

Microstructure and Mechanism Study of Polylactide Obtained by the Copolymerization of L-Lactide and D,L-Lactide

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ABSTRACT: The stereosequence of polylactide has been analyzed with ¹³C-NMR spectroscopy, according to which syndiotactic addition is preferred. According to Markovian statistics, the reactivity ratio, which determines the extent of the syndiotactic stereosequence in the polymer chain, can be calculated by an analysis of the carbonyl and methine regions in the spectra. Moreover, the average lengths of seg-

ments SS and RR can be proposed and calculated with the distributing function of the sequence. On this basis, we have investigated the formation mechanism with respect to the preference for the syndiotactic addition of polylactide chains. © 2009 Wiley Periodicals, Inc. *J Appl Polym Sci* 115: 2955–2961, 2010

Key words: biopolymers; copolymerization; microstructure

INTRODUCTION

Recently, much attention has been focused on biodegradable polymers such as polylactide (PLA), poly(butylene succinate), and poly(ϵ -caprolactone). PLA, formed by the ring-opening polymerization of lactide,^{1–3} is the most typical of the biodegradable plastics based on aliphatic polyesters because of its excellent biocompatibility, nontoxicity, and biodegradability and its high physicochemical properties.^{3,4} Additionally, PLA, generated from annually renewable natural resources such as corn, can reduce the consumption of nonrenewable petrochemicals. PLA is also superior to conventional petrochemical polymers because of less energy consumption and carbon dioxide emission.

Because it has two stereocenters, lactide, the cyclic dimer of lactic acid,⁵ has three isomers: L-lactide (SS), D-lactide (RR), and meso-lactide (RS) (Scheme 1). D,L-Lactide is an equimolar mixture of RR and SS isomers.⁶ The Monte Carlo method⁷ has been used

to study the stereochemical structure of lactide polymerization. According to a previous investigation, two kinds of mechanisms of chain propagation, Bernoullian and Markovian,⁸ can be used to describe the polymerization of lactide. On the basis of Bernoullian statistics, the reaction rate constants for isotactic addition and syndiotactic addition are equal. On the contrary, the stereosequence distribution corresponding to Markovian statistics is complicated because of the different reaction efficiencies of isotactic addition and syndiotactic addition.

The amount and stereosequence arrangement of the R and S stereocenters in the polymer chain have a significant influence on the physicochemical properties (e.g., thermal, crystalline, mechanical, and biological properties) of PLA.^{9–14} The final stereosequence distribution of the polymer is dependent on lots of factors, including the lactide feed composition, polymerization kinetics (e.g., catalyst, temperature, and reaction time), and conversion percentage.^{7,15–18} Extensive research has been conducted on the influence of the polymerization kinetics on the microstructure starting from D,L-lactide and especially the catalyst, reaction temperature, and transesterification.

Until recently, only polymerization in the presence of the catalyst Al(acac)₃ could match Bernoullian statistics according to Bero et al.¹⁹ and Bellency et al.²⁰ Kricheldorf and coworkers^{21–24} did lots of work on the polymerization of lactide and studied stereoselective initiators capable of enhancing the isotacticity of poly(D,L-lactide). Kasperczyk and Bero^{25,26}

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compared the microstructures of poly(D,L-lactide) chains obtained in the presence of different initiators, including Al(acac)₃, BuLi, and Bu₂Mg, and they also reported that the LiOtBu catalyst could produce predominantly syndiotactic poly(D,L-lactide).²⁷ Wizniewski²⁸ showed that isoselectivity could be obtained in the polymerization of D,L-lactide with stereoselective initiators of salen-type aluminum complexes. Transesterification rearrangement is another factor strongly influencing the microstructure of the polymer. The contribution of transesterification reactions has been observed at a high reaction temperature with stannous octoate.¹ In contrast, a contribution of transesterification reactions is unlikely in the case of polymerization with stannous octoate under mild conditions.^{1,24} Thakur et al.⁶ examined the stereosequence distribution of lactide stereoisomers polymerized to various extents of conversion, and they reported the preference for syndiotactic addition.

However, no one has investigated the formation mechanism of the stereosequence of PLA chains. In this study, by comparing and calculating the extent of the syndiotactic stereosequence in the polymer chain, we investigated the formation mechanism of the stereochemical structure.

EXPERIMENTAL

Polymerization

Ring-opening polymerization was carried out under a vacuum of 10 mmHg in a sealed flask with typical stannous octoate as the initiator. The polymer was prepared at 160°C for 1 h with a monomer-to-initiator weight ratio of 500 : 1. Chloroform was added to the flask when the polymerization was finished. The polymer, obtained by volatilization of the chloroform from the solution, was dried *in vacuo* at 40°C for 48 h.

Measurements

The specific optical rotations of the polymers were measured in chloroform with a WZZ-2SS polarimeter (Precision & Scientific Instrument Co., Ltd., Shanghai, China) at the wavelength of 589 nm, the concentration of 5 g/dL, and the temperature of 20°C. The average molecular weight and polydispersity index of PLA were determined with a Waters 150C gel permeation chromatograph (Waters/Millipore Corp., Milford, MA) with tetrahydrofuran as the solvent. All molecular weights were determined with a calibration curve prepared with narrow-distribution polystyrene standards. ¹³C-NMR spectra were recorded with a Bruker DMX 500-MHz spectrometer (Bruker, Karlsruhe, Germany) with chloro-

TABLE I
PLAs with Different Lactide Compositions and Specific Rotations

Sample	L-Lactide (%)	D,L-Lactide (%)	$[\alpha]^{20}$ (°)	M_w ($\times 10^5$)	M_w/M_n
A	0	100	0	2.28	2.17
B	60	40	-95.54	2.26	2.21
C	80	20	-123.21	2.77	2.17
D	90	10	-136.12	2.82	2.42
E	95	5	-146.64	2.61	2.25
F	100	0	-156.44	2.48	2.24

M_n = number-average molecular weight; M_w = weight-average molecular weight.

form-*d* as the solvent at 25°C with a 6.3- μ s pulse width (45° pulse angle), 5-s pulse repetition, a 25,000-Hz spectral width, 64,000 data points, and 2000–10,000 accumulations.

RESULTS AND DISCUSSION

Stereosequence of PLA

PLA samples with different compositions of L-lactide and D,L-lactide, prepared by the aforementioned method, are listed in Table I. In the experiments, to verify the lactide composition, various stereosequence structures of the polymer chains were determined from NMR measurements. The specific rotation at 20°C ($[\alpha]^{20}$) was approximately -156.44° for poly(L-lactide) (sample F) and 0° for poly(D,L-lactide) (sample A), and this was in good agreement with the literature values.²⁹ Table I shows that the $[\alpha]^{20}$ values of the samples increased with the L-lactide composition increasing.

$k_{RR/RR}$ and $k_{SS/SS}$ are the rate constants of homopropagation, and $k_{RR/SS}$ and $k_{SS/RR}$ are the rate constants of cross-propagation. The reactivity ratio (r) is defined as follows:

$$r = k_{RR/RR}/k_{RR/SS} = k_{SS/SS}/k_{SS/RR}$$

Equal rate constants ($r = 1$) correspond to Bernoullian statistics; Markovian statistics is based on different rate constants ($r \neq 1$). If r is greater than 1, the isotactic structure is favored. On the contrary, syndiotactic polymer chains are predominant when r is less than 1. Another important parameter is the instantaneous enantiomeric composition of the monomer ($p = [SS]/[RR]$).

In Table II, the theoretical values of the tetrads and hexads for the polymerization of lactide are described with equations in the case of first-order Markovian statistics. "i" indicates the RR or SS structure in the polymer chain, and "s" indicates the RS or SR structure. Markovian statistics has a more general character than Bernoullian statistics, which is based on random pair addition ($r = 1$).

TABLE II
Theoretical Values of the Tetrads and Hexads in the Polymer Chains in Terms of r and p

Tetrads	Ratio ^a
iii + sii + iis + sis	$(1 + rp + r/p)/(2 + rp + r/p)$
isi	$1/(2 + rp + r/p)$
Hexads	Ratio
siiis + iiiis + iiiii + siii	$1 - (2r^2 + 2rp + 2r/p + 2)/[(2 + r/p + rp)(1 + r/p)(1 + rp)]$
iiisi + isiii + iisii + sisii + iisis + sisis	$(4r^2 + 3rp + 3r/p + 2)/[2(1 + r/p)(1 + rp)(2 + r/p + rp)]$
isisi	$1/[2(2 + r/p + rp)]$

^a These data were taken from ref. 20.

In the case of carbonyl resonance, carbonyl carbon atoms are sensitive to hexads, as reported by Bero et al.¹⁹ Because of the dramatic band overlapping in the ¹³C-NMR spectra, it was difficult to calculate the signal intensity of each band accurately. Attempts were made to overcome overlapping by consideration of the three broad bands present in the complex NMR multiplet signals of the carbonyl region. The three broad bands received signals of different ranges (Fig. 1): band I covered the range of 169.45–169.70 ppm, including siiiis, iiiis, iiiii, and siii hexads; band II covered the range of 169.15–169.45 ppm, including iiisi, isiii, iisii, sisii, iisis, and sisis hexads; and band III covered the range of 169.05–169.15 ppm, including isisi hexads.

The ¹³C-NMR spectra of the carbonyl region of the samples (listed in Table I) are shown in Figure 1. The hexad stereosequence assignments for the main peaks were made by the comparison of the distributions observed in many samples with various lactide feed compositions. Obtained from the spectra, the relative intensities of bands II and III decreased remarkably with an increased amount of L-lactide. In contrast, the relative intensities of band I were enhanced until 100% with L-lactide as the raw material. The concrete data are listed in Table III.

Previously, many reports have stated that the tetrad stereosequence distribution is sensitive to the methine resonance. The two broad bands are considered to avoid the influence of overlapping in the NMR multiplet signals of the methine region. The two broad bands received signals of different ranges (Fig. 2): band IV covered the range of 69.10–69.30 ppm, including only isi tetrads, and band V covered the range of 68.90–69.10 ppm, including iii, sii, iis, and sis tetrads.

In this case, the best fit was obtained for $r_A = 0.66$, $r_B = 0.59$, $r_C = 0.64$, $r_D = 0.64$, and $r_E = 0.64$. The value of r was a relative constant ($r = 0.64$) with the same reaction parameters and different lactide compositions, whereas r_B deviated from constancy to some extent. It can be concluded from the results ($r < 1$) that syndiotactic addition was preferred in our work, in agreement with the previous reports.⁶

Table III shows the theoretical and experimental relative intensities of bands I–V in terms of r and p . In the case of sample A, the data showed that the

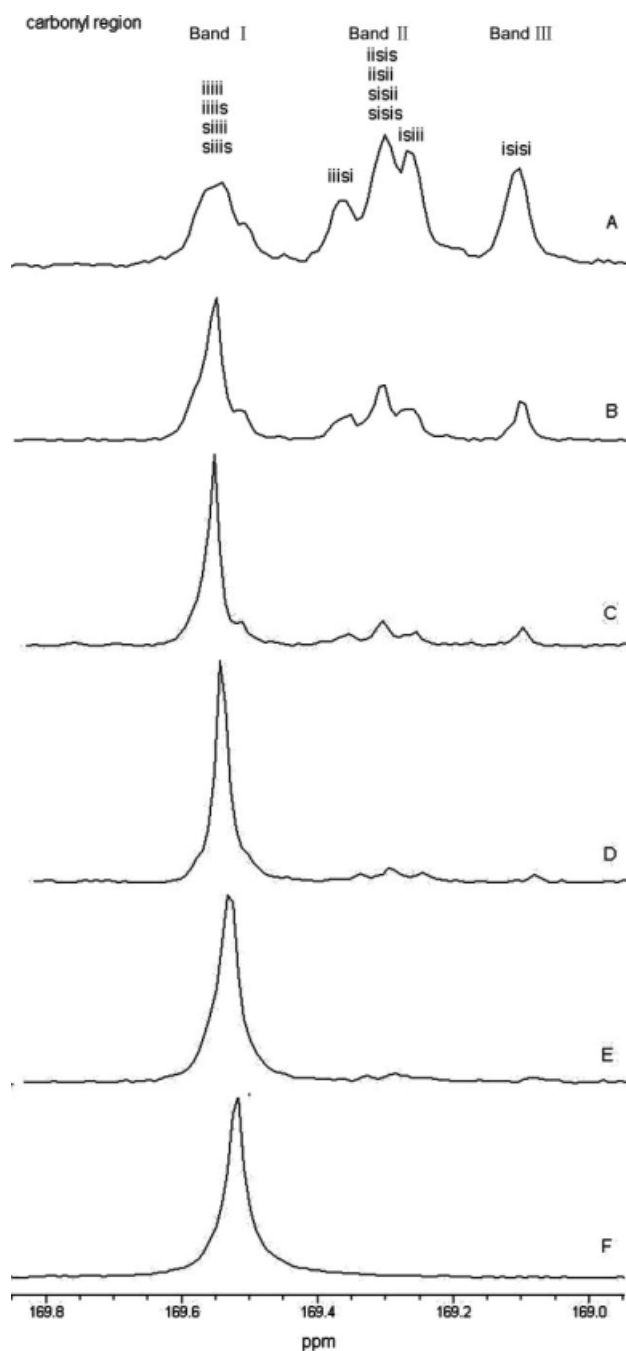


Figure 1 ¹³C-NMR spectra of the carbonyl resonances of PLA samples A–F (see Table I).

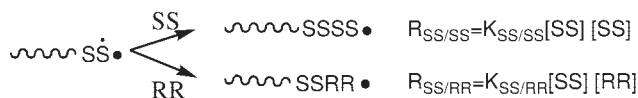
TABLE III
Theoretical and Experimental Values of the Hexads and Tetrads in the Polymer Chains in Terms of r and p

Sample	P	r	Hexad intensity (%)						Tetrad intensity (%)			
			Theoretical value			Experimental value			Theoretical value		Experimental value	
			Band I	Band II	Band III	Band I	Band II	Band III	Band IV	Band V	Band IV	Band V
A	1	0.66	39.76	45.18	15.06	26.98	53.88	19.14	30.12	69.88	30.21	69.79
B	4	0.59	55.63	33.28	11.09	52.71	35.27	12.02	22.18	77.82	20.29	79.71
C	9	0.64	74.46	19.16	6.38	72.16	21.21	6.63	12.77	87.21	12.26	87.74
D	19	0.64	85.91	10.57	3.2	82.42	14.34	3.24	7.04	92.96	7.52	92.48
E	39	0.64	92.59	5.56	1.85	89.19	8.91	1.90	3.71	96.29	6.26	93.74
F	—	—	100.00	0.00	0.00	100.00	0.00	0.00	0.00	100.00	0.00	100.00

relative weights of band III (isisi) and band IV (isi) were 19.14 and 30.21, respectively; they were 12.5 and 25 for the predominantly isotactic structure, 3.125 and 12.5 for the atactic structure, and 50 and 50 for the completely disyndiotactic structure.²⁶ The good agreement between the theoretical and experimental relative intensities indicates that the microstructure of the obtained polymers can be described according to the chain-end control mechanism (Markovian statistics).

Evaluation of the average length of the isotactic stereosequences (N_i)

The distributing functions of the chain segments are as follows:



where R is the reactivity ratio and K is the rate constants. The probabilities of forming $SSSS$ ($P_{SS/SS}$) and $SSRR$ ($P_{SS/RR}$) in the competing reaction are determined as follows:

$$P_{SS/SS} = \frac{R_{SS/SS}}{R_{SS/SS} + R_{SS/RR}} = \frac{r[SS]}{r[SS] + [RR]} = \frac{rp}{1 + rp}$$

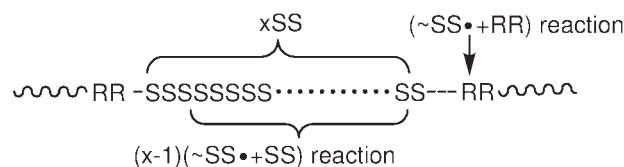
$$P_{SS/RR} = \frac{R_{SS/RR}}{R_{SS/SS} + R_{SS/RR}} = \frac{[RR]}{r[SS] + [RR]} = \frac{1}{1 + rp}$$

According to the same approach, the probabilities of forming $RRRR$ ($P_{RR/RR}$) and $RRSS$ ($P_{RR/SS}$) are determined as follows:

$$P_{RR/RR} = \frac{R_{RR/RR}}{R_{RR/RR} + R_{RR/SS}} = \frac{r[RR]}{[SS] + r[RR]} = \frac{r}{r + p}$$

$$P_{RR/SS} = \frac{R_{RR/SS}}{R_{RR/RR} + R_{RR/SS}} = \frac{[SS]}{r[RR] + [SS]} = \frac{p}{r + p}$$

The probability of forming xSS and xRR (sequence) is determined as follows:



The distributing functions of the sequence amount are as follows:

$$(P_{SS})_x = P_{SS/SS}^{x-1} P_{SS/RR} = P_{SS/SS}^{x-1} (1 - P_{SS/SS})$$

$$(P_{RR})_x = P_{RR/RR}^{x-1} P_{RR/SS} = P_{RR/RR}^{x-1} (1 - P_{RR/RR})$$

The average lengths of segments xSS (N_{SS}) and xRR (N_{RR}) are determined as follows:

$$\begin{aligned} \bar{N}_{SS} &= \sum_{x=1}^{\infty} x (P_{SS})_x = \sum_{x=1}^{\infty} x P_{SS/SS}^{x-1} (1 - P_{SS/SS}) \\ &= \frac{1}{1 - P_{SS/SS}} = 1 + rp \end{aligned}$$

$$\begin{aligned} \bar{N}_{RR} &= \sum_{x=1}^{\infty} x (P_{RR})_x = \sum_{x=1}^{\infty} x P_{RR/RR}^{x-1} (1 - P_{RR/RR}) \\ &= \frac{1}{1 - P_{RR/RR}} = 1 + r/p \end{aligned}$$

Figure 3 shows that N_{SS} varies remarkably in terms of the L-lactide fraction and r in the case of a majority of L-lactide (fraction > 0.5) and the other monomer D-lactide. On the contrary, N_{RR} changes slightly with the variation of r and the L-lactide fraction.

For a Bernoullian pair addition ($r = 1$) and poly (D,L-lactide) ($p = 1$), $N_{SS} = N_{RR} = 2$. However, $N_i = 4$ without the distinction of the RR and SS sequence proposed by Coudane et al.³⁰ In the case of sample A, $r = 0.66$, $p = 1$, and $N_{SS} = N_{RR} = 1.66$. For sample B, $r = 0.59$, $p = 4$, and $N_{SS} = 3.36$ with $N_{RR} = 1.15$. For sample C, $r = 0.64$, $p = 9$, $N_{SS} = 6.76$, $N_{RR} = 1.07$, and so on. The results also show that the polymerization in our study was syndioselektive, and this was in agreement with the outcomes obtained from the spectra.

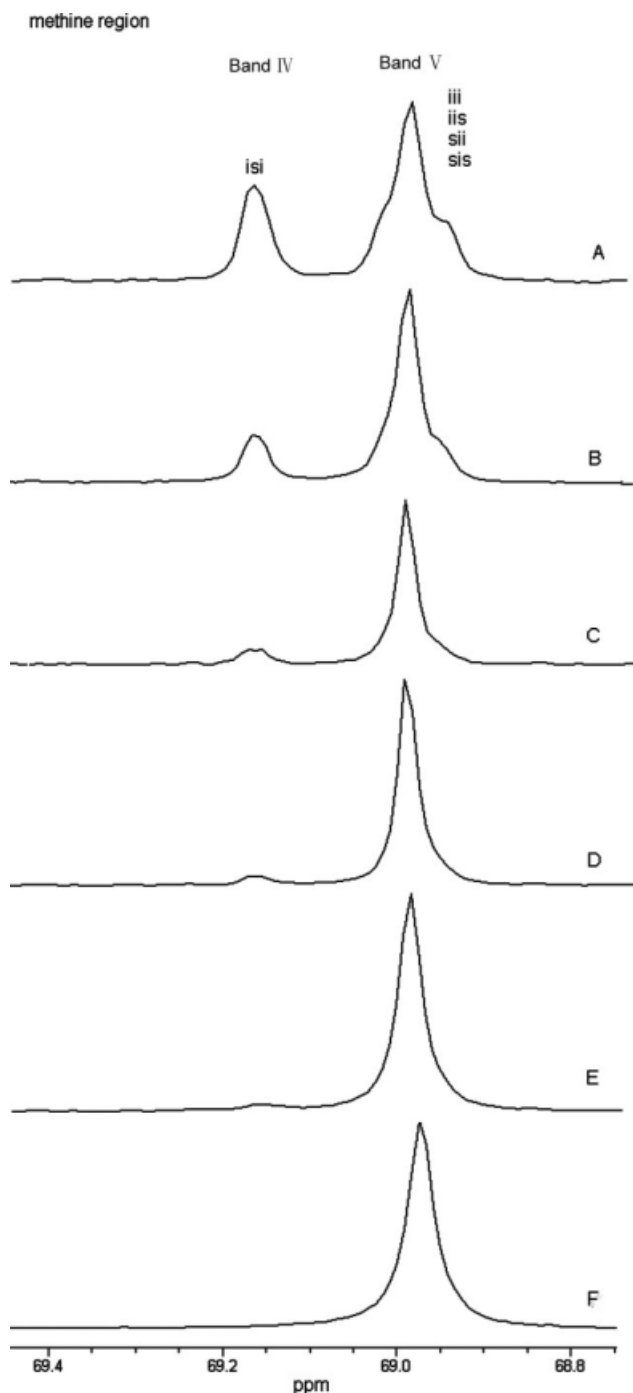


Figure 2 ^{13}C -NMR spectra of the methine resonances of PLA samples A–F (see Table I).

Formation mechanisms of the chain structure

The results presented in this work demonstrate that syndiotactic addition is preferred, and the extent of syndiotactic addition is demonstrated by the calculation of the value of r . Lots of reports have proposed that polymers with different extents of syndiotactic addition can be obtained with diversified catalysts.^{19–27} However, the reasons and formation mechanisms have not been studied in detail.

As illustrated in Scheme 2, two characteristic steps of an insertion mechanism are the reversible association of the L-monomer or D-monomer and the active chain end. First, the electrostatic interaction of an adjacent group can influence the reactivity of the group. As shown in Scheme 2, methyl is an electron-donating group, and hydrogen shows a positive electric field. Therefore, on the basis of the principle of electrostatic interaction, reaction rate k_1 is lower than k_2 for the same electron group at the same position of the polymer chain. Second, a steric effect also changes the reactivity of the group. The D-lactate unit is easily added to the L-lactate unit for the larger occupied space of methyl in comparison with hydrogen. Third, the different reaction rate of depolymerization is another factor for syndiotactic addition. The depolymerization rate of isotactic PLA is quicker than the rate of the atactic structure because the position of the adjacent group in the isotactic structure is beneficial for forming lactides.

In addition, a racemization reaction among lactides and on PLA chains is a frequent occurrence during polymerization. The presence of an equilibrium among L-lactide, meso-lactide, and D-lactide is shown in Scheme 3. Also, the way of racemization in the polymer chains is also proposed in Scheme 3. Obviously, the meso-lactide formed in the process of racemization directly leads to the syndiotactic addition. Taking the electrostatic interaction and steric effects into account, we find that the optically active chain unit with the same adjacent units is prone to changing the optical rotation, and this also leads to the preference for the syndiotactic structure.

The intermolecular transesterification reactions occurring between the polymer chains are shown in Scheme 4. On the basis of the previous conclusions,

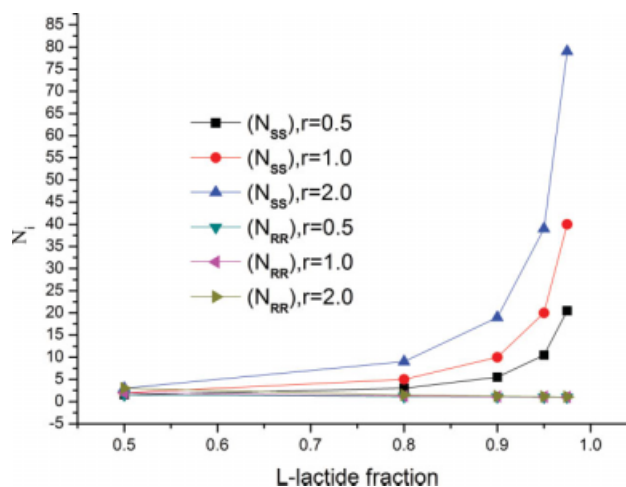
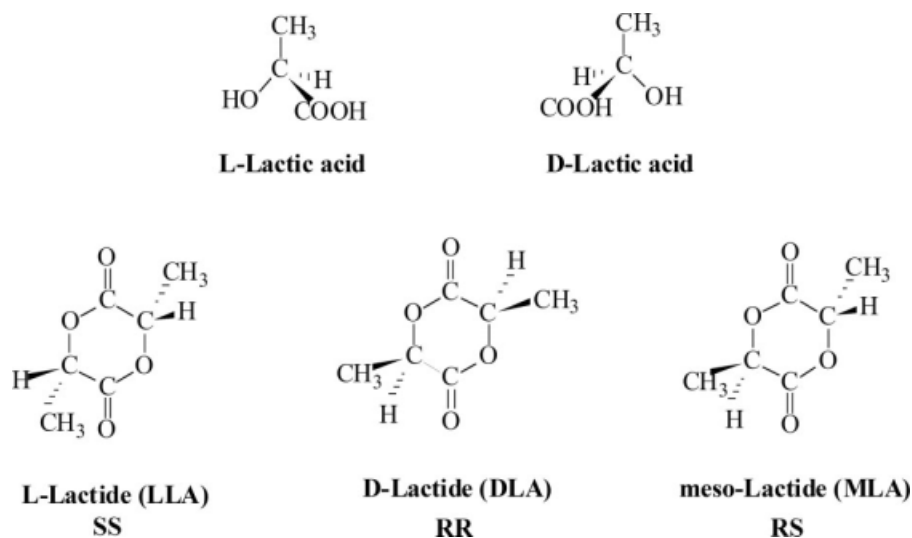


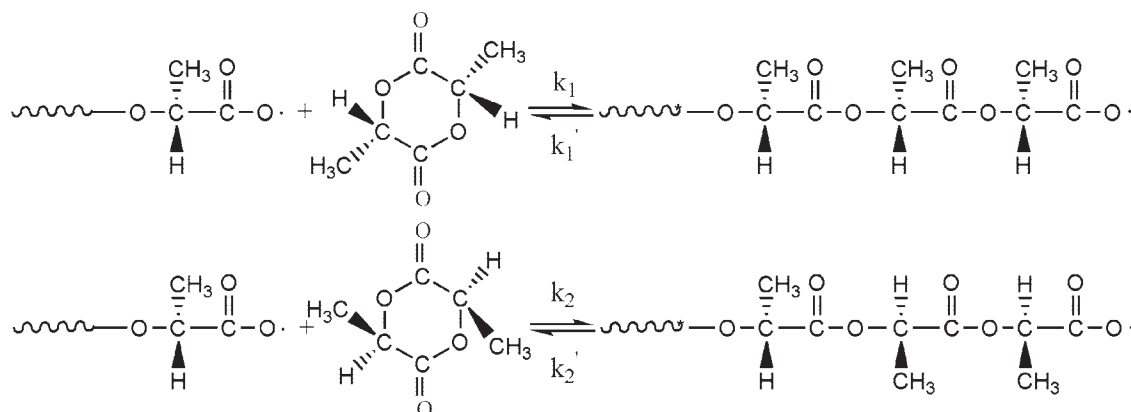
Figure 3 Variation of N_{SS} and N_{RR} with the L-lactide fraction. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]



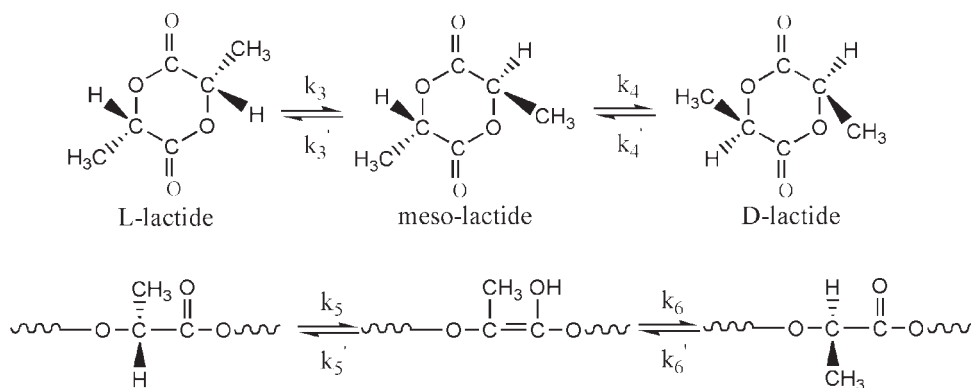
Scheme 1 Stereochemical structures of the lactic acids and lactides.

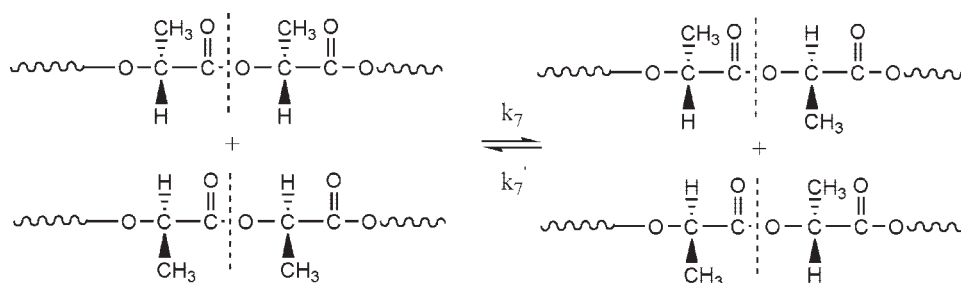
the right polymer chains are relatively stable in comparison with the left polymer structures. Rate constant k_7 is greater than k'_7 , and this leads to the preference for a syndiotactic structure.

Most likely, the catalyst influences the stereostructure of PLA by changing the rate constants of the reversible reactions of the polymerization, racemization, and transesterification.



Scheme 2 Pathways for the polymerization of the polymer.





Scheme 4 Intermolecular transesterification reactions in PLA.

CONCLUSIONS

In this work, the microstructure and the extent of the feed composition, which affect the stereosequence of PLAs, were monitored with ^{13}C -NMR spectroscopy. A preference for syndiotactic addition was observed for the copolymerization of L-lactide and D,L-lactide with stannous octoate as the initiator. Good agreement between the theoretical and experimental relative intensities indicated that the microstructure of the obtained polymers could be described according to the chain-end control mechanism (Markovian statistics). Besides, N_{SS} and N_{RR} were calculated with the distributing function of the chain segments. Lastly, we investigated the mechanism of the preference for syndiotactic addition, and we believe that the electrostatic interaction, steric effect, racemization, and intermolecular transesterification are the possible and potential reasons for the preference for syndiotactic addition.

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