

The Ring-Opening Polymerization of D,L-Lactide Catalyzed by New Complexes of Cu, Zn, Co, and Ni Schiff Base Derived from Salicylidene and L-Aspartic Acid

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ABSTRACT: D,L-lactide (LA) was first successfully ring-opening polymerized in melt by Schiff base complexes $K[ML]_nH_2O$ [$M = Cu(II), Zn(II), Co(II), Ni(II); n = 2, 2, 3, 3.5; H_3L = L$ -aspartic acid-salicylidene Schiff base], which were prepared by Schiff base ligand derived from salicylidene and L-aspartic acid and corresponding acetates. The effects of various complexes, the molar ratio of $K[ML]_nH_2O/LA$, the polymerization temperature, and time were studied in detail. The results show that all complexes studied have the ability to initiate the ring-opening polymerization of D,L-lactide in melt. More than 90% high polymerization conversion and narrow molecular weight distribution (MWD) can be obtained very easily. However, the

Ni(II) complex shows better catalytic property than other complexes on the polymerization and the molecular weight (MW) of poly(D,L-lactide) (PLA) produced. With a rise in temperature and a prolongation of time, the MW of PLA decreased remarkably. The MW of PLA prepared by all complexes is not very high, which might be related to the crystalline water of complexes. X-ray study indicated that PLA produced by Ni(II) complex is an amorphous polymer. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 86: 3312–3315, 2002

Keywords: biodegradable; biomaterials; catalysts; ring-opening polymerization; synthesis

INTRODUCTION

For several decades, poly(D,L-lactide) (PLA) was known as a biocompatible and biodegradable polymer which could be developed to apply in the biomedical field as sutures, screws, prostheses, orthopedics, and controlled drug-release devices. In view of these features, the synthesis of PLA, preparation of D,L-lactide (LA) block copolymer, and possible application for biomedical materials was extensively investigated. Ring-opening polymerization of lactides and glycolides under mild conditions is a favorable method used in biomaterial preparations with different initiators, such as $SnCl_4$, $Sn(Oct)_2$, $Sn(C_6H_5)_4$, zinc lactate, $[(n-C_4H_9O)_2AlO]_2Zn$,^{1–5} and others. We have reported the polymerization of D,L-LA in toluene with high yield and controllable molecular weight (MW) of PLA by rare earth compounds activated by trialkyl aluminum and water,⁶ the preparation of an amorphous PLA by one-component rare earth catalysts.⁷ It was also reported that another type of aluminum alkoxide initiator for the controlled polymerization of lactide was discovered.⁸ More recently, HAPENAlOMe, which is Schiff base derived from 2-hydroxyacetophenone,

proved to be an interesting initiator for the controlled polymerization of D,L-lactide. Spassky et al. showed that the polymerization of D,L-lactide with HAPENAlOMe proceeds by insertion of monomer into the aluminum methoxide bond which is analogous to the polymerization mechanism of lactide by aluminum isopropoxide.^{9–11} We recently found that a series of typical Schiff base complexes without metal alkoxide bond can initiate ring-opening polymerization of D,L-lactide in melt state. More than 90% high conversion and poly(D,L-lactide) (PLA) with narrow MW distribution were obtained easily. Here, we preliminarily report the features of ring-opening polymerization of D,L-lactide by Schiff base complexes and morphology study by X-ray.

EXPERIMENTAL

Materials

D,L-LA was prepared from lactic acid (obtained from Shuangling Chemical Factory, China) according to the procedure described by Kulkarni et al.¹²

Preparation

The preparation of ligand compound $K_2[HL]1.5H_2O$, $L = H_8C_{11}NO_5$, and complexes were carried out by the methods as described in literature.¹³

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TABLE I
Data of Elemental Analysis (data in parentheses are calculated values) and Molar Conductance of the Complexes

Compound	Data of elemental analysis (%)				Λ_m (S cm ² /mol)
	C	H	N	M	
K[CuL]2H ₂ O	35.74 (35.39)	3.15 (3.24)	3.69 (3.75)	16.94 (17.02)	90
K[ZnL]2H ₂ O	34.98 (35.22)	2.81 (3.22)	3.46 (3.73)	17.66 (17.43)	87
K[CoL]3H ₂ O	34.44 (34.16)	3.17 (3.65)	3.77 (3.62)	15.34 (15.23)	80
K[NiL]7/2H ₂ O	33.02 (32.74)	3.30 (3.82)	3.63 (3.54)	14.54 (14.84)	109

Polymerization procedure

The polymerization was performed in a 25-mL ampoule, which was heated, evacuated, and filled with purified argon for several cycles before use. After the addition of D,L-LA and catalyst and after flushing with purified argon, ampoules were sealed and then placed in an air heat bath at constant temperature. After the desired time of polymerization, acetone was introduced into the ampoule. PLA was dissolved in acetone and precipitated by petroleum ether containing 5% hydrochloric acid and washed with petroleum ether several times. PLA obtained was dried at 50°C under vacuum.

Measurements

C, H, and N analysis of ligand and complexes was carried out on a Carlo-Erba analyzer. The metal contents of complexes were measured by EDTA. Molar conductance of complexes was determined at room temperature in 10⁻³ mol L⁻¹ CH₃OH solution with a DDS-II conductometer.

The intrinsic viscosity of PLA in tetrahydrofuran (THF) was determined by an Ubbelohde viscometer at 37°C. The viscosity-average molecular weight (\bar{M}_η) was calculated according to the equation¹⁴:

$$[\eta] = 1.04 \times 10^{-4} \bar{M}_\eta^{0.75} \text{ (dL/g)}$$

The molecular weight distribution (MWD) of the PLA was determined with a Waters Associates Model 208 gel permeation chromatograph with THF as eluant at 37°C. X-ray diffraction study was carried out with a model Y-4 X-ray diffractometer; scanning scale, 3–50°; scanning speed, 4°/min; step, 0.02°.

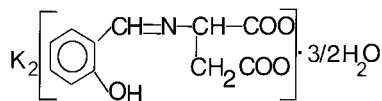


Figure 1 Molecular structure of the ligand.

RESULTS AND DISCUSSION

Synthesis and characterization of ligand and complexes

The ligand compound K₂[HL]·1.5H₂O, L = H₈C₁₁NO₅ was synthesized from L-aspartic acid and alkaline in absolute methanol.

ELEMENTAL ANAL. calcd: C, 38.88; H, 3.26; N, 4.12. Found: C, 39.02; H, 3.11; N, 3.96. It has a molar conductance value of 161 Ω⁻¹ cm² mol⁻¹, which suggests that this compound is a 2 : 1 electrolyte in absolute methanol.¹⁵

The complexes were synthesized from M(CH₃COO)₂·1–4H₂O and ligand compound was prepared in absolute methanol. The results of elemental analysis and molar conductance values of complexes are shown in Table I, which indicated that all complexes have the general formula K[ML]·nH₂O, where M = copper(II), zinc(II), cobalt(II), and nickel(II), n = 2, 2, 3, 3.5. The complexes are a 1 : 1 electrolyte in absolute methanol. The molecular structure of ligand and complexes are shown in Figures 1 and 2.

Polymerization of D,L-lactide

Melt polymerization of D,L-lactide by various complexes

All complexes cannot initiate D,L-lactide to polymerize in some solutions because of their insolubility in common solvents, such as toluene, chloroform, and others. However, they are soluble in the melt state of D,L-lactide to form a homogenous polymerization system. By using all complexes as catalysts for the polymerization of D,L-lactide in melt, it is found that all polymerization conversions easily reached more than 90% (see Table II).

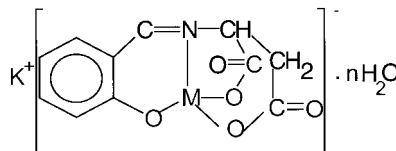


Figure 2 The structure of the complexes (M = Cu, Zn, Co, Ni; n = 2, 2, 3, 3.5).

TABLE II
Polymerization of D,L-Lactide with Various Amino Acid Schiff Base Transition Metal Complexes

Complex	Conversion (%)	$\bar{M}_n (\times 10^{-3})$
K[CuL]2H ₂ O	97	4.86
K[ZnL]2H ₂ O	97	5.23
K[CoL]3H ₂ O	96	5.16
K[NiL]3.5H ₂ O	99	11.1

Condition: [CAT]/[LA] = 1:200, 130°C, 24 h.

From Table II, in comparison to all complexes listed, it can also be seen that K[NiL] 3.5H₂O is the best catalyst for D,L-lactide polymerization in melt, because both the polymerization conversion and the MW of PLA are higher than others. The MW of PLA in Table II is somewhat lower than the PLA produced by *Mt*(AcAc)₂ (*Mt* = Zn, Co, Ni),¹⁶ and it may be related to the crystalline water contained in the complexes.

Effect of K[NiL] 3.5H₂O/LA molar ratio on the melt polymerization of D,L-lactide

The effect of K[NiL] 3.5H₂O/LA molar ratio on the melt polymerization of D,L-lactide is shown in Figure 3. It shows the increase in both polymerization conversion and MW of PLA with a rise in the K[NiL] 3.5H₂O/LA molar ratio, which are similar to the polymerization of D,L-lactide by *Mt*(AcAc)₂ (*Mt* = Zn, Co, Ni).¹⁶ If the K[NiL] 3.5H₂O/LA molar ratio is >0.002, the increase in K[NiL] 3.5H₂O/LA molar ratio does not obviously influence the polymerization conversions, which reach nearly 100%. However, the MW of PLA rises linearly with an increase in K[NiL] 3.5H₂O/LA molar ratio; it may be attributed to some catalyst in resumption elimination of impurities existing in the polymerization

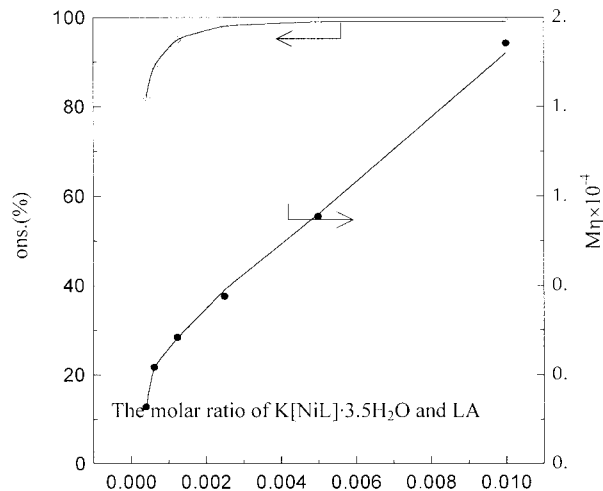


Figure 3 The effect of K[NiL] 3.5H₂O/LA on the polymerization of D,L-lactide. Condition: 130°C, 24 h.

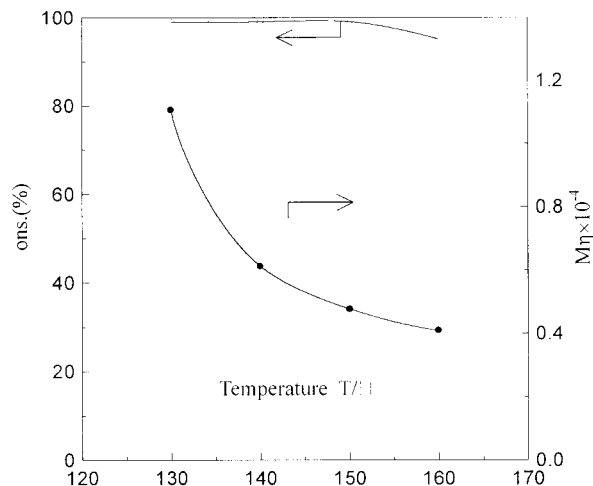


Figure 4 The effect of temperature on the polymerization of D,L-lactide. Condition: [CAT]/[LA] = 1:200, 24 h.

system, which might act as chain transfer agents in the polymerization process.

Effect of temperature on the melt polymerization of D,L-lactide

As is known from the characteristics of kinetics and thermodynamics of melt polymerization, higher temperature is favorable to reasonable polymerization rates.¹⁷

Figure 4 is indicated as the dependence of polymerization on temperature. It indicates that quite high polymerization conversion is convenient to reach at the temperature in the range of 130 to 160°C. This result is almost identical with bulk polymerization of D,L-lactide catalyzed by tin-ethylhexanoate¹⁸ or by one component of rare earth catalyst.⁷ However, the MW of PLA drops remarkably with rising temperature, caused by some side reactions, such as chain degradation or transesterification.⁹

Effect of time on the melt polymerization of D,L-lactide

The dependence of polymerization on time is indicated in Figure 5. Both polymerization conversion and MW of PLA increase within 12 h, suggesting a slow initiation and long-lifetime active species analogous to bulk polymerization of D,L-lactide by another catalyst system. Although polymerization conversion increases gradually with further prolongation of time, but the MW of PLA decreases obviously, a long amount of time at a high temperature is an important factor, leading to the degradation of PLA; as is known, PLA is an easily degradable polymer material. This phenomenon is in accordance with PLA produced by *Mt*(AcAc)₂ (*Mt* = Zn, Co, Ni)¹⁶ and one-component

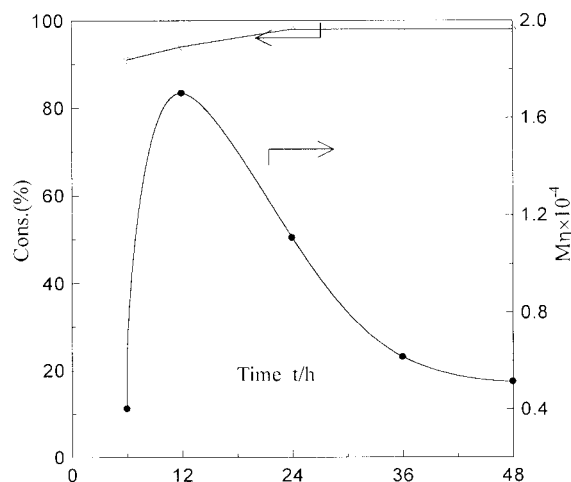


Figure 5 The effect of time on the polymerization of D,L-lactide.

rare earth catalysts.⁷ On the other hand, it might arise from transesterification reaction.⁹

Further study on the MWD of PLA (produced under LA/cat = 200, 130°C for 12 or 48 h) with GPC showed that the MWD of PLA produced under LA/cat = 200, 130°C 12 h is 1.35, which is narrower than the MWD of PLA produced, the value of which is 1.49, under LA/cat = 200, 130°C 48 h. It is also quite in agreement with the effect of time on the polymerization of LA, namely, longer times at high temperatures will cause degradation of PLA.

In the study of X-ray diffraction of PLA (produced under LA/cat = 200, 130°C, 12 h), no sharp peaks were observed, and it is indicated that PLA is an amorphous polymer. This result is consistent with our previous research.^{7,16}

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