24 hours.

### One-Pot Diblock Copolymerization of L- and D-lactide (PLLA- *b*-PDLA Synthesis)

A Schlenk flask previously dried in oven at 100°C for 24 hours was charged with 5.0 g of D-lactide and 20 mL of toluene. The Schlenk flask was then immersed in oil bath at 70°C. After the complete dissolution of the monomer the desired amount of initiator was added (0.2 wt %) and the first step of the reaction was carried out for 3 hours. After that, 20 mL of a solution of 5.0 g of L-lactide previously dissolved in 20 mL of toluene at 70°C was added to the Schlenk flask and the reaction was carried out for more 3 hours to complete the copolymerization. The copolymer was immediately precipitated in an excess of cold ethanol, filtered and dried in oven at 50°C for 24 hours.

## RESULTS AND DISCUSSION

### Homopolymerizations

The Mg/Ti mixed alkoxide system (Catylen<sup>®</sup> S200) was tested as initiator of the ROP of L- and D-lactide in toluene at 70°C (Scheme 1). The results are summarized in Table I.

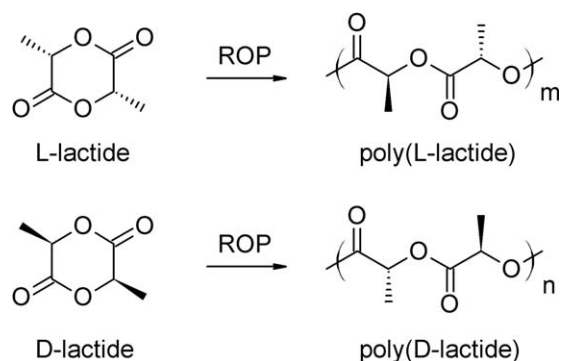
**Table I.** Solution Polymerization Data of L- and D-lactide in Toluene at 70°C

Entry	Monomer	Initiator (wt %) <sup>a</sup>	Yield <sup>b</sup> (%)	$M_n^c$ (kg mol <sup>-1</sup> )	PDI
1	L-lactide	1.0	86.4	8.3	1.60
2		0.5	90.4	11.4	1.58
3		0.05	92.6	40.7	1.12
4	D-lactide	1.0	89.1	8.0	1.67
5		0.5	92.6	16.5	1.85
6		0.05	97.1	50.5	1.17

<sup>a</sup> Calculated using total metal content (Mg and Ti)

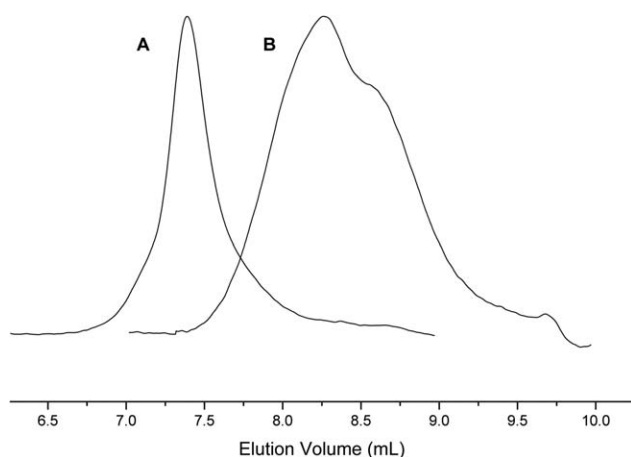
<sup>b</sup> Isolated yield.

<sup>c</sup> Determined by GPC (CHCl<sub>3</sub>) with polystyrene standards.

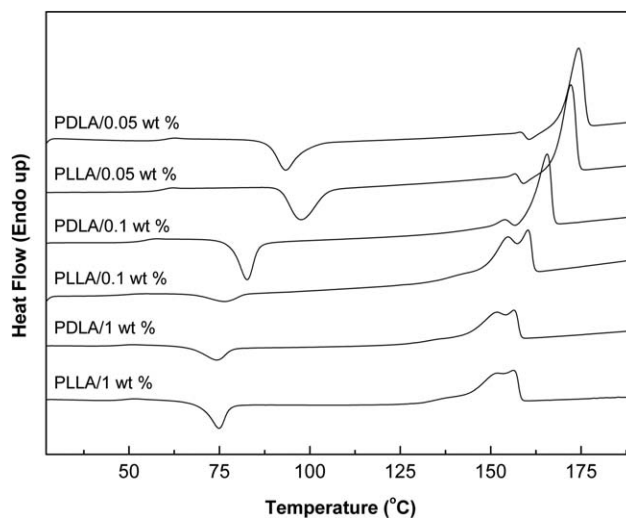


**Scheme 1.** Synthesis of PLLA and PDLA via Ring Opening Polymerization (ROP) using Catylen® S200 as Initiator System.

Catylen® S200 is a commercial product designed to be employed as support for Ziegler-Natta-type olefin polymerization catalysts composed of a 30 wt % solution of magnesium-ethanolate and titanium-*n*-butanolate in hexane forming a soluble complex with molecular formula  $[\text{Mg}(\text{OEt})_2]_2 \cdot [\text{Ti}(\text{O}i\text{Bu})_4]$ .<sup>19</sup> Under the selected conditions, the initiator showed good activity furnishing high yields of polylactide in all cases with low to medium molecular weights. The increasing polymer yield with the decreasing initiator content can be ascribed to the changes in PLA solubility in ethanol according to the differences in molecular weight and crystallinity. Regardless of the presence of two metal centers in Catylen® S200 the gel permeation chromatography showed a monomodal molecular weight distribution and a very narrow polydispersity when the polymerization of L- or D-lactide is carried out with 0.05 wt % of initiator. Nonetheless when higher amounts of initiator are used the molecular weight distribution broadens (an example of which is shown in Figure 1). The narrow molecular weight distribution obtained at low concentrations of initiator suggests the formation of a living polymerization system. The activity of titanium and magnesium compounds in lactide polymerization is well described in the literature. As a representative example, Harrane *et al.* used Maghnite- $\text{H}^+$ , a proton exchanged clay for the polymerization of *rac*-lactide.<sup>20</sup> The non-toxic catalyst was tested in polymerizations in bulk and solution, furnishing only moderate to low product



**Figure 1.** GPC curves corresponding to the polymerization of L-lactide using (A) 0.05 wt % of initiator; (B) 1.0 wt % of initiator.



**Figure 2.** DSC second heating curves of poly(lactides) (initiator concentrations in weight percent are indicated for each sample).

yields with  $M_v$  values up to 55,000 in bulk and 24,4100 when dioxane was employed as solvent. On the other hand, Dakshinamoorthy *et al.* synthesized a series of titanium isopropoxide complexes based on aminodiols ligands which showed significant activity on *rac* and L-lactide polymerizations in toluene at 70°C.<sup>21</sup> The  $M_n$  values observed by means of GPC analysis ranged from 14,920 to 35,660  $\text{g mol}^{-1}$  with good control of the molar mass distributions. However, relatively long reaction times (22 h) were required for high conversions. Through  $^1\text{H-NMR}$  studies the authors were able to determine the isopropyl group in the polymer terminus, suggesting a coordination-insertion mechanism where the lactide is inserted into the Ti—O bond. The same analysis was performed for the polymers prepared in the present work; however, the superposition of signals in the  $^1\text{H-NMR}$  spectra of our samples revealed that the identification of the real active specie through end-group analysis is not a trivial task. Titanium alkoxides are known to adopt extended structures in solution due to the tendency of Ti(IV) to increase its coordination number.<sup>22</sup> The formation of larger units *via* alkoxo bridges with heteroatoms, including magnesium, barium, and calcium among other metals is also well established.<sup>19</sup> Unfortunately, no detailed information describing Catylen® S200 structure in solution is available. In order to clarify the specific role of the two metals in the polymerization and propose a consistent mechanism for the lactide polymerization, detailed studies on the polymerization kinetics and the structure of Catylen® S200 are underway and will be subject of another report. Nevertheless, despite the lack of structural data, our results indicate that Catylen® S200 is an efficient initiator system for lactide polymerization when compared with the aforementioned titanium and magnesium examples.

### Thermal Properties of Poly(lactides)

The thermal properties of the poly(lactides) were investigated by DSC. The DSC thermograms with the second heating curves can be seen in Figure 2. The  $T_g$ ,  $T_c$ ,  $T_m$  and  $\Delta H_m$  of the homopolymers were evaluated from the DSC runs and the values are shown in Table II.

**Table II.** Thermal Properties of the Homochiral Poly lactides Prepared with Catylen<sup>®</sup> S200

Entry	$T_g$ (°C)	$T_c$ (°C)	$T_m$ (°C)	$\Delta H_m$ (J/g)	$X_c$ (%)
1	51.3	74.7	151.9/156.5 <sup>a</sup>	49.0	46.2
2	48.3	75.9	154.7/160.2 <sup>a</sup>	49.4	46.6
3	61.6	97.7	172.0	63.7	60.1
4	50.5	74.4	151.7/156.7 <sup>a</sup>	44.5	42.0
5	57.0	82.7	165.5	40.1	37.8
6	60.2	93.2	174.4	67.6	63.8

<sup>a</sup>Bimodal melting profile.

All homochiral PLA samples show a steplike change due to the glass transition in the range between 48 and 62°C clearly affected by the distinct molecular weights. Other significant changes were observed in the crystallization temperatures which varied in a large range (74–98°C) indicating the increasing crystallizability of the samples with lower molecular weight. It is interesting to note the bimodal behavior of the melting temperatures in some PLA scans. Bimodality is a common phenomenon seen in melting transitions of polylactides. It can be attributed to the presence of two distinct crystal structures in the initial sample but sometimes the annealing effect of the DSC scan itself allows crystals of lower degree of perfection to melt, recrystallize, and remelt few degrees above.<sup>23</sup>

#### PLLA/PDLA Stereocomplexes

The polylactide samples obtained with the Mg/Ti system as initiator were used for stereocomplexation through coprecipitation from chloroform solutions. The PLLA and PDLA were mixed using homochiral polymers with similar molecular weights aiming to promote a more efficient interaction between the polymer chains (Table III).

Among the many techniques employed for polymer analysis, the Wide Angle X ray Diffraction is one of the most valuable tools in PLA stereocomplexes characterization, due to the remarkable differences between the diffraction patterns of the stereocomplexes and the homochiral PLA. The WAXD patterns of the prepared stereocomplexes and homochiral PLA are shown in Figure 3. For the PLLA and PDLA samples the characteristic reflections around 15, 17, 19, and 22° assigned to the  $\alpha$ -form of PLA can be observed with no considerable differences between their diffraction patterns.<sup>24</sup> Conversely, the PLLA and PDLA blends showed a WAXD pattern with the same three peaks around 12, 20, and 24° which are related to the formation of

PLA stereocomplexes crystallized in triclinic unit cell.<sup>25,26</sup> Although the first two sc-PLA showed high degree of stereocomplexation with no signals of reflections of the individual PLA stereoisomers, the third sample (sc-PLA-3) showed a small peak at 17.0° assigned to remaining homochiral PLA. As mentioned before this result was not unexpected because the higher the polymer molecular weight the harder is to achieve fully stereocomplexation as the phenomena is hindered by crystallization of homopolymers.<sup>7,27</sup>

#### Thermal Properties of PLA Stereocomplexes

The PLA stereocomplexes were also analyzed by DSC. Figure 4 presents the DSC profiles recorded during the first heating scan. The scans demonstrated melting temperatures *ca.* 60°C higher than the homochiral PLA, confirming the obtention of three PLA stereocomplexes. The DSC runs of the two first stereocomplexes, sc-PLA-1 and sc-PLA-2, showed single melting temperatures at 215.3 and 224.2°C, respectively, indicating that these samples possessed only stereocrystals. However, the DSC curve of sc-PLA-3 showed a weak endotherm at 173.9°C attributed to the PLA homopolymer melting, corroborating the X ray data discussed above. Surprisingly, the first heating DSC scan of sc-PLA-3 revealed two endotherms related to stereocrystal melting at 235.1 and 250.1°C. To date, this is one of the highest melting temperatures reported for a polylactide stereocomplex. Aiming to guarantee the higher temperature event was not due to thermal degradation, the sample was characterized by thermogravimetric analysis (Figure 5). The TGA demonstrated that the weight loss is <2% at 260°C, confirming that the highest endothermic event can be attributed to crystal melting. Although less common phenomena, it has been already reported that, similarly to homochiral PLA samples, stereocrystals can reorganize at elevated temperatures before complete melting.<sup>28</sup>

**Table III.** Polylactides Used for Stereocomplexation

Entry	Polylactides selected for stereocomplexation			
	PLLA		PDLA	
	$M_n$ (kg mol <sup>-1</sup> )	$T_m$ (°C)	$M_n$ (kg mol <sup>-1</sup> )	$T_m$ (°C)
sc-PLA-1	8.3	151.9/156.5	8.0	151.7/156.7
sc-PLA-2	11.4	154.7/160.2	16.5	165.5
sc-PLA-3	40.7	172.0	50.5	174.4

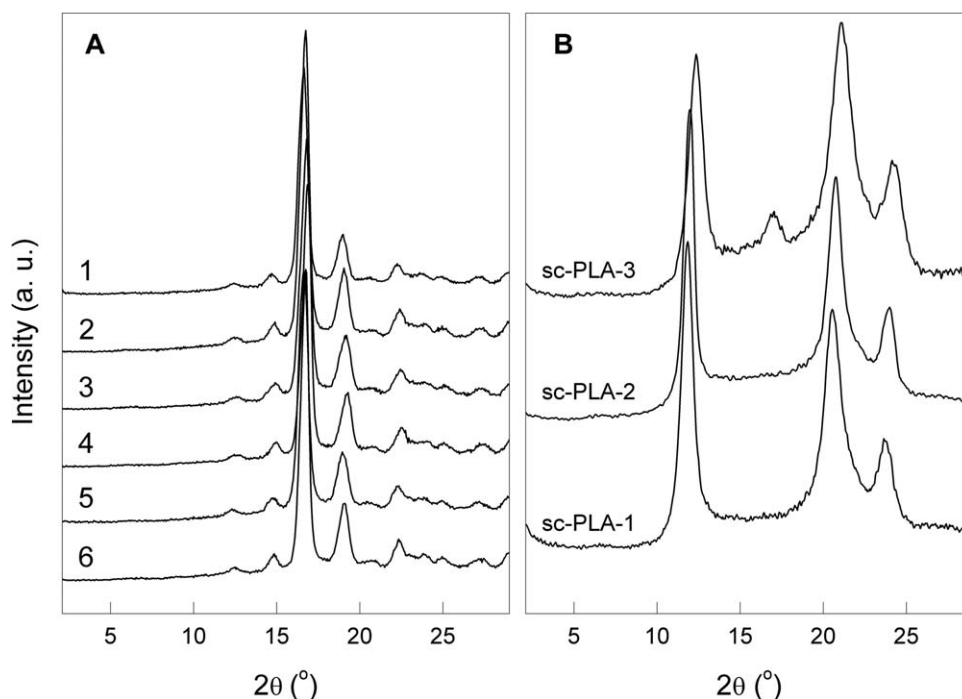


Figure 3. X ray curves of (A) PLLA and PDLA homopolymers (B) PLA stereocomplexes.

Nevertheless, the melting behavior of stereocomplex sc-PLA-3 showed remarkable differences when the first and second melting curves were compared, as shown in Figure 6. The calorimetry experiment was performed as follows: sc-PLA-3 sample was first heated to 260°C, kept at that temperature for 1 minute and then rapid cooled from the melt. As one can note in the second heating process an intense crystallization temperature ( $T_c$ ) appeared at 93.3°C. The two distinct melting peaks seen in the first heating scan merged into one single peak at 225.4°C while the homochiral PLA melting peak was shifted to 170.4°C and became more intense. These results seen in the second heating can be explained by the concomitant formation of homochiral PLA and imperfect stereocomplex crystals from the molten sample which agrees with He and co-workers observations from their DSC analyses of PLA stereocomplexes prepared *via* co-precipitation from methylene

chloride solutions.<sup>29</sup> They studied the differences between the first and second heating curves of the PLA stereocomplex performing a series of DSC experiments under distinct conditions, where the samples were cooled from increasing temperatures after the first heating scan. The change in the molten state temperature from 224 to 226°C in the cooling curve clearly affected the melting crystallization temperature ( $T_{mc}$ ), shifting its value from 144 to 120°C. When the molten state temperature was increased to 230°C, the authors reported that  $T_{mc}$  is almost undetectable. He *et al.* also verified the influence of the melting time in the crystallinity of the PLA stereocomplex performing isothermal DSC scans, keeping the samples for 1, 2, and 3 minutes in the molten state before rapid cooling. As result, the crystallization ability was depressed with the prolonged

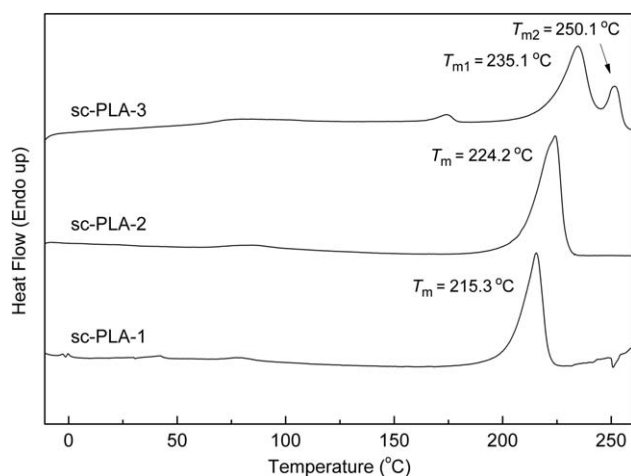


Figure 4. DSC first heating curves of PLA stereocomplexes.

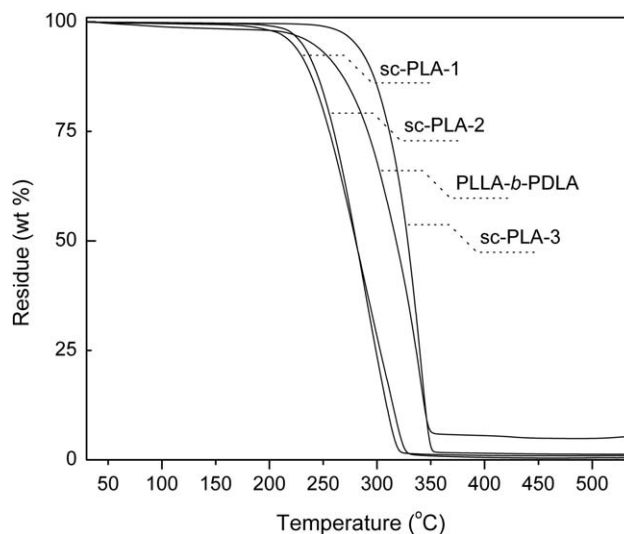
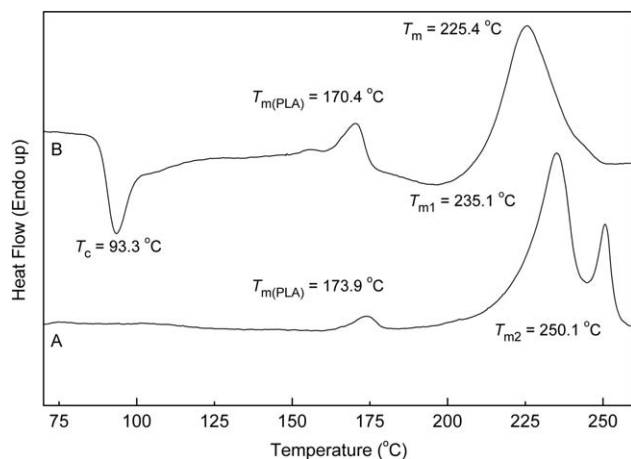


Figure 5. TGA charts of stereocomplexes.



**Figure 6.** DSC traces of sc-PLA-3. (A) First heating Scan. (B) Second heating scan.

melting time. Based on these results they developed a model where the PLA stereocomplex thermal behavior can be explained by the capacity of the PDLA and PLLA chains to retain their interactions after crystal melting. Therefore, they concluded that the crystallization behavior of PLLA/PDLA stereocomplexes strongly depends on the initial melt state. However, even keeping our sample in molten state for a short period of time (1 min) to preserve the PDLA/PLLA interactions, the PLA homocrystallization was not suppressed, and the homochiral crystal melting can be observed in the second heating curve of our sample.

#### One-pot Diblock Copolymerization of L- and D-lactide

In order to investigate strategies to prepare PLA stereocomplexes with reproducible thermal profiles, the initiator was tested in one-pot sequential copolymerization of L- and D-lactide to synthesize a stereoblock, as shown in Scheme 2.

#### Polymerization (ROP) Using Catylen® S200 as Initiator System

The copolymerization was carried out in toluene in two steps: first, the D-lactide was polymerized for 3 hours at 70°C in presence of Catylen® S200 and then a solution of L-lactide in toluene was immediately added to the flask to continue the reaction for 3 hours. After a total of 6 hours of reaction the copolymer was easily isolated from precipitation in ethanol. The GPC analysis showed that the copolymer has  $M_n 2.7 \times 10^4 \text{ g mol}^{-1}$  with monomodal peak elution similar to the previously seen in the homopolymerizations discussed above. The relatively narrow

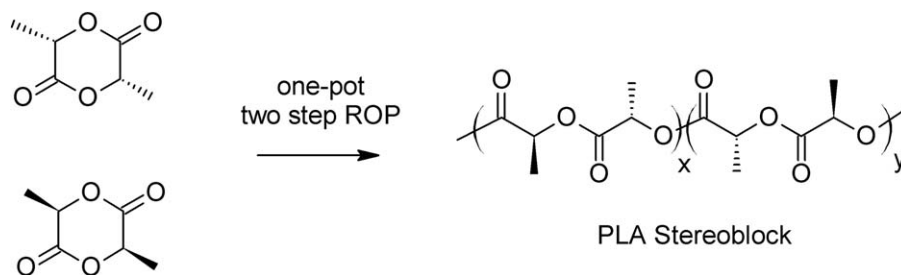
polydispersity (1.31) is an indication of the low degree of molecular scrambling along the course of copolymerization. The WAXD pattern of the PLA stereoblock (Figure 7) showed only the characteristic peaks of stereocomplex crystals at 11.9, 20.8, and 24.1°, confirming that, after direct precipitation in a non-solvent, stereocrystals are obtained in good yield (84%).

The stereoblock microstructure was investigated by  $^{13}\text{C}$ -NMR. The Figure 8 shows the expanded spectra of the carbonyl region of the PLA stereoblock and one of the synthesized polyactides (entry 3, Table I) for comparison. The dominant signal at 169.5 ppm present in both spectra can be assigned to the *iiii*, *siii*, *iiis*, and *siis* hexads, attesting the isotactic nature of the two samples. Nevertheless the signal at 169.27 ppm, detected only in the spectrum of PLLA-*b*-PDLA copolymer, indicates the presence of racemic sequences due to the PLLA-PDLA heterolinks connecting the two blocks (*iisii*, *sisii*, *iisii*, and *sisii* hexads).<sup>30</sup> The low intensity of the racemic peak is indicative of the long block structure of the copolymer.

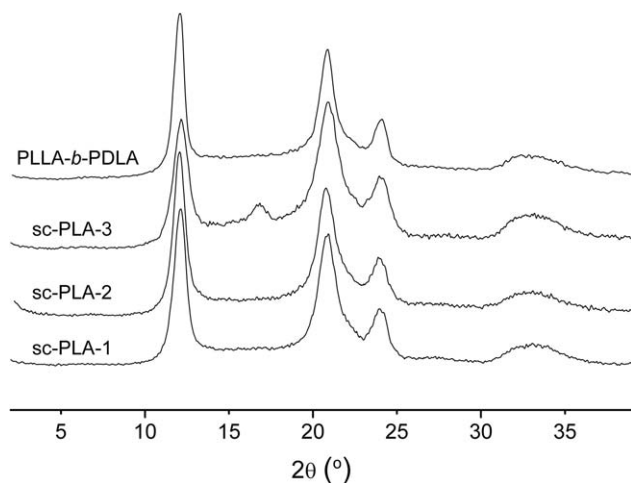
The thermal behavior of the PLA stereoblock was investigated by DSC. The endotherms found in the calorimetry analysis corroborate the stereoblock obtention. The melting profile determined in the first heating scan was bimodal showing  $T_m$  values at 192.8 and 213.2 °C. After rapid cooling, a  $T_c$  appears at 86.6°C and the melting temperature observed was similar to the one seen in the first heating curve, showing a  $T_m = 210.9^\circ\text{C}$ . In the third heating scan, which was performed after slow cooling from 230 to  $-30^\circ\text{C}$ , the melting temperature remains practically unchanged, with stereocrystal melting at 210.6°C (Figure 9). A reproducible thermal profile is an inherent feature of PLA stereoblocks that is very important for commodity applications such as food packing. Further studies are underway in our laboratory to investigate the possibility to obtain diblock PLA copolymers with  $M_n > 100 \text{ kg mol}^{-1}$  employing the same methodology.

#### CONCLUSION

Catylen® S200 was investigated as initiator for ring opening polymerization of L- and D-lactide in toluene at 70°C. Catylen was found to be an efficient initiator for the ROP of lactide in all tested conditions. The GPC data suggest that under certain conditions the initiator can produce polymers with controlled molecular weight with a narrow polydispersity. The WAXD analyses showed the formation of crystalline polymers with high degree of isotacticity which is corroborated by crystallinity

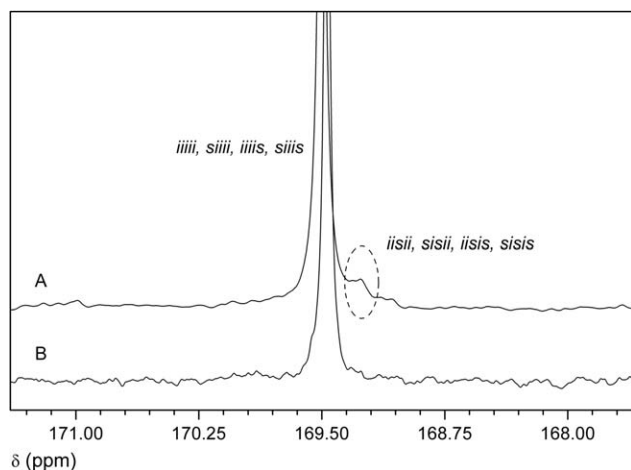


**Scheme 2.** Synthesis of PLLA-*b*-PDLA (PLA Stereoblock) via Two Step Ring Opening Polymerization (ROP) using Catylen® S200 as Initiator System.

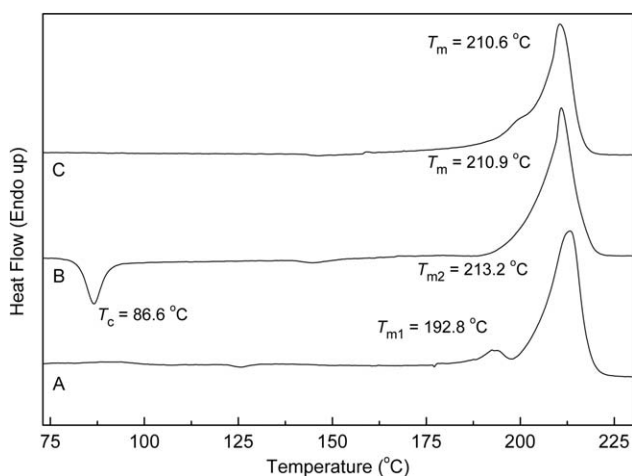


**Figure 7.** WAXD charts of stereocomplexes and the PLLA-b-PDLA copolymer.

degree calculated from the DSC results. Polylactide stereocomplexes were successfully obtained through the co-precipitation from mixed solutions of polylactides produced with Catylen<sup>®</sup> S200. Nevertheless, the X-ray diffraction indicates that when polymers with high molecular weight ( $\sim 50,000$  g/mol) are mixed, the stereocomplexation is not totally effective. Considering the well known difficulties in molecular-level mixing of medium and high molecular weight polymers, these results are in agreement with previously reported studies on PLA stereocomplexation. However, even with signals of homocrystallization, one of the stereocomplexes showed an endotherm event assigned to stereocrystal melting at  $250.1^{\circ}\text{C}$ , which is one of the highest melting temperatures reported for a PLA stereocomplex. To our knowledge this is the first report of the use of Catylen<sup>®</sup> S200 as initiator for lactide polymerization with subsequent use of resulting polymers to prepare PLLA/PDLA stereocomplexes. The initiator system was also successfully employed in a sequential copolymerization of L- and D-lactide to prepare a PLA stereoblock. The copolymer showed a reproducible thermal profile



**Figure 8.** Expanded regions of carbonyl signals from  $^{13}\text{C}$ -NMR spectra of (A) diblock copolymer (PLLA-b-PDLA) and (B) selected PLLA sample (Table I, entry 3).



**Figure 9.** DSC chart of PLLA-b-PDLA. (A) First heating scan. (B) Second heating scan. (C) Third heating scan.

in the DSC analysis, showing a melting temperature close to  $210^{\circ}\text{C}$ , confirming the obtention of a PLA stereocomplex. The long block structure of the copolymer is suggested by the  $^{13}\text{C}$  NMR spectroscopy, due to the low intensity of the carbonyl signal corresponding to the PLLA-b-PDLA heterolinks. The production of polylactides and their respective stereocomplexes using biocompatible initiators is especially important for the manufacture of medical and pharmaceutical devices where the presence of potentially harmful metals in the bulk of the polymer matrix is undesirable. Our first results on lactide polymerization indicate that Catylen<sup>®</sup> S200 could be a potential candidate to replace tin and aluminum based catalysts in PLA production for medical applications.

## ACKNOWLEDGMENTS

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support.

## REFERENCES

- Ikada, Y.; Jamshidi, K.; Tsuji, H.; Hyon, S. H. *Macromolecules* **1987**, *20*, 904.
- Slager, J.; Domb, A. J. *Adv. Drug Deliv. Rev.* **2003**, *55*, 549.
- Fukushima, K.; Kimura, Y. *Polym. Int.* **2006**, *55*, 626.
- Kakuta, M.; Hirata, M.; Kimura, Y. *Polym. Rev.* **2009**, *49*, 107.
- Tsuji, H.; Tsuruno, T. *Macromol. Mater. Eng.* **2010**, *295*, 709.
- Tsuji, H. *Macromol. Biosci.* **2005**, *5*, 569.
- Tsuji, H.; Hyon, S. H.; Ikada, Y. *Macromolecules* **1991**, *24*, 5651.
- Spassky, N.; Wisniewski, C.; Pluta, C.; Le Borgne, A. *Macromol. Chem. Phys.* **1996**, *197*, 2627.
- Majerska, K.; Duda, A. *J. Am. Chem. Soc.* **2004**, *126*, 1026.

10. Yui, N.; Dijkstra, P. J.; Feijen, J. *Makromolekulare Chemie* **1990**, *191*, 481.
11. Komazawa, Y.; Tang, Z.; Musashino Chemical Laboratory, Ltd.: Japan; Mutual Corporation, **2008**, PCT/JP2007/065778, p. 53.
12. Fukushima, K.; Furuhashi, Y.; Sogo, K.; Miura, S.; Kimura, Y. *Macromol. Biosci.* **2005**, *5*, 21.
13. Kricheldorf, H. R.; Hachmann-Thiessen, H.; Schwarz G. *Bio-macromolecules* **2004**, *5*, 492.
14. Dechy-Cabaret, O.; Martin-Vaca, B.; Bourissou, D. *Chem. Rev.* **2004**, *104*(12), 6147.
15. Wheaton, C. A.; Hayes, P. G.; Ireland, B. J.; *Dalton Trans.* **2009**, 4832.
16. Dobrzynski, P.; Kasperczyk, J.; Janeczek, H.; Bero, M. *Polymer* **2002**, *43*, 2595.
17. Platel, R. H.; Hodgson, L. M.; Williams, C. K. *Polym. Rev.* **2008**, *48*, 11.
18. Sarasua, J-R.; Arraiza, A. L.; Balerdi, P.; Maiza, I. *Polym. Eng. Sci.* **2005**, *45*, 745.
19. Rauleder, H.; Standke, B.; Horn, M.; Kotsch, H.-J.; Srebny, H.-G. Patent No : US 6,294,682 B1, **2001**.
20. Harrane, A.; Belaouedj, M. E. A.; Belbachir, M. *React. Funct. Polym.* **2011**, *71*, 126.
21. Dakshinamoorthy, D. Peruch, F. *Polymer* **2011**, *21*, 4686.
22. Fric, H.; Kogler, F. R.; Puchberger, M.; Schubert, U. Z. *Naturforsch* **2004**, *59b*, 1241.
23. Sarasua, J-R.; Prud'homme, R. E.; Wisniewski, M.; Le Borgne, A.; Spassky, N. *Macromolecules* **1998**, *31*, 3895.
24. Di Lorenzo, M. L.; Cocca, M.; Malinconico, M. *Thermochimica Acta* **2011**, *1*(522), 110.
25. Brizzolara, D.; Cantow, H-J.; Diederichs, K.; Keller, E.; Domb, A. J. *Macromolecules* **1996**, *29*, 191.
26. Sarasua, J-R.; Rodríguez, N. L.; Arraiza, A. L.; Meaurio, E. *Macromolecules* **2005**, *38*, 8362.
27. Tsuji, H.; Hyon, S. H.; Ikada, Y. *Macromolecules* **1991**, *24*, 5657.
28. Uehara, H.; Karaki, Y.; Wada, S.; Yamanobe, T. *ACS Appl. Mater. Interf.* **2010**, *2*, 2707.
29. He, Y.; Xu, Y.; Wei, J.; Fan, Z.; Li, S.; *Polymer* **2008**, *49*, 5670.
30. Hirata, M.; Kobayashi, K.; Kimura, Y. *J. Polym. Sci.: Part A: Polym. Chem.* **2010**, *48*, 794.