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Basic Properties of Polylactic Acid Produced by the Direct Condensation Polymerization of Lactic Acid

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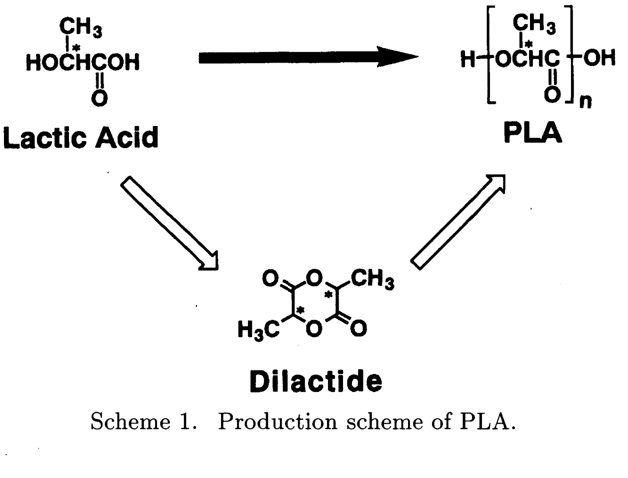
The direct condensation polymerization of lactic acid has been studied, and polylactic acid having a high molecular weight was obtained in an organic solvent without any isolation of the intermediate, dilactide. The molecular weight was raised up to 300000 through the examination of several reaction conditions, e.g., solvent, catalyst, etc. Thus-obtained high-molecular-weight polylactic acid can be processed into films and molded products having sufficient strength and toughness. The characteristic features of polylactic acid obtained by this direct process were compared to that obtained by the conventional ring-opening polymerization process. In addition, copolymerization of lactic acid with a variety of D/L ratios is discussed.

Polylactic acid (PLA) has been known since the 1920's as a polyester for fibers. It has been used as resorbable materials in medical practice. PLA has been currently recognized as a suitable material for packaging and consumer goods, due to its several preferable properties, such as mechanical strength, transparency, safety, and degradability in compost. Especially, the biodegradable feature has received much attention from the environmental viewpoint.

PLA has been produced by a multi-step process, including the isolation of an intermediate dilactide (a cyclic dimer of lactic acid) followed by a ring-opening polymerization (Scheme 1).[1—5] After the intense trial by many chemists,[6,7] the direct condensation of lactic acid (also shown in Scheme 1) is commonly known as a process unable to obtain a high-molecular-weight polymer having useful properties; an equilibrium between free acids, water, and polyesters[8] along with the formation of dilactide, was explained to prevent the desired reaction to get a sufficiently high-molecular weight polymer.[6,9]



Scheme 1. Production scheme of PLA.

In order to develop a feasible process for the commercial production of PLA and its application to some other aliphatic polyesters, we started to study the direct condensation polymerization of lactic acid.

The breakthrough for a direct process may be attributed to overcome the following three subjects:

(1) Kinetic Control
(2) Efficient Removal of Water
(3) Suppression of Depolymerization.

In order to approach to the desired process for a high-molecular-weight polylactic acid, we concentrated on testing a variety of catalysts, solvents, and reaction temperature. In this paper, we report the synthesis method of high-molecular-weight polylactic acid by direct polymerization, and the basic properties of the polymer.

Copolymers of lactic acid having random D/L unit can be uniquely synthesized by the direct polymerization, while copolymers of dilactide having the mixture of tandem unit from D-dilactide and L-dilactide are obtained by the conventional ring-opening polymerization. The properties and characteristics of these two types of copolymers are discussed. PLA and copolymers from this direct method shows considerable potential for medical and industrial application.

Results and Discussion

Polymerization. Polymerization conditions of lactic acid in various kinds of solvents are shown in Fig. 1. The reaction temperature was kept at 130 °C under a reflux condition. The relationship between the boiling point of the solvent and the polymerization rate during an early stage of the reaction is shown in Fig. 1. The rate of polymerization is proportional to the boiling point of the solvents. It was assumed that removal of water was efficiently achieved by using a high boiling-point solvent under a high vacuum at a relatively low temperature.

A lot of catalysts such as protonic acids, metals, metal-oxides, metal-halides, and organic acid salts of metals were examined. The molecular weights of polymers obtained by using various catalyst are summarized in Table 1. Tin compounds and protonic acids were found to be a superior catalyst obtaining high-molecular-weight polymers at relatively low temperature (130 °C). In the case of zinc compounds and transition-metal compounds, the molecular weights between 10000 and 150000 were achieved at 160 °C. However high-molecular-weight polymers were not obtained by using the other catalysts even at 160 °C.

A flow diagram of the direct process is shown in Fig. 2. In this process, polymerization of lactic acid is carried out in a solvent with a catalyst. Water generates as the polymerization proceeds, and a removal of the water from the reaction mixture under mild conditions should be a key to get a high-molecular-weight polymer. In the presence of a solvent, a small amount of water remaining in the reaction mixture can be removed azeotropically under high vacuum at a relatively low temperature. In this system, the solvent is then returned to the reaction mixture after drying.

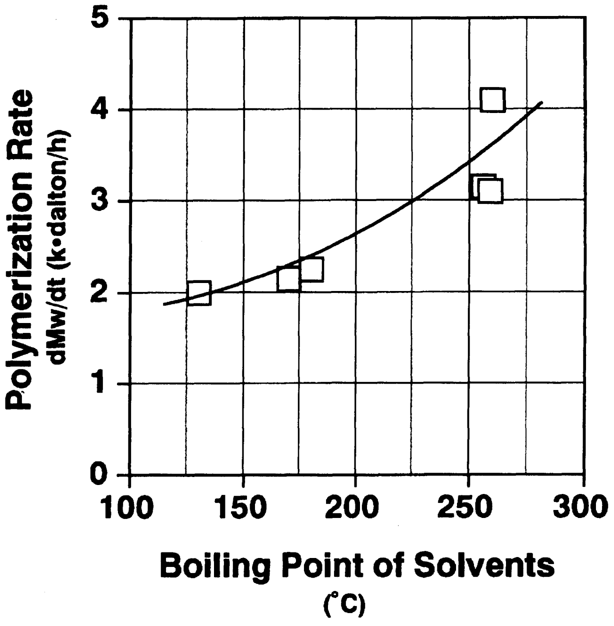


Fig. 1. Effect of boiling point of solvent to polymerization rate in condensation polymerization of lactic acid. Reaction temperature: 130 °C, concentration of polymer: 25 wt%, amount of catalyst: 0.5 wt%/PLA.

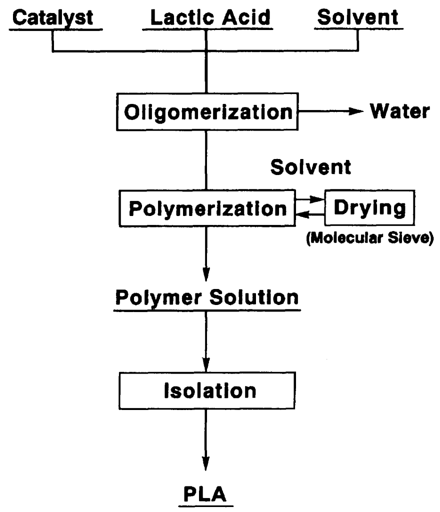


Fig. 2. Flow diagram of the direct process.

Under the optimized condition, polylactic acid having a molecular weight higher than 300000 was obtained.

Poly (L-lactic acid). The basic properties and structures of PLA obtained by the direct condensation polymerization of L-lactic acid (poly(L-lactic acid)) were studied by using spectrometric methods, and then compared to those of PLA obtained by the ring-opening polymerization of dilactide(poly(L-dilactide)). A GPC curve of poly(L-lactic acid) is shown in Fig. 3(a). Two peaks were observed in this distribution curve. The component of low-molecular-weight region was separated as a solid powder by fractional precipitation method (chloroform and methanol as solvents). The GPC peak of the isolated powder is also shown in

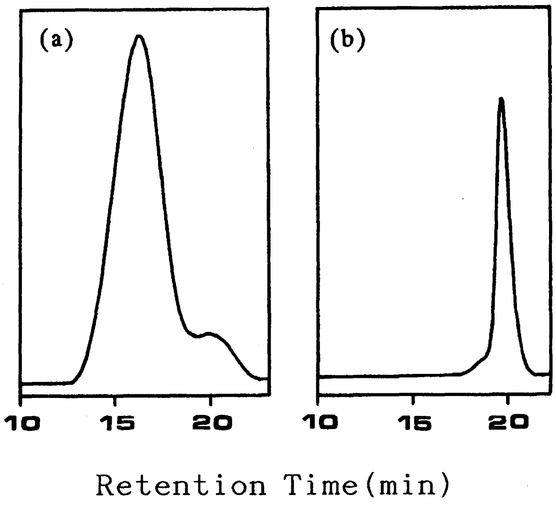


Fig. 3. GPC chart of (a): poly (L-lactic acid) and (b): isolated low molecular weight component.

Table 1. Polymerization of L-Lactic Acid

Catalyst	Cat./PLA wt%	Temp[a] °C	M_W
H_3PO_4	2.5	160	1300
H_2SO_4	2.5	130	65000
CH_3SO_3H	2.5	130	20000
CH_3-⌬-SO_3H	2.5	130	100000
Nafion-H®[b]	2.0	160	4000
Mg	0.5	160	2100
Al	0.5	160	5400
Ti	0.5	160	1400
Zn	0.5	160	35000
Sn	0.5	130	240000
TiO_2	0.83	160	1600
ZnO	0.62	160	20000
GeO_2	0.72	160	1300
ZrO_2	0.68	160	1500
SnO	0.57	130	230000
SnO_2	1.26	160	1000
Sb_2O_3	0.60	160	39000
$ZnCl_2$	1.04	160	18000
$SnCl_2$	0.80	130	230000
$SnCl_4$	1.10	130	29000
$Mn(AcO)_2$	1.57	160	19000
$Fe_2(LA)_3$	1.70	160	27000
$Co(AcO)_2$	1.50	160	32000
$Ni(AcO)_2$	1.51	160	140000
$Cu(OA)_2$	2.75	160	1900
$Zn(LA)_2$	1.86	160	20000
$Y(OA)_3$	2.92	160	20000
$Al(i\text{-}PrO)_3$	3.79	160	1500
$Ti(BuO)_4$	3.55	130	8000
$TiO(acac)_2$[c]	2.74	130	7000
$(Bu)_2SnO$	1.05	130	13000

a) The reactions were carried out at 130 °C for 24 h in diphenyl ether, and if the molecular weights were less than 5000 at this stage, the reactions were continued another 16 h at 160 °C. b) Nafion-H®: Perfluorinated resinsulfonic acid (registered trademark of the Dupont Company). c) acac: acetylacetonato anion.

Fig. 3(b). This powder exhibited peaks having an order of 72×*n* in mass number (Fig. 4(a)). This 72×*n* suggests the polymer has no polymer-chain-ends (72 corresponds to the repeating unit of PLA). On the other hand, peaks having an order of 72×*n*+18 in mass number were observed in the spectrum of the linear oligomer independently prepared by dehydration of L-lactic acid (Fig. 4(b)). These results indicate that the low-molecular-weight component should be a cyclic oligemer of L-lactic acid.

The properties of poly(L-lactic acid) and poly(L-dilactide) are summarized in Table 2. The glass transition temperatures (T_gs) of these polymers show almost same value, however, the value of melting point of poly(L-lactic acid) (T_m=163 °C) is lower than that of poly(L-dilactide) (T_m=178 °C).

Mechanical properties (tensile strength and ultimate elongation) of poly(L-lactic acid) and poly(L-dilactide) having various molecular weights are shown in Fig. 5. PLA having high molecular weight (M_W > 100000) is easily processed to commercially applicable products, such as cups and bottles. The melt-flow rates of poly (L-lactic acid) having various molecular weights are shown in Fig. 6. Injection-molded articles are produced from polymers (M_w=100000—150000) having a melt flow rate of about 10—20 g min^{-1}.

Copolymers of D-Lactic Acid and L-Lactic Acid. Copolymers of D-lactic acid and L-lactic acid with various isomer ratios were synthesized by the direct method. The molecular weights, glass transition temperatures (T_gs) and melting points (T_ms) are summarized in Table 3. T_gs of these polymers show almost the same value when the molecular weights of the copolymers are higher than 100000, and the T_g values of the copolymers are decreasing according to the increase of D-lactic acid content. We also prepared copolymers of D-dilactide and L-dilactide (poly(D-dilactide-co-L-dilactide)) by the ring-opening polymerization. It is very interesting to note that the T_gs of polylactic acid are lower than those of dilactide. The differences of T_g values are increasing according to the increase of D-lactic acid content. These differences are assumed to come from a difference in the polymer sequence (Scheme 2).

Figure 7(a) shows the carbonyl signals of a copoly-

Table 2. Properties of PLA

Property	Unit	PLA (Direct Process) M_W=140000	PLA (Lactide Process) M_W=140000
T_g	°C	58	59
T_m	°C	163	178
Tensile strength	kgf cm^{-2}	630	620
Ultimate elongation	%	6	7
Izod impact strength notched	kgf cm cm^{-2}	2	2
Rockwell hardness	(R)	119	119
Vicat softening point under load, 1 kg	°C (annealed)	63 (150)	62 (164)
Melt flow rate (E method : 190 °C)	g/10 min	10	10

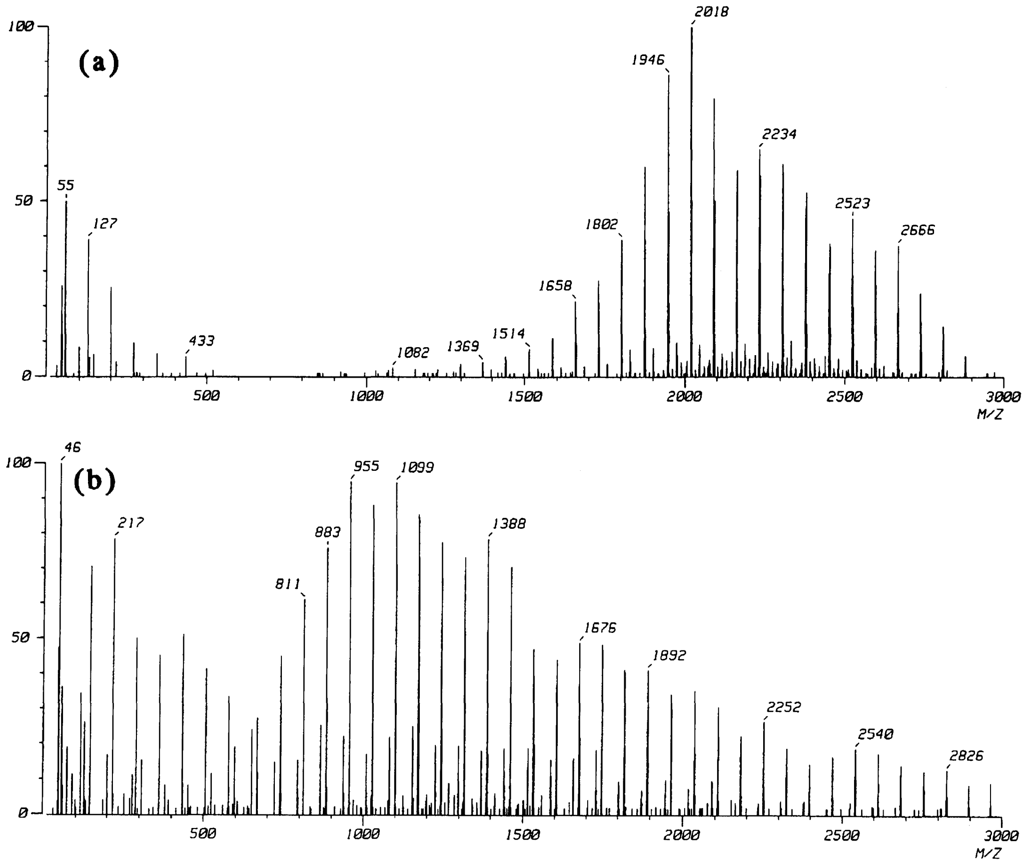


Fig. 4. Mass spectra of (a): isolated low molecular weight component of poly(L-lactic acid) and (b): oligomer obtained by dehydration of L-lactic acid.

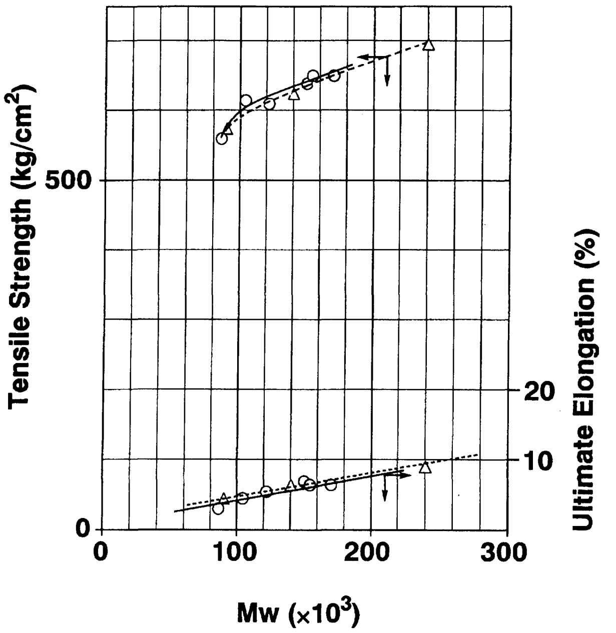


Fig. 5. Tensile strength and Ultimate elongation of polylactic acid (—○—) and polydilactide (--▲--) with different molecular weight.

mer which was prepared by the direct condensation of a mixture of L-lactic acid and D-lactic acid with a L/D isomer ratio of 90/10. Copolymer was also synthesized

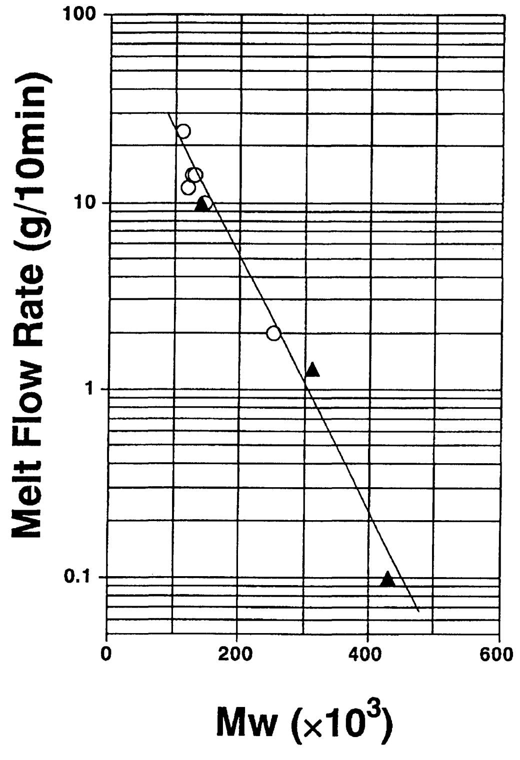


Fig. 6. Melt flow rate of polylactic acid (○) and polydilactide (▲) with different molecular weight.

by the ring-opening polymerization of L-dilactide and D-dilactide (L/D isomer ratio of 90/10), whose carbonyl signals are shown in Fig. 7(b). ^{13}C NMR spectra of copolymers of D-dilactide and L-dilactide was studied by F. Chabot and M. Vert[10)] and the fine structures in carbonyl carbon region was discussed. The copoly(dilactide) obtained in our study has signals at 169.36, 169.40, 169.45, and 169.66 ppm. The pattern of these signals is identical to that shown in their report.

On the other hand, the copolylactic acid obtained by the direct method has five characteristic signals at 169.27, 169.31, 169.42, 169.49, and 169.66 ppm. According to the theoretical stereosequence distributions, the signal at 169.66 ppm can be assigned to the carbonyl carbon atom of successive L-lactic acid units due to large intensities. The other four small signals at 169.27, 169.31, 169.42, and 169.49 can be assigned to carbonyl carbons influenced by D-lactic acid units in the polymer sequence. The differences in the pattern of these signals are attributed to the differences in the polymer sequence. In the direct polymerization, L-lactic acid and D-lactic acid are seemed to be introduced into the polymer at random, while in the ring-opening polymerization, they are introduced in pairs (Scheme 2).

Conclusions

The novel direct polymerization method was established for the first time accessing to the higher-molecular-weight PLA. The PLA has sufficient mechanical properties for the production of practically usable products. In addition, this method includes the synthesis of new copolymers having random sequence of D-lactic acid and L-lactic acid which have never been obtained by the conventional lactide process. Due to its easy approach to the commercial production and the excellent biodegradable feature of the PLA, our direct polymerization method may open the door for the new market.

Experimental

General. The molecular weights were obtained by gel permeation chromatography (GPC) on a Shodex GPC SYSTEM-11 (Showa Denco). Two columns (Shodex GPC K-805L: 300 mm×8 mm) were placed in series and were operated at a flow rate of 1 ml min^{-1} in chloroform at 40 °C. The molecular weights were calculated relative to polystyrene standards without a further calibration. The ^{13}C NMR spectra were obtained on a JEOL EX-400 100 MHz spectrometer using chloroform-d_1 as a solvent and tetramethylsilane as an internal reference. The mass spectra were recorded on a JEOL JMS-SX102 mass spectrometer by a field-desorption method. The glass transition temperature (T_g) and the melting points (T_m) were measured with a differential scanning calorimeter (Shimadzu DSC-50). The standard heating rate for all of the polymers was 10 K min^{-1}. Tensile measurements were made using an Orientec Tensilon UCT-1T 1122 at room temperature according to an ASTM D638. The tensile strength and tensile modulus as well as the elongation at the yield and break were determined under ambient conditions. In all cases, the tensile values were calculated from the arithmetic average of at least four measurements, obtained from four separate specimens per polymer sample. The melt flow rates were determined on a Toyo Seiki melt indexer. For compression molding a Shinto Kinzoku press equipped with heated platens with thermostats was used. Polymers were placed in a stainless-steel mold and heated to the required temperatures. A pressure of 1—2×10^3 kg was then applied for 5 min.

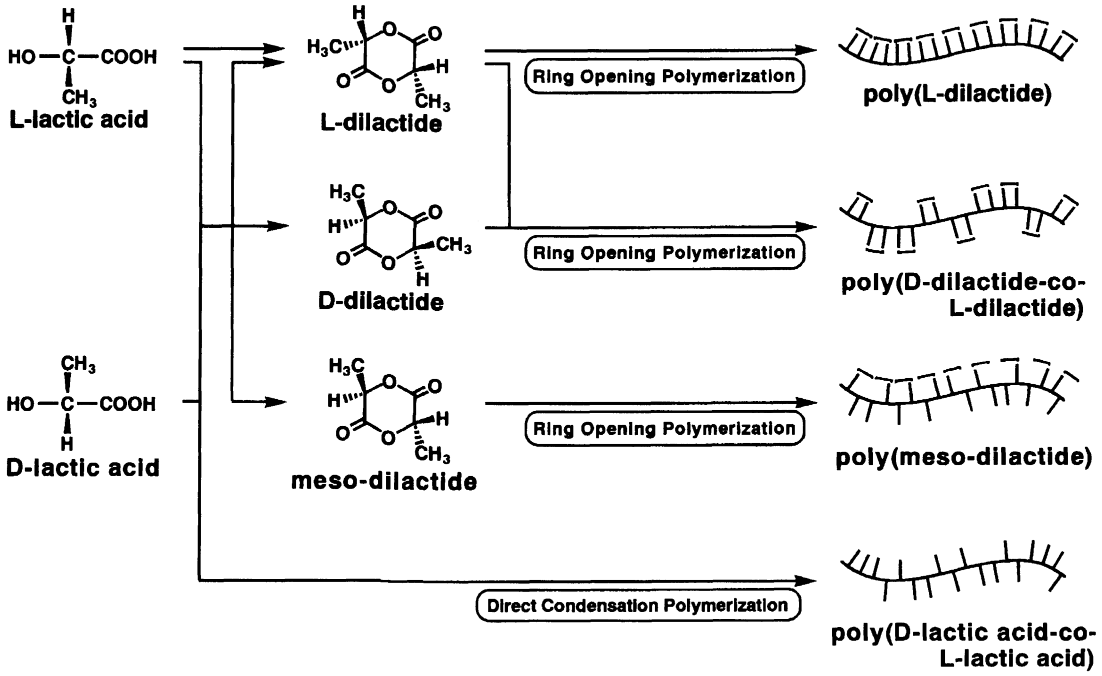
Table 3. Copolymers of L-Lactic Acid (L-LA) and D-Lactic Acid (D-LA)

L-LA/D-LA	Method	M_W	T_g / °C	T_m / °C	
100/0	DC[a)]	22000	53	154	160
		63000	57	162	
		94000	56	159	
		124000	58	162	
		140000	58	162	
		183000	56	162	
		250000	58	163	
	RO[b)]	140000	58	178	
		310000	59	178	
		430000	59	179	
90/10	DC	60000	53	—	
		81000	55	—	
		127000	54	—	
	RO	92000	55	—	
		227000	56	—	
80/20	DC	51000	50	—	
		53000	49	—	
		74000	51	—	
		183000	52	—	
		241000	52	—	
	RO	236000	54	—	
70/30	DC	54000	47	—	
		106000	48	—	
		125000	52	—	
	RO	266000	53	—	
50/50	DC	185000	49	—	
		366000	48	—	
	RO	187000	52	—	

a) DC: Direct condensation polymerization. b) RO: Ring opening polymerization.

Heat-stable grade L-lactic acid was purchased as a 90 wt% aqueous solution from Purac Co. Aqueous 90% solution of DL-lactic acid was purchased from Wako Pure Chemical Industries. L-lactide and DL-dilactide were purchased from Boehringer Ingerhime. All of the solvents were obtained from commercial sources and were dried over molecular sieves (3A) prior to use. The molecular sieves were purchased from Merck and dried at 350 °C before use.

General Procedure for the Synthesis of Polylactic Acid (Direct Process). Using a reaction vessel equipped with a Dean Stark trap, 40.2 g of 90% L-lactic acid was azeotropically dehydrated in 400 ml of organic solvent for 2 h at 140 °C in the presence of 0.14 g of tin powder.



Scheme 2. Polymerization scheme of copolymers from L-lactic acid and D-lactic acid.

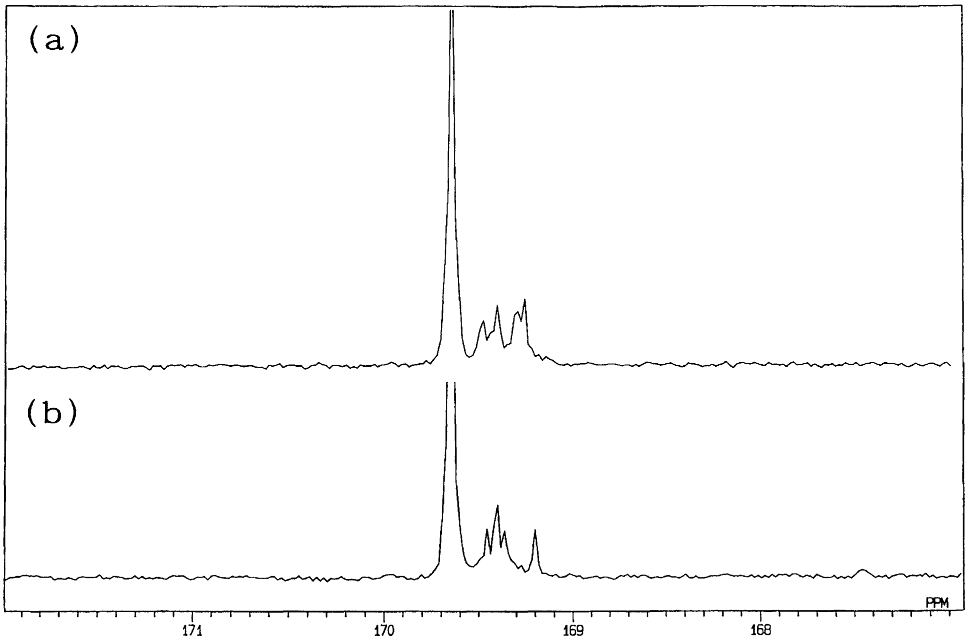


Fig. 7. ^{13}C NMR spectra of (a): poly(D-lactic acid-co-L-lactic acid) and (b): poly(D-dilactide-co-L-dilactide) with 10% D-lactic acid content.

After removing water in a Dean Stark trap, a tube packed with 40 g of molecular sieve (3A) was mounted on the reactor in place of the Dean Stark trap so as to recycle the distilled solvent through the molecular sieve to the reactor. Azeotripic dehydration was carried out for 20 to 40 h at 130 °C. The water content of the solvent was 3 ppm or less after passing through the molecular sieve. After the reaction mixture was concentrated to about half volume, 300 ml of chloroform was successively added. The catalyst was removed by filtration or extraction, and the resulting mixture was poured into 900 ml of methanol. Precipitated crystals were collected by suction filtration, washed with methanol and dried under reduced pressure. The molecular weights, glass transition temperatures and melting points are listed in Table 3.

Synthesis of Cyclic Oligomer of L-Lactic Acid. First, 10.0 kg of 90% aqueous solution of L-lactic acid was azeotropically dehydrated in 81.1 kg of diphenyl ether for 2 h at 150 °C in the presence of 6.2 g of tin powder. Then, after removing water, a column packed with 4.6 kg molecular sieve (3A) was mounted on the reactor so as to recycle the distilled solvent through the molecular sieve to the reactor. Azeotropic dehydration was carried out for 40 h at 130 °C and a reaction mixture containing polylactic acid with a molecular weight of 60000 was obtained. The reaction mixture was concentrated to about 70 kg and cooled to 40 °C. The precipitated crystals were filtered off and the filtrate was concentrated to 5.8 kg. Then, 11.6 kg of hexane was added to the filtrate and the oil separated was dissolved in 5.8 kg of acetonitrile and 1 M hydrochloric acid (1 M=1 $\mathrm{mol\,dm^{-3}}$) was added. After stirring for 0.5 h, an oily product was separated and washed with 5.8 kg water. After the oily product was dissolved in 2.9 kg of chloroform, the solution was poured into 50 l of isopropyl alcohol. Precipitated crystals were collected by suction filtration, washed with isopropyl alcohol and dried under reduced pressure. A white powder was thus obtained in an amount of 350 g. Found: C, 50.72; H, 5.79%. Calcd for $(C_3H_4O_2)_n$: C, 50.00; H, 5.60%.

Synthesis of Linear Oligomer of L-Lactic Acid. One kilogram of 90% aqueous solution of L-lactic acid was dehydrated for 3 h at 150 °C under reduced pressure of 50 mmHg (1 mmHg=133.322 Pa), and was dehydrated for 6 h in the presence of 0.6 g of tin powder under a pressure of 30 mmHg. After the mixture was dissolved in 4.5 kg of acetonitrile, insoluble materials were filtered off and 1 M hydrochloric acid was added to the filtrate. After starring for 0.5 h, an oily product was separated and washed with 4.5 kg of water. The oily product was dissolved in 2.3 kg of chloroform and the solution was poured into 4 l of isopropyl alcohol. The precipitated crystals were collected by suction filtration, washed with isopropyl alcohol and dried under reduced pressure. A white powder was thus obtained in an amount of 405 g.

General Procedure for the Synthesis of Polydilactide (Lactide Process). In a thick-walled cylindrical stainless-steel polymerization vessel equipped with a stirrer, 216 g (1.5 mol) of L-dilactide, 0.01% by weight of tin(II) octonoate and 0.03% by weight of 1-dodecanol were sealed. The polymerization vessel was deaerated under vacuum for 2 h and replaced by nitrogen gas. The mixture was heated with stirring at 200 °C for 3 h under a nitrogen atmosphere. While maintaining the mixture at the same temperature, the polymerization vessel was gradually evacuated to a reduced pressure of 3 mmHg through an exhaust tube and glass receiver with a vacuum pump. One hour after starting the evacuation, the distillation of monomers and low-molecular-weight volatiles ceased. The vessel was filled with nitrogen and the polymer was discharged from the bottom of the vessel in the form of a strand. This strand was pelletized to obtain while poly(L-dilactide) in a yield of 96%. The polymer had an average molecular weight of 140000. The glass transition temperature and melting point were measured, and are listed in Table 2.

Synthesis of Poly(D-lactic acid-co-L-lactic acid). Copolymers of L-lactic acid and D-lactic acid (poly(D-lactic acid-co-L-lactic acid) were prepared by the methods described in the general procedure for the synthesis of polylactic acid using L-lactic acid and DL-lactic acid as a starting material instead of L-lactic acid. The molecular weights, glass transition temperatures, and melting points were measured, and are summarized in Table 3.

Synthesis of Poly(D-dilactide-co-L-dilactide). Copolymers of L-dilactide and D-dilactide (poly (D-dilactide-co-D-dilactide) were prepared by the methods described in the general procedure for the synthesis of polydilactide using L-dilactide and DL-dilactide as the starting material instead of L-dilactide. The molecular weights, glass transition temperatures, and melting points were measured, and are summarized in Table 3.

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