

## Kinetics of ring-opening polymerization of *d,l*-lactide catalyzed by functional Zn–guanidine complex with biphenyl-4-methanol activator

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### Experimental section

**Monomer.** *d,l*-Lactide was purchased from Corbion (Netherlands) and was used for the polymerization after recrystallization from ethyl acetate solution followed by 3 h of drying in vacuum. The residual concentration of lactic acid in *d,l*-lactide was determined by spectrophotometry using Rhodamine 6G buffer solution, which is sensible to the acidic impurities. The concentration of the carboxyl groups was calculated based on the difference in the absorption of Rhodamine 6G solution at 515 nm before and after mixing with the *d,l*-lactide solution in benzene.<sup>1</sup> After the recrystallization, the concentration of lactic acid in *d,l*-lactide was  $3.5 \times 10^{-7}$  mol g<sup>-1</sup>. The optical purity control was performed by measuring specific rotation of the *d,l*-lactide benzene solution (0.1 g cm<sup>-3</sup>), which was found to be  $[\alpha]_{298}^{633} = 0^\circ$ . Temperature and enthalpy of *d,l*-lactide melting were determined by differential scanning calorimetry: 125 °C and 150 J g<sup>-1</sup>, correspondingly. No melting peaks which can be attributed to *l*- or *meso*-form were observed.

**Catalysts and activator.** 2-Ethylhexanoic acid tin(II) salt (stannous octoate), 405.11 g mol<sup>-1</sup>, was purchased from Aldrich. Reported purity is 95%, with 4.6% ethylhexanoic acid, 0.3 – 0.5% water, and less than 0.05% *tert*-butylcatechol (stabilizer). The catalyst was added to the monomer as a solution in dry petroleum ether with the concentrations of 3 – 5 g l<sup>-1</sup>. The solvent was then removed under vacuum.

The zinc-based complex stabilized by 1,1,3,3-tetramethyl-2-(quinoline-8-yl)guanidine (TMGqu) ligands and triflate ions ([Zn(TMGu)<sub>2</sub>OTf]OTf) was synthesized according to the previously described procedure.<sup>2</sup> The structure was confirmed by <sup>1</sup>H-NMR. Biphenyl-4-methanol (Aldrich) was used as an initiator in order to accelerate the polymerization of *d,l*-lactide catalyzed by [Zn(TMGu)<sub>2</sub>OTf]OTf. The polymerization mixtures were prepared by intensive mixing of the Zn-based catalyst and the initiator with *d,l*-lactide at room temperature.

*Polymerization in DSC cell.* The kinetic curves were calculated from the DSC thermograms according to the procedure described earlier.<sup>3</sup> The experiments were performed using Mettler DSC20 calorimeter in the isothermal mode.

*Polymerization in flask.* About 3 g of the reaction mixtures of *d,l*-lactide with the catalyst and the initiator (optionally) were transferred to glass ampoules containing a magnetic stirrer. The ampoules were vacuumed to 0.5 Torr, then sealed and immersed into an oil bath heated to the polymerization temperature. At the end of reaction, the ampoules were broken, the content was dissolved in dichloromethane and precipitated to a cooled methanol (−15 °C). The precipitate was dried under vacuum (0.1 Torr) at 50 °C till constant weight.

*Monomer conversion analysis.* <sup>1</sup>H NMR was used to determine the monomer conversion. The resonance signals of protons in methine and methyl groups of *d,l*-lactide and poly(*d,l*-lactide) have different chemical shifts thus allowing to determine the monomer conversion precisely.<sup>4</sup> The experiments were carried out on Bruker WP 250 SY spectrometer using poly(*d,l*-lactide) solutions in CDCl<sub>3</sub> with concentration of about 10 g l<sup>−1</sup>.

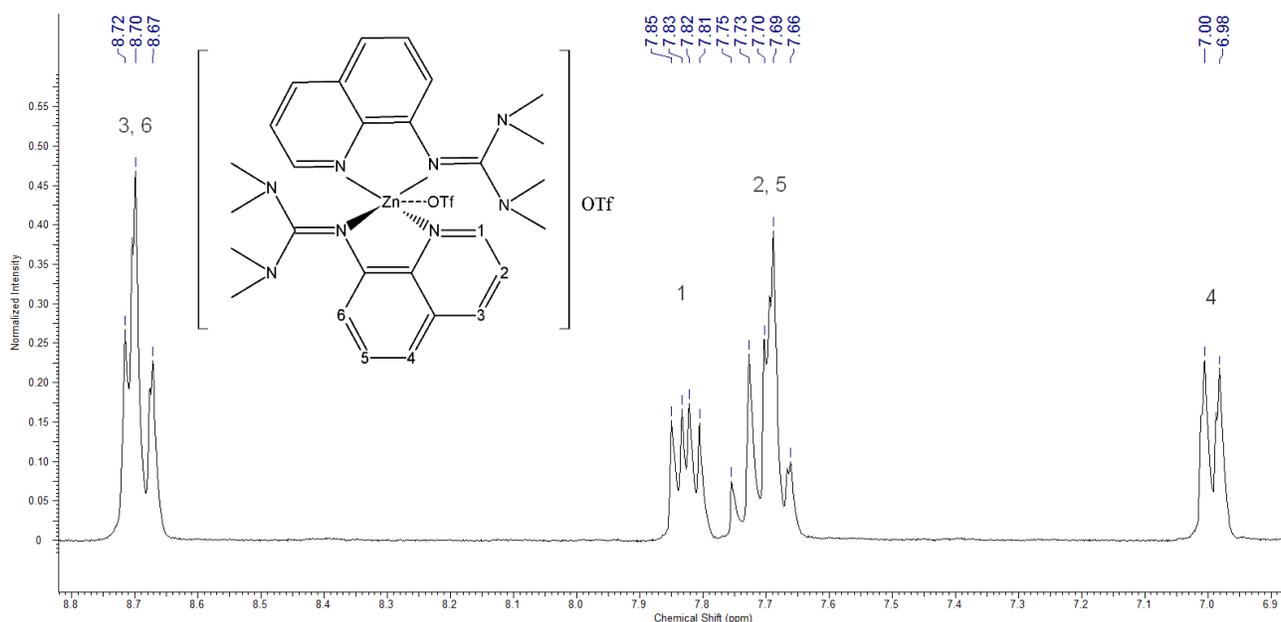
*Molecular weight analysis.* Poly(*d,l*-lactide) samples obtained in the DSC cell and in the flask were studied by gel permeation chromatography (GPC) using Knauer liquid chromatograph equipped with a RI detector. Tetrahydrofuran was used as eluent with a flow rate of 1 ml min<sup>−1</sup>. Poly(*d,l*-lactide) solutions in THF were filtered through 0.45 μm membrane filters before the injection. The experiments were performed at 40 °C using Agilent Phenogel 500 column (pore size 10<sup>4</sup> Å) calibrated with polystyrene standards.

*Thermal properties.* Glass transition temperature of the synthesized poly(*d,l*-lactide) samples was determined by differential scanning calorimetry using Perkin-Elmer DSC8500 calorimeter at a heating rate of 20 °C min<sup>−1</sup>. The heating curves of [Zn(TMGu)<sub>2</sub>OTf]OTf were measured on Mettler DSC30 in the range of 35 – 260 °C at a heating rate of 20 °C min<sup>−1</sup>. Thermal stability of the [Zn(TMGu)<sub>2</sub>OTf]OTf catalyst was studied by thermogravimetric analysis using Perkin-Elmer Pyris TGA1 from 30 up to 700 °C with heating rate of 10 °C min<sup>−1</sup> with a nitrogen gas flow of 100 ml min<sup>−1</sup>.

*Spectrophotometry.* Spectra of the catalyst and the poly(*d,l*-lactide) solutions were recorded on Shimadzu UV3600 spectrophotometer in the 310 – 750 nm wavelengths range. 2 mm quartz cuvettes were filled with the acetone solutions of [Zn(TMGu)<sub>2</sub>OTf]OTf (0.5 mg ml<sup>−1</sup>) and poly(*d,l*-lactide) (22 mg ml<sup>−1</sup>).

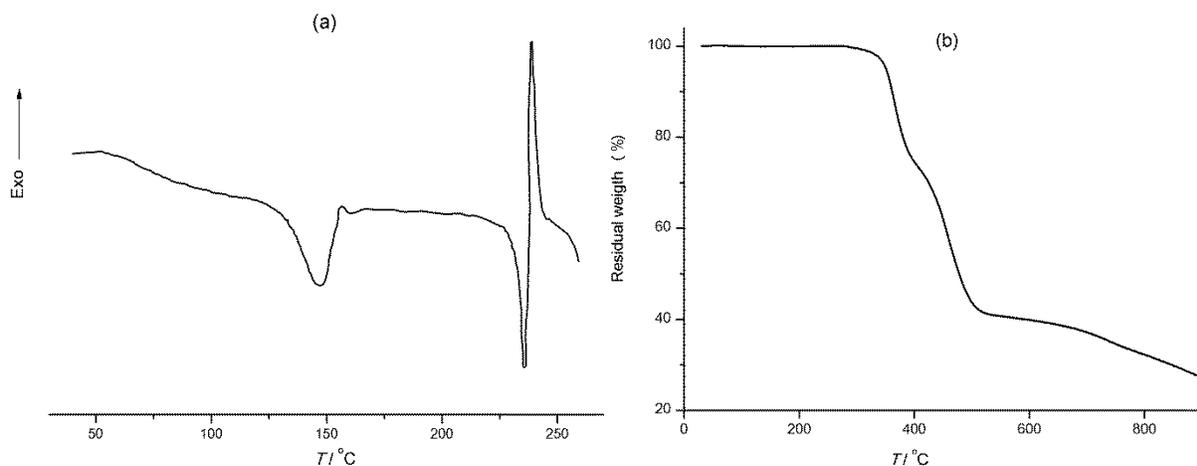
*Fluorescence spectroscopy.* The experiments were carried on Varian Cary Eclipse spectrofluorometer. Luminescence was registered from the front of the 2 mm quartz cuvette filled with the solutions of [Zn(TMGu)<sub>2</sub>OTf]OTf (0.5 mg ml<sup>−1</sup>) and poly(*d,l*-lactide) (22 mg ml<sup>−1</sup>) in acetone.

*Catalyst characterization.*  $^1\text{H}$  NMR spectrum of the synthesized catalyst is depicted in Figure S1. The resonances between 6.98 – 8.72 ppm refer to the CH-groups of the  $[\text{Zn}(\text{TMGqu})_2\text{OTf}]\text{OTf}$  catalyst. Due to the short distance between the signals, some of them form together more complicated multiplets. Two mixed doublets at 8.67 – 8.72 ppm refer to the protons of CH-groups number 3 and 6. The distorted double signal at 7.83 ppm refers to the proton number 1. Two mixed triplets at 7.66 – 7.8 ppm refer to the protons 2 and 5. The doublet 7 ppm refers to the CH groups number 4. Singlets 2.43 – 3.02 ppm refer to  $\text{CH}_3$  groups.



**Figure S1**  $^1\text{H}$ -NMR spectrum of  $[\text{Zn}(\text{TMGu})_2\text{OTf}]\text{OTf}$  (methine groups region).

The experimental DSC and TGA curves of the synthesized catalyst are depicted in Figure S2. The profound endothermic effect at 146 °C corresponds to the melting of the catalyst (Fig. 2a). The next thermal effect appears at around 215 °C and comprises two peaks. Such thermogram can be explained by decomposition of the catalyst resulting in the loss of its activity. At the same time according to the TGA curve (Figure S2b) the catalyst does not lose a mass until 270 °C.



**Figure S2** Heating thermogram (a) and TGA curve (b) of  $[\text{Zn}(\text{TMGu})_2\text{OTf}]\text{OTf}$  catalyst.

**Table S1** Influence of polymerization conditions on poly(*d,l*-lactide) characteristics. Reactions were carried out in flask with  $[\text{Zn}(\text{TMGu})_2\text{OTf}]\text{OTf}$  catalyst and (optionally) biphenyl-4-methanol activator

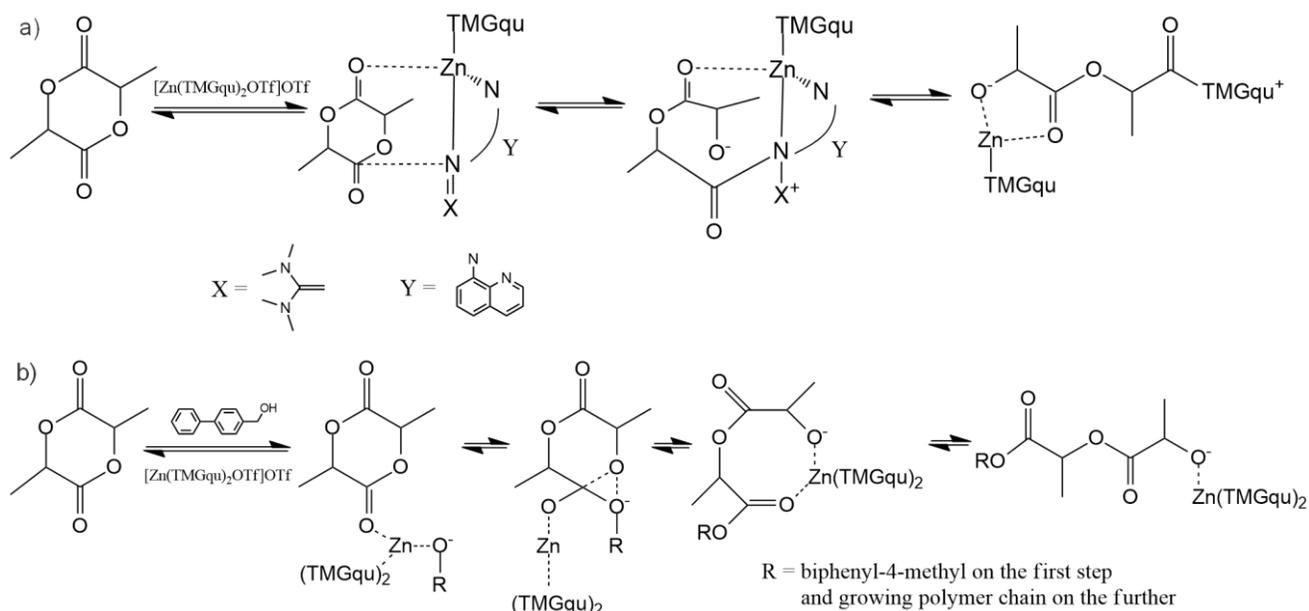
Sample	T, °C	[Catalyst], mol ppm	[Activator], mol ppm	time, hr	Conversion, %	$M_w$ , kDa	PDI	$T_g$ , °C	Product color
1	150	1000	-	24	94	129	2.39	48	brownish
2	200	1000	-	6	92	48	2.4	44	brown
3	150	1000	2000	6	94	87	2.25	47	colorless
4	150	1000	10000	6	97	n/d	n/d	n/d	colorless

### Mechanism of *d,l*-lactide polymerization catalyzed by Zn-guanidine complex

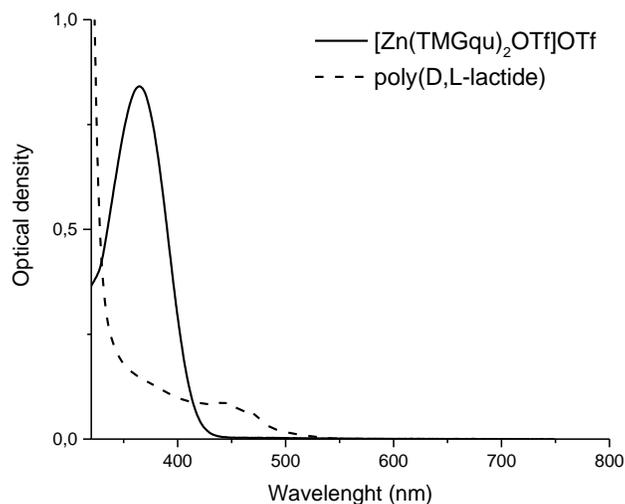
Without addition of the activator (Scheme S1a), basic guanidine nucleophilically attacks the lactide ring leading to its breakage. Lactide replaces the triflate ion in the catalytic complex, and the carbonyl oxygen atom coordinates to the zinc center resulting in the transition state. The guanidine nitrogen atom nucleophilically attacks the carbonyl C atom on the reverse side of the lactide molecule forming a bond. Simultaneously, the C-O bond in the lactide ring breaks. The opened lactide ring coordinates to the Zn center as an alcoholate anion. The N atom is released from Zn and remains on the end of the polylactide chain with the whole guanidine ligand. Further chain propagation proceeds by the coordination of

lactide molecules to the Zn center. The coordinated alcoholate ion of the growing chain opens new lactide molecules.

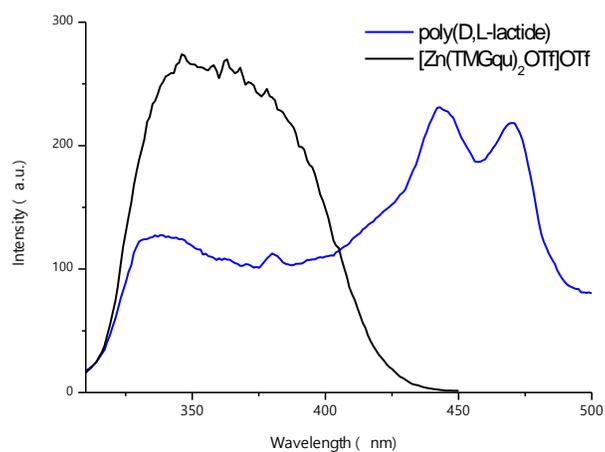
The calculated kinetic curves clearly showed an increase in the reaction rate upon addition of biphenyl-4-methanol. We suggest that the polymerization in the presence of the activator can be described by the following mechanism (Scheme S1b). An addition of biphenyl-4-methanol leads to the formation of a new catalytic complex: biphenyl-4-methylate ion replaces the triflate ion in the catalyst. The lactide molecule coordinates to the Zn atom of the new catalytic complex via carbonyl oxygen atom. The oxygen atom of biphenyl-4-methylate nucleophilically attacks the carbonyl atom and the C-O bond in the lactide ring breaks. The opened lactide ring coordinates to the Zn center. The activator detaches from catalytic complex and stays bonded to the opposite end of the polymer chain. Chain propagation proceeds by the coordination of new lactide molecules to the catalytic Zn center. The coordinated alcoholate ion acts as an initiator. We suggest that both these mechanisms can proceed simultaneously, especially at low concentrations of the activator.



**Scheme S1** Mechanism of the lactide polymerization reaction with  $[Zn(TMGu)_2OTf]OTf$  catalyst: a) pure and b) activated by biphenyl 4 methanol.



**Figure S3** Absorption spectra of  $[\text{Zn}(\text{TMGu})_2\text{OTf}]\text{OTf}$  solution and solution of poly(*d,l*-lactide) synthesized in presence of this catalyst.



**Figure S4** Excitation spectra of  $[\text{Zn}(\text{TMGu})_2\text{OTf}]\text{OTf}$  and poly(*d,l*-lactide) solutions in acetone.

## References

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