An Onium Salt-catalyzed Direct Polycondensation of Lactic Acid

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Poly(L-lactic acid) of $M_w \approx 160000$ (PDI = 1.6) was produced by direct polycondensation of water-containing lactic acid using triphenylphosphonium triflate as a catalyst.

Poly(lactic acid) (PLLA) has attracted keen attention as one of the promising bio-base polymers. The monomer of PLLA, L-lactic acid, can be produced from corn or other plants, so even after combustion of the wasted PLLA, CO_2 emission can be counted as zero. PLLA is usually produced by the ring-opening polymerization method using tin(II) 2-ethylhexanoate as a catalyst.[1] Although the ring-opening polymerization method affords high molecular weight PLLA, this inherently uses purified L,L-lactide (dimer of L-lactic acid) as a starting monomer, which requires steps from readily available L-lactic acid.

The direct polycondensation method has advantages over the ring-opening polymerization, because in addition to the ready availability of the starting monomer, at the initial stage of the polymerization rigorous anhydrous conditions are not essential to ensure high degree of polymerization, which are critical for the latter. Direct polycondensation of lactic acid, however, has been less studied.[2–7] Previous efforts to find catalyst for direct polycondensation were hampered by the low activity of the catalysts and racemization of the resulting polymer. Although tin compounds, such as Sn metal or $SnCl_2$,[2] and distannoxane derivative,[6] were reported to be very reactive for direct polycondensation, other metal catalysts afforded PLLA with low molecular weight,[4,6,7] and sulfonic acids[2] requires relatively high catalyst loadings to ensure high molecular weight ($M_w \approx 100000$).[8] Combined use of $SnCl_2$ and *p*-toluenesulfonic acid (*p*-TSA) (1:1) in the melt polycondensation led to PLLA of high molecular weight ($M_w \approx 500000$) after solid-state polymerization.[5]

Recently, Tanabe et al. developed pentafluorophenylammonium triflate (PFPAT **1**) and diphenylammonium triflate (DPAT **2**) as Brønsted acid catalysts for condensation of a carboxylic acid and an alcohol to esters.[9] These acid catalysts are characterized as onium salts of weak base and super acid, and tolerate water generated during condensation. Soon after these, DPAT was reported to be a good catalyst for ring-opening polymerization of lactide or ε-caprolactone.[10] We have investigated direct polycondensation of lactic acid using onium salt as a catalyst and found triphenylphosphonium triflate (TPPT)[11] is superior to PFPAT and DPAT in thermal stability and reactivity for synthesis of PLLA and related copolymers. Herein results are summarized.

Table 1 summarizes results of initial survey of several onium salt catalysts. In addition to the conventional catalysts for PLLA synthesis as well as PFPAT and DPAT, triflate salts of representative weak bases were tested for direct polycondensation of aqueous lactic acid in toluene with 1 mol % of catalyst for 24 h with the Dean–Stark apparatus. Resulting PLLA was analyzed by gel permeation chromatography (GPC) or ^1H NMR.

Table 1. Catalyst screening for the direct polycondensation

	Catalyst	1 mol %		0.1 mol %	
		M_w[a]	PDI[b]	M_w[a]	PDI[b]
1	$SnCl_2$	7900	1.4	360[c]	—
2	Tin(II) 2-ethylhexanoate	180[c]	—		
3	*p*-TSA	23000	1.6	4000	1.7
4	PFPAT (**1**)	33000	1.6	31000	1.5
5	DPAT (**2**)	17000	1.5	6800	1.8
6	$PyH^+ {}^-OTf$ (**3**)	13000	1.3	900[c]	—
7	Me-imid$H^+ {}^-OTf$ (**4**)	8700	1.2	810[c]	—
8	$Cl_2C_6H_3NH_3^+ {}^-OTf$ (**5**)	69000	1.4	17000	1.4
9	$Ph_3PH^+ {}^-OTf$ (**6**)	16000	1.3	48000	1.7
10	No	360[c]	—		

[a] M_w by GPC with polystyrene standards. [b] PDI = M_w/M_n. [c] By ^1H NMR.

Without catalyst, condensation of lactic acid resulted in a formation of oligomer (Entry 10). Among tin compounds tested only $SnCl_2$ was active for direct condensation to produce PLLA of $M_w = 7900$ (Entries 1 and 2). *p*-TSA gave higher M_w of 23000. Several onium salt catalysts, **1**, **2**, pyridinium triflate (**3**), *N*-methylimidazolium triflate (**4**), 2,5-dichlorophenylammonium triflate (**5**), and triphenylphosphonium triflate (**6**) showed as high activity as *p*-TSA. These results clearly show onium salts acted as the Brønsted acid catalyst with the Fischer esterification mechanism.

Under reduced catalyst loadings (0.1 mol %, toluene, reflux 22.5 h), $SnCl_2$, **3**, and **4** afforded oligomers, presumably owing to their weaker acidity. Although *p*-TSA was active for polycondensation, M_w of the resulting PLLA was significantly lowered compared to that obtained by the use of 1 mol % catalyst. This should be attributed to esterification of the sulfonic acid itself to deactivate the catalyst during condensation reaction. Also **2** and **5** afforded PLLA of lower molecular weight.

Naturally, the reaction proceeded depending on the reaction time. With **3** (0.1 mol %), the M_w of the resulting PLLA increas-

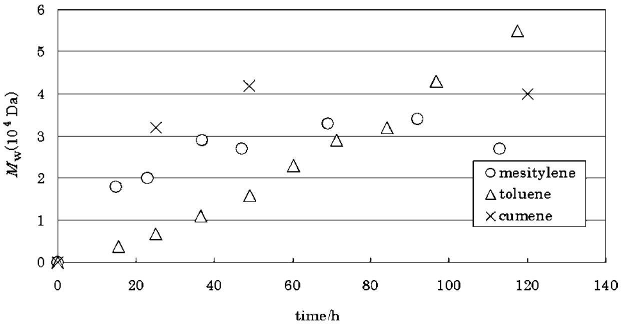

Figure 1. Molecular weight vs. reaction time.

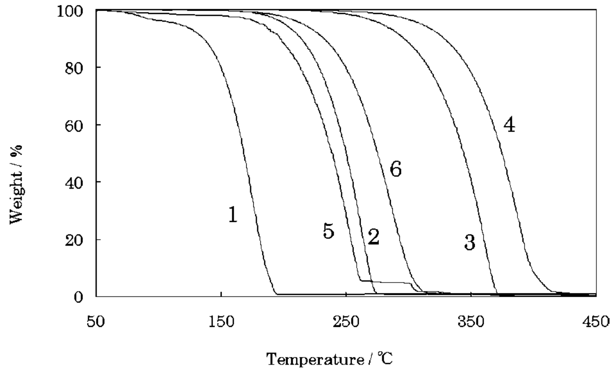

Figure 2. Thermogravimetric analysis of onium salts.

Table 2. Direct polycondensation of L-lactic acid with TPPT catalyst[a]

TPPT loadings	Solvent	Time/h	M_w (GPC)	PDI
0.1 mol %	xylene	24	18000	1.6
		72	83000	1.7
0.5 mol %		24	35000	1.5
		72	160000	1.6
0.1 mol %	cumene	24	30000	1.5
		72	21000	1.5
0.5 mol %		24	69000	1.4

[a] Aliquot was taken and analyzed at the indicated time.

ed linearly in cumene and ethylbenzene, with higher M_w in higher temperature. Contrary to this, with **6** (0.1 mol %) linearity was retained in toluene (≈120 h), but in cumene or mesitylene the polymerization terminated after 20–40 h (Figure 1), when the reaction turned badly colored. This should be attributed to the decomposition of the catalyst. Thermogravimetric-analysis (TGA) measurements of the onium salts are summarized in Figure 2. The order of thermal stability of the salts was $\mathbf{4} > \mathbf{3} > \mathbf{6} > \mathbf{2} > \mathbf{5} > \mathbf{1}$. From the viewpoint of thermal stability and reactivity, TPPT **6** was found to be a catalyst of choice.

With 0.1 mol % of **6**, M_w of the resulting PLLA reached to 83000 after 72 reflux in xylene.[12] Higher catalyst loadings (0.5 mol %) accelerated the condensation and M_w of 160000 was attained after 72 h. At higher reaction temperature (in cumene), **6** gradually decomposed after 24 h, and PLLA of $M_w = 69000$ was obtained using 0.5 mol % of **6** (Table 2).

In order to improve the physical properties of PLLA, introduction of aromatic substituents in the polymer chain have been examined.[13,14] For this purpose, the conventional ring-opening polymerization methodology requires preparation of cyclic dimer of lactic acid and the corresponding α-hydroxy acids, such as 3-phenyllactic acid, and can not utilize other hydroxy acids than α-hydroxy acids. Without such limitations, several co-polymers of lactic acid and hydroxy acids with an aromatic ring were synthesized using TPPT as a catalyst (Table 3).

Although the molecular weight was moderate or low, a variety of hydroxy acids, including phenol compounds, were introduced in the polymer. It should be noted that the composition of the co-polymer was almost the same as used for the polycondensation.

Table 3. Synthesis of co-polymers by direct polycondensation

HA[a]	LA:HA loadings	TPPT loadings /mol %	Yield /%	M_w (GPC)	PDI	LA:HA found
7	95:5	0.5	71	7000	1.6	94:6
	90:10	1	65	2900	1.7	86:14
8	95:5	0.5	75	6800	1.6	95:5
	90:10	1	70	7100	1.5	95:5
9	95:5	0.5	70	8300	1.6	95:5
	90:10	0.5	67	6200	1.7	91:9
10	90:10	1	45	1700	1.9	91:9
	70:30	1	41	1100	1.5	72:28

[a] HA: **7**: *p*-Hydroxybenzoic acid, **8**: *m*-Hydroxybenzoic acid, **9**: *p*-(Hydroxymethyl)benzoic acid, and **10**: 3-Phenyllactic acid.

In conclusion we have introduced new onium salt catalyst, TPPT, as a thermally more stable catalyst useful for direct polycondensation of lactic acid and related hydroxy acids to polyesters. Further studies on the application of this catalyst for synthesis of various bio-base polymers are in progress in our laboratories.

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