Use of Non-isothermal DSC in Comparative Studies of Tin(II) Systems for the Ring-Opening Polymerization of D-lactide

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*Abstract*

Understanding the kinetics and mechanism of polymerization, particularly the role of the catalyst or initiator used, allows for the manipulation and control of the fabrication of new materials by the most convenient, straightforward routes. The kinetics of the bulk ring-opening polymerization (ROP) of D-lactide, a useful monomer employed to control the properties of poly(L-lactide), have been studied herein to identify a relatively quick (1 h), controlled, yet convenient, route to moderately high molecular weight poly(D-lactide). Tin(II) octoate [Sn(Oct)2], Sn(Oct)2/*n*-butanol (*n*BuOH) and liquid tin(II) butoxide [Sn(O*n*Bu)2] as initiating systems were investigated by non-isothermal differential scanning calorimetry (DSC). Isoconversional methods were employed to determine the activation energy (*Ea*) for each reaction. The results showed that liquid Sn(O*n*Bu)2 was a more efficient initiator than the commonly reported initiating systems of Sn(Oct)2 and Sn(Oct)2/*n*BuOH in terms of producing higher polymerization rates and polymer molecular weights. High molecular weight Poly D-lactide (1.8×105 Da) with moderate dispersity (*Ð* 1.3) was obtained using 0.1 mol% liquid Sn(O*n*Bu)2 as the initiator at 120 °C. This present work describes the applications of non-isothermal DSC and isoconversional methods in comparing the effectiveness of different initiators in the bulk ROP of D-lactide for the first time.

Keywords: D-lactide, ring-opening polymerization, liquid tin(II) butoxide, non-isothermal DSC

1. *Introduction*

Since there are two chiral centers in lactide, there are three stereoisomers namely: D-lactide, L-lactide (LL) and meso-lactide which contribute to a variety of properties in polylactide [1-3]. Owing to the poor elongation and high modulus in polylactide homopolymers, poly(D-lactide) (PDL) is frequently utilized with poly(L-lactide) (PLL) in the preparation of stereocomplex polylactide (ScPL) in order to enhance their mechanical, thermal and degradative properties [2, 4-6]. Because of the poor elongation and high modulus of poly(L-lactide) homopolymers, D-lactide is frequently incorporated together with L-lactide in the preparation of stereocomplex polylactide (ScPL) in order to enhance mechanical, thermal and degradative properties (see references [2, 4-6]). Despite these benefits of D-lactide incorporation, and the logical assumption that with non-chiral initiating systems D and L-lactide polymerization will be identical, there are relatively few separate reports of D-lactide polymerization. Our work herein, which compares three different initiating systems, shows that D-lactide does behave similarly to L-lactide with these initiators..

Nowadays, the development of new catalysts and initiators has become of great interest in terms of controlling the ring-opening polymerization (ROP) of cyclic esters. Many research groups have focused on the development of metal-free initiating systems [7-11], which are very fast but tend to produce only low molecular weight polymers. In contrast, metal-containing initiators such as metal alkoxides and carboxylates are able to produce high molecular weights [12-14]. Tin(II) octoate [Sn(Oct)2] is the most widely used initiator in the ROP of cyclic esters because it is easy to handle and is soluble in both the monomers and common organic solvents. Additionally, Sn(Oct)2 gives reasonably high reaction rates, polymer yields and molecular weights of up to 105 Da [12-15] However, it is now widely accepted that Sn(Oct)2 and either a purposely-added alcohol (ROH) or OH-containing impurities present in the system react together *in situ* to form firstly a tin(II) monoalkoxide, Sn(Oct)OR, and then the tin dialkoxide, Sn(OR)2, either or both of which then become the true initiators in a coordination-insertion mechanism [16-18]. Consequently, when Sn(Oct)2 is used either alone or in combination with an alcohol, the exact concentration of the true initiating species is unknown.

To address this problem, solid tin(II) alkoxides [Sn(OR)2] have been synthesized and used as initiators in the ROP of cyclic esters directly [19, 20]. As reported by Penczek *et al*.[21], solid Sn(O*n*Bu)2 produced PLL with high molecular weights of up to 106 Da and dispersity (*Ð*) of 1.15-1.85, although this route relied on more complex high pressure conditions for several (~ 20) hours. Better control over the structure of poly(L-lactide-*co*-*ɛ*-caprolactone) [P(LL/CL)] using the conventional Sn(O*n*Bu)2 initiator has also been reported [22]. A disadvantage of solid Sn(O*n*Bu)2 is its poor solubility in cyclic ester monomers and organic solvents due to its molecular aggregation. Thus, the incomplete dissolution of Sn(O*n*Bu)2 in the monomer leads to an uncertain effective Sn(O*n*Bu)2 concentration [23]. To overcome this uncertainty, Meepowpan *et* *al*. [24] have recently proposed a synthetic route for a soluble Sn(OR)2 liquid initiator. In comparative kinetic studies by dilatometry, the liquid Sn(O*n*Bu)2 was found to be more effective in the ROP of *ɛ*-caprolactone (*ɛ*-CL) than both the solid Sn(O*n*Bu)2 and Sn(Oct)2/*n*BuOH initiating systems [25].

Differential scanning calorimetry (DSC) has been applied to the kinetic study of the bulk ROP of cyclic esters. With its rapid determination and continuous kinetic evaluation, it is suitable for a comparative study of the reactivities of different monomers or the efficiencies of the initiating systems [26-33]. The effects of the initiator concentration and temperature on the kinetic and thermodynamic parameters for the ROP of LL [31] and *ɛ*-CL [32] using Sn(Oct)2 and *n*Bu3SnO*n*Bu were investigated using non-isothermal and isothermal DSC methods. Meelua *et al.*[30] and Limwanich *et al.* [33] utilized DSC for the ROP of *ɛ*-CL using Ti(IV)OR (R = *n*Pr, *n*Bu, *t*Bu and 2-ethylhexyl) and tributyltin alkoxide (*n*Bu3SnOR; R = Me, Et, *n*Pr and *n*Bu) as initiators, respectively, in order to describe the steric influence of the alkoxide group on the rate of polymerization. Non-isothermal DSC was also used to determine the optimum conditions for preparing *γ*-valerolactone (*γ*-VL)-based copolymers despite *γ*-VL being thermodynamically difficult to polymerize. [34]

In the work presented here, the efficiency of the recently discovered liquid Sn(O*n*Bu)2 initiator is examined and compared with the conventional Sn(Oct)2 initiating systems of Sn(Oct)2 alone and Sn(Oct)2/*n*BuOH, in the bulk ROP of D-lactide using non-isothermal DSC. The kinetics results obtained are used to identify the optimum conditions for synthesizing high molecular weight PDL. As far as we are aware, this paper is the first report of the use of liquid Sn(O*n*Bu)2 in the bulk ROP of D-lactide using both dynamic and isoconversional kinetics methods. These kinetic data obtained could provide valuable information for establishing the appropriate conditions for the controlled synthesis of a wide range of high molecular weight polyesters created from cyclic monomers.

*2. Experimental*

*2.1. Materials*

D-lactide was synthesized from D-lactic acid (NatureWorks, 88%) via linear polycondensation of the acids to form low molecular weight poly(lactic acid) (PLA) followed by thermal decomposition reaction at high temperature (200 to 220 °C) and reduced pressure. Then, crude D-lactide was recrystallized from distilled ethyl acetate (RCL Labscan) three times before being dried in a vacuum oven at 55 °C to constant weight. The purity of the recrystallized lactide monomer was determined prior to polymerization by DSC purity analysis. *n*-Butanol (*n*BuOH, Merck, 99.4%) was distilled over sodium metal. Anhydrous tin(II) chloride (SnCl2) (Acros Organics, 98%) was used as received. Diethylamine (Et2NH, Panreac, 99.5%) and *n*-heptane (BDH, 99.5%) were purified by fractional distillation over calcium hydride before use. Sn(Oct)2 (Sigma, 95%) was distilled under vacuum at approximately 90 °C to remove impurities before use.

*2.2. Synthesis of liquid tin(II) n-butoxide*

Sn(O*n*Bu)2 liquid initiator was synthesized according to the method described elsewhere [24, 35]. In short, SnCl2 was dissolved in dried *n*-heptane and stirred. Next, dried Et2NH and then dried *n*BuOH were slowly added into the flask under a nitrogen atmosphere and the reaction mixture was allowed to proceed at room temperature for 24 h. After purification and characterization, it was used as a soluble initiator in the bulk ROP of D-lactide. Due to its air and moisture-sensitivity, the liquid Sn(O*n*Bu)2 was stored under nitrogen in a tightly sealed container prior to use.

*2.3. Kinetic studies by non-isothermal DSC*

The ROP of D-lactide was conducted using non-isothermal DSC in order to compare the efficiencies of the three different types of tin(II) initiating systems. 2.00 g of D-lactide monomer and 1.0 mol% of Sn(Oct)2, Sn(Oct)2/*n*BuOH (1.0:2.0) or liquid Sn(O*n*Bu)2 as the initiating system were prepared in a dry vial. Each was thoroughly and uniformly mixed before 7-8 mg were transferred into the DSC pan. The DSC pan was hermetically sealed and kinetic runs conducted under dynamic conditions using a Perkin-Elmer DSC-7 Differential Scanning Calorimeter. The temperature range that was used in this study was 20-260 °C for D-lactide at heating rates of 5.0, 10.0, 15.0 and 20.0 °C min-1. A rate of nitrogen gas flow of 20 ml min-1 was purged through the DSC cell. After the non-isothermal DSC thermograms were analyzed by Pyris DSC-7 software, they were interpreted and the kinetic parameters obtained.

*2.4. Bulk ring-opening polymerization of* D-lactide *monomer*

Polymerization mixtures were prepared by mixing D-lactide (4.0 g) with 0.10, 0.20, 0.30, 0.40 and 0.50 mol% of liquid Sn(O*n*Bu)2, Sn(Oct)2/*n*BuOH (1:2) or Sn(Oct)2 in dry 10 ml round-bottomed flasks. All sample preparation was performed inside a controlled humidity glove box (Labconco) under dry nitrogen. The flasks were immersed in a silicone oil bath at a constant temperature of 120 ± 0.1 °C for 60 min after which they were allowed to cool to room temperature. The crude polylactides obtained were dissolved in chloroform, precipitated in cold methanol, filtered and washed with more methanol, before being finally dried in a vacuum oven at 55 °C to constant weight.

In this study, 1H-NMR spectra of the purified PDL product were recorded at 400 MHz using a Bruker Advance NMR spectrometer and obtained using MestReC data processing software. CDCl3 and TMS were used as the solvent and internal standard, respectively. The molecular weight averages and dispersities of the purified products were obtained using a Waters 2414 GPC with RI detector and THF as eluent at 40 °C at a flow rate of 1.0 ml min-1. The Perkin Elmer DSC-7 with Pyris software was also employed for the characterization of the melting temperature (*Tm*). Samples with a mass of 4-5 mg were encapsulated in an aluminum pan and scanned from 20 to 200 °C at a heating rate of 10.0 °C min-1. After the sample was held at 200 °C for 1 min, it was quickly cooled down to 20 °C at a cooling rate of 10.0 °C min-1 and then reheated to 200 °C at 10.0 °C min-1.

*3. Results and discussion*

*3.1. Kinetic studies of the ROP of* D-lactide *by non-isothermal DSC*

The kinetics of the ROP of D-lactide using 1.0 mol% liquid Sn(O*n*Bu)2, Sn(Oct)2/*n*BuOH and Sn(Oct)2 as initiating systems were determined by non-isothermal DSC by heating from 20.0 to 260.0 °C at heating rates of 5.0, 10.0, 15.0 and 20.0 °C min-1. The thermograms of normalized heat flow against temperature for the ROP of D-lactide using the liquid Sn(O*n*Bu)2 initiator are illustrated in **Figure 1**.



**Figure 1**. Non-isothermal DSC thermograms for the ROP of D-lactide initiated by 1.0 mol% of Sn(O*n*Bu)2 at heating rates of 5.0, 10.0, 15.0 and 20.0 °C min-1.

The DSC thermograms in **Figure 1** show a sharp endothermic peak followed by a broad exotherm. The former peak is the melting transition of the D-lactide monomer whereas the latter peak is due to the exothermic heat release during polymerization. It has been previously mentioned by Mazzaro *et al.* [29] that polymerization kinetics of the ROP of D,L-lactide (DLL) using Zn(Oct)2 as the initiator derived from DSC measurements can lead to erroneous polymerization parameters due to overlapping endothermic melting and exothermic polymerization peaks. In this present work, the D-lactide melting endotherm did not overlap with the polymerization exotherm and so this error was avoided. The results in **Figure 1** show that the temperatures at which the polymerization exotherm starts and finishes are shifted to a higher temperature range as the heating rate increases [26–33, 36]. Similar trends were also obtained for the Sn(Oct)2/*n*BuOH and Sn(Oct)2 initiators (see supporting information, Figure S1).



**Figure 2.** Non-isothermal DSC curves for the ROP of D-lactide initiated by 1.0 mol% of Sn(Oct)2, Sn(Oct)2/*n*BuOH and Sn(O*n*Bu)2 at a heating rate of 10 °C min-1

The DSC thermograms of the ROP of D-lactide using the three different initiating systems at the same concentration of 1.0 mol% and heating rate of 10.0 °C min-1 are compared in **Figure 2**. As the initiator was changed from Sn(Oct)2 → Sn(Oct)2/*n*BuOH → liquid Sn(O*n*Bu)2, the exothermic polymerization peak shifted to a lower temperature range. The results clearly indicate that the reactivities are different for the three initiators explored. .

The fraction of monomer conversion *α* at any time *t* and temperature *T* can be calculated by dividing the heat of reaction at that time (∆*Ht*) by the total heat of reaction (∆*Htotal*) [33, 37]. The rate of change in monomer conversion (d*α*) with time (d*t*) leads to the determination of the polymerization rate (d*α*/d*t*). The plots of *α* and d*α*/d*t* against temperature *T* for the ROP of D-lactide using the various initiating systems are shown in Figures 3(a) and 3(b) respectively. The *α* and d*α*/d*t* curves in **Figure 3** show the polymerization to vary with the initiator used in the order of Sn(O*n*Bu)2 > Sn(Oct)2/*n*BuOH > Sn(Oct)2. This reaffirms the view that the liquid Sn(O*n*Bu)2 initiator is the most reactive of the three initiators studied.



**Figure 3.** Plots of monomer conversion (a) and polymerization rate (b) against temperature for the ROP of D-lactide initiated by 1.0 mol% of Sn(Oct)2, Sn(Oct)2/*n*BuOH and Sn(O*n*Bu)2 at a heating rate of 10 °C min-1.

*3.2 Determination of activation energies*

In order to understand the system further, the activation energy (*Ea*) values for the ROP of D-lactide using Sn(Oct)2, Sn(Oct)2/*n*BuOH and liquid Sn(O*n*Bu)2 were determined by fitting the non-isothermal DSC thermograms to various kinetic methods. Generally, DSC kinetic investigations that involve heat flow measurement can be correlated with the fraction of conversion (*α*) and polymerization rate (d*α*/d*t*) as shown in equation (1).

 (1)

For dynamic thermal investigations, d*α*/d*t* can be substituted with *β*(d*α*/d*T*), where *β* is the constant heating rate (°C min-1) used. The temperature-dependent Arrhenius equation can be used to represent the *k*(*T*) term; therefore, equation (1) can be rewritten as shown in equation (2) [38].

 (2)

where *Ea* is the activation energy, *A* is the frequency factor, *T* is the temperature, and *R* is the universal gas constant. Integration of equation (2) leads to the general equation for DSC kinetic methods as shown in equation (3).

 (3)

where *g*(*α*) is the integral conversion function, x = *Ea*/*RT*, and *p*(*x*) is the temperature integral for which there is no analytical solution. In order to solve the limitation of the temperature integral, a combination of approximation methods, series expansions and numerical solution methods are employed [39]. The Kissinger-Akahira-Sunose (KAS) [40] and the Friedman [41] isoconversional methods were used to analyze the DSC data and provide supportive evidence relating to the effect of the initiating system. The equation for the method of KAS is shown in equation (4).

 (4)

This KAS equation (4) is obtained through the derivative of equation (2) and by approximating the integral *p*(*x*) in equation (3) as *p*(*x*) e-x/x2 where x is valid for 20 ≤ x ≤ 50. The slope of the plot of polymerization rate [ln(*β*/)] against 1000/T*p* at constant conversion enables the determination of *Ea* at each conversion. Whereas this method employs the Murray and White approximation for the temperature integral, no approximation is used in the method of Friedman [28, 30, 32, 33]. Thus, the *Ea* values can be directly determined from the slope of the plot of ln(d*α*/d*t*) against 1000/T*p* according to equation (5).

 (5)

where *I* refers to data for a given heating rate.

In this present work, both the KAS and Friedman methods were employed to determine *E*a for the ROP of D-lactide with each of the three types of initiating system. The plots of ln[(*β*/)] and ln(d*α*/d*t*) against 1000/*Tp* based on the isoconversional methods of KAS and Friedman for the ROP of D-lactide are shown in **Figures 4 (a) and (b)** respectively. The reliability of the polymerization rate measurements was confirmed by the straight-line plots obtained (R2 > 0.95). The *E*a values at each fraction of conversion *α* were plotted as shown in **Figure 5** to examine their consistency and support the ROP mechanism.



**Figure 4.** Plots of ln(*β*/) (a) and ln(d*α*/d*t*) (b) against 1000/T*p* based on the isoconversional methods of KAS and Friedman for the ROP of D-lactide initiated by 1.0 mol% of Sn(Oct)2, Sn(Oct)2/*n*BuOH and Sn(O*n*Bu)2 at various fractions of conversion *α*.

From **Figure 5**, the *E*a values determined using the KAS and Friedman isoconversional methods were in good agreement for the D-lactide polymerization using Sn(O*n*Bu)2 (56-70 and 52-61 kJ mol-1 for KAS and Friedman). These values were lower than those for Sn(Oct)2/*n*BuOH (69-77 and 63-77 kJ mol-1 for KAS and Friedman) and Sn(Oct)2 (79-82 and 77-83 kJ mol-1 for KAS and Friedman), thereby indicating an order of initiating efficiency of: liquid Sn(O*n*Bu)2 > Sn(Oct)2/*n*BuOH > Sn(Oct)2. The variation in *Ea* between the two different methods was mainly caused by the differences in the mathematical approximations used. Even though the *Ea* values from the two methods were different, the trends were similar with the same order of initiator efficiency.

From the relative consistency of the *Ea* versus *α* plots in **Figure 5**, the ROP of D-lactide using these three tin(II) initiating systems appears to proceed through a single mechanism which is generally referred to in the literature as the coordination-insertion mechanism [21, 22]. Similar findings were also observed in the ROP of *ɛ*-CL using Ti(IV) alkoxide initiators as reported by Meelua *et al.* [30]. However, the slightly greater variations in *E*a with *α* in the Friedman plots than in the KAS plots indicates that the latter method is perhaps better suited to determining *E*a in D-lactide polymerization initiated by these tin(II) initiating systems, especially Sn(Oct)2/*n*BuOH.



**Figure 5.** Plots of *Ea* as a function of monomer conversion *α* from the KAS (a) and Friedman (b) methods for the ROP of D-lactide initiated by 1.0 mol% of Sn(Oct)2, Sn(Oct)2/*n*BuOH and Sn(O*n*Bu)2

It is well known that there needs to be a reaction between Sn(Oct)2 and a compound which has a hydroxyl group (-OH) (in this case, BuOH) to generate a Sn(II) monoalkoxide (OctSnOR) and Sn(II) dialkoxide [Sn(OR)2] prior to the initiation process. The Sn alkoxide then reacts with the cyclic monomer to form the polyester [17, 18, 42–44]. The *in situ* generation of OctSnO*n*Bu and Sn(O*n*Bu)2 can slow down the rate of polymerization by extending the induction period. Also, the concentration of the true initiator needs to be sufficient to initiate polymerization. In the coupled reversible reactions, it takes time for a steady state concentration of the active species to be reached. Even then, the exact concentration of the active initiating species is unknown. As a result, the polymerization kinetics, and final molecular weight of the target polymer, are difficult to control precisely. The situation is further complicated by the fact that octanoic acid (OctH), the by-product from the reaction of Sn(Oct)2 and BuOH (or other OH-containing compound), can reduce the polymerization rate [18, 42, 43]. The Sn(Oct)2:BuOH ratio is also important for determining the number of active sites. An excess of unreacted BuOH may cause chain transfer, alcoholysis of the ester bonds in the polymer chain, and/or other unwanted side reactions [18, 45, 46].

In summary, the combined kinetic evidence of the plots of conversion and polymerization rate against time, as well as the values of *Ea*, have shown that liquid Sn(O*n*Bu)2 gave the highest polymerization rate with the lowest *Ea* value. This is because liquid Sn(O*n*Bu)2 is itself the true initiator. Despite some possible molecular aggregation of the liquid Sn(O*n*Bu)2, this initiator would have been expected to have the highest concentration of Sn-OR active sites at the beginning of polymerization since it is already in its active form for initiation. In contrast, both the Sn(Oct)2/*n*BuOH and Sn(Oct)2 initiating systems need to generate the Sn-OR bonds *in situ* in the form of monoalkoxide and/or dialkoxide before initiation can occur, hence they both gave lower polymerization rates than liquid Sn(O*n*Bu)2. When comparing Sn(Oct)2 and Sn(Oct)2/*n*BuOH, the polymerization rates using Sn(Oct)2 were lower with higher values of *Ea* due to the fact that, without added alcohol, the absence of alkoxy (-OR) groups meant fewer active sites were available for polymerization. Whether Sn(OH)2 or HOSn(Oct) is formed from the reaction of Sn(Oct)2 with -OH impurities, -H is considered to be a much poorer electron donating group than *n*Bu. Hence, -OH groups result in less elctron density on the O atom compared to that in -O*n*Bu. The *n*Bu group in -O*n*Bu creates a higher electron density on the O atom which in turn increases the positive charge on the adjacent Sn atom and facilitates the coordination step. Thus, the Sn-O bond in Sn(O*n*Bu)2 coordinates with the carbonyl carbon of the D-lactide monomer faster than that in Sn(OH)2. As a result, Sn(O*n*Bu)2 generated *in situ* via the reaction of Sn(Oct)2 and *n*BuOH had a greater reactivity than Sn(Oct)2 alone with a shorter induction period.

*3.3 Synthesis of poly(D-lactide) (PDL) via bulk polymerization*

To compare further the efficiencies of the liquid Sn(O*n*Bu)2,Sn(Oct)2 and Sn(Oct)2/*n*BuOH initiators, the bulk ROP of D-lactide was carried out using concentrations of 0.10, 0.20, 0.30, 0.40 and 0.50 mol% at 120 °C for 60 min. All three initiating systems gave very high reaction rates in contrast to the slow rates obtained when using tributyltin alkoxides (Bu3SnOR) initiators, as reported in our previous study [32]. The *Mn*, *Mw*and *Ð* values of the purified Poly D-lactide samples obtained using the various initiator are compared in Tables 1.

Table 1.Bulk ROP of D-lactide using various concentrations of Sn(Oct)2, Sn(Oct)2/*n*BuOH and Sn(O*n*Bu)2 as the initiating systems at 120 °C for 60 min.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Initiating System | [*I*]0  (mol%) | *Mn,tha* | *Mn,GPC* | *Mw,GPC* | *Ð b* | *Tmc*  (°C) | %Yield*d*  (%) |
| Sn(Oct)2 | 0.10 | 2.8×105 | 5.0×104 | 6.6×104 | 1.3 | 163.0 | 45 |
| 0.20 | 1.4×105 | 9.7×104 | 1.3×105 | 1.3 | 177.5 | 72 |
| 0.30 | 9.6×104 | 6.0×104 | 8.4×104 | 1.4 | 176.4 | 72 |
| 0.40 | 7.2×104 | 8.8×104 | 1.3×105 | 1.5 | 181.2 | 84 |
| 0.50 | 5.8×104 | 5.0×104 | 8.0×104 | 1.6 | 164.0 | 76 |
| Sn(Oct)2/  *n*BuOH | 0.10 | 2.8×105 | 9.3×104 | 1.2×105 | 1.3 | 182.5 | 76 |
| 0.20 | 1.4×105 | 4.8×104 | 5.7×104 | 1.2 | 181.7 | 88 |
| 0.30 | 9.6×104 | 2.8×104 | 3.9×104 | 1.4 | 158.7 | 87 |
| 0.40 | 7.2×104 | 5.5×104 | 6.6×104 | 1.2 | 179.7 | 87 |
| 0.50 | 5.8×104 | 1.9×104 | 2.6×104 | 1.4 | 155.1 | 88 |
| Sn(O*n*Bu)2 | 0.10 | 2.8×105 | 1.8×105 | 2.4×105 | 1.3 | 181.7 | 76 |
| 0.20 | 1.4×105 | 1.6×105 | 2.3×105 | 1.4 | 183.0 | 86 |
| 0.30 | 9.6×104 | 1.1×105 | 1.8×105 | 1.6 | 182.5 | 88 |
| 0.40 | 7.2×104 | 7.6×104 | 1.2×105 | 1.5 | 180.5 | 90 |
| 0.50 | 5.8×104 | 4.9×104 | 8.3×104 | 1.7 | 177.7 | 92 |

*a Mn,th*is the theoretical number-average molecular weight as calculated from [(Mol.wt. of PDL repeating unit = 144.14 g mol-1) × [*M*]0/[*I*]0] + mol.wt. of initiator end-groups; *b Ð* is the dispersity (= *Mw*/*Mn*); *c Tm* is the melting point from DSC (taken from the peak of the melting endotherm); *d* %Yield is the amount of polymer obtained after purification compared with the theoretical amount at 100% yield.

At the same initiator concentration [*I*]0, the highest molecular weight PDL samples, closest to the target and theoretical values (*M*n*,th*), were obtained from Sn(O*n*Bu)2. In contrast, the *Mn* trends for Sn(Oct)2 and Sn(Oct)2/*n*BuOH were more variable. This is again a reflection of the fact that Sn(O*n*Bu)2 is the only true initiator whereas Sn(Oct)2 and Sn(Oct)2/*n*BuOH need to react first to generate the Sn(II) alkoxide active species *in situ*. These molecular weight observations are consistent with the previous DSC kinetic results which rank the initiator efficiency in the order: Sn(O*n*Bu)2 > Sn(Oct)2/*n*BuOH > Sn(Oct)2. All of the initiating systems produced unimodal molecular weight distributions with *Ð* in the range of 1.2-1.6. These *Ð* values indicate relatively narrow distributions as a consequence of the coordination-insertion mechanism resulting in chain propagation with limited termination. Yields were generally high (>70%) except for Sn(Oct)2 at the lowest [*I*]0 concentration of 0.10 mol% and there is a suggestion that the liquid initiator could lead to slightly higher yields at higher concentrations.

In order to confirm the coordination insertion mechanism,1H-NMR spectroscopy was used to determine the end group of the PDL synthesized using Sn(Oct)2, Sn(Oct)2/nBuOH and liquid Sn(OnBu)2, as shown in Figure 6.

The 1H NMR spectra in Figure 6 reveal all of the expected peaks for PDL (see assignments in Figure 6). Most pertinently, the peak appearing at approximately 4.34 ppm reveals the presence of Sn-O-C**H**, which is a characteristic feature of tin alkoxide compounds [19-21], confirming that the polymerization proceeds via the expected coordination insertion mechanism. The molecular aggregation in liquid Sn(OnBu)2 is detected and labeled as two different (a′) and (a′) peaks [21].

For the Sn(Oct)2/nBuOH system, the polymerization mechanism is similar to that of Sn(OnBu)2 except that the Sn(Oct)2 must first react with the nBuOH to generate Sn(OnBu)2 before initiation can occur. For this reason, 1H-NMR spectrum of PDL synthesized using Sn(Oct)2/nBuOH as an initiating system is similar to that of PDL synthesized using liquid Sn(OnBu)2as an initiator. However, when Sn(Oct)2 is used alone, is has to react with OH-containing impurities present in the system (such as lactic acid and/or moisture) before it can initiate polymerization, clearly indicated by the broad peak at approximately 3.5 ppm. Additionally, the multiplet of the -CH3 groups could not be detected in the spectrum of PDL synthesized using Sn(Oct)2, indicating that the active initiating species was generated prior to the initiation.

*Diagram, engineering drawing

Description automatically generated*

**Figure 6.** 400 MHz 1H-NMR spectra of purified PDL synthesized using (i) Sn(Oct)2, (ii) Sn(Oct)2/nBuOH and (iii) liquid Sn(OnBu)2 alongside that of (iv) liquid Sn(OnBu)2.

*4. Conclusions*

The effectiveness of Sn(O*n*Bu)2 as an active liquid initiator for the ROP of D-lactide is kinetically explored. The kinetics of ROP of D-lactide initiated by 1.0 mol% of Sn(Oct)2,Sn(Oct)2/*n*BuOH and liquid Sn(O*n*Bu)2 have been investigated and compared using non-isothermal DSC. The reactivity of liquid Sn(O*n*Bu)2 was higher than that Sn(Oct)2/*n*BuOH and Sn(Oct)2 due to its ability to directly initiate polymerization. In contrast, Sn(Oct)2/*n*BuOH and Sn(Oct)2 both require the *in situ* generation of OctSnO*n*Bu and/or Sn(O*n*Bu)2 which, even then, occur in ill-defined concentrations. From bulk ROP studies, liquid Sn(O*n*Bu)2 yielded higher molecular weight PDL (= 1.8×105) with moderate *Ð* (1.3) as well as yields of over 75% within 60 min compared to the other two tin(II) initiating systems. Such a high molecular weight could not be attained using the Sn(Oct)2/*n*BuOH and Sn(Oct)2 initiating systems. In addition, the molecular weights of PDL from GPC were close to the targeted values using liquid Sn(O*n*Bu)2, whereas Sn(Oct)2 and Sn(Oct)2/*n*BuOH gave less predictable results. In its wider context, this work has demonstrated the useful role that DSC kinetic data can play in the choice of initiator and provides a system for the fabrication of PDL with controlled molecular weight and relatively low dispersity. Through a combination of kinetic and thermodynamic data, initiator efficiencies and appropriate polymerization temperatures can be determined and provides further understanding of the polymerization of cyclic monomers to produce biodegradable materials. This work herein can be beneficial in the design of PDL with controllable molecular weight, for potential future use in stereocomplex structure to broaden the use of sustainable PLL/PDL blends.

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