



'Immortal' ring-opening polymerisation of ω -pentadecalactone by $\text{Mg}(\text{BHT})_2(\text{THF})_2$

Journal:	<i>Polymer Chemistry</i>
Manuscript ID:	PY-COM-01-2014-000034.R1
Article Type:	Communication
Date Submitted by the Author:	15-Feb-2014
Complete List of Authors:	Wilson, James; University of Warwick, Department of Chemistry Hopkins, Sally; Infineum UK Ltd., Wright, Peter; Infineum USA, Dove, Andrew; University of Warwick, Department of Chemistry

COMMUNICATION

'Immortal' ring-opening polymerisation of ω -pentadecalactone by $\text{Mg}(\text{BHT})_2(\text{THF})_2$

Cite this: DOI: 10.1039/x0xx00000x

James A. Wilson,^a Sally A. Hopkins,^b Peter M. Wright^c and Andrew P. Dove^{a*}Received 00th January 2012,
Accepted 00th January 2012

DOI: 10.1039/x0xx00000x

www.rsc.org/

The 'immortal' ring-opening polymerisation (iROP) of pentadecalactone (PDL), catalysed by magnesium 2,6-di-tert-butyl-4-methylphenoxide ($\text{Mg}(\text{BHT})_2(\text{THF})_2$) is reported for the first time. The polymerization was shown to occur without the requirement for extensive drying techniques or inert atmosphere whilst retaining end-group fidelity. The iROP technique is also further demonstrated to be applicable to ϵ -caprolactone (ϵCL).

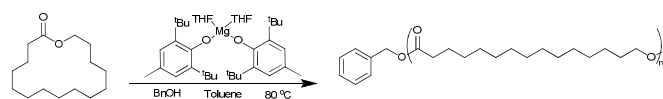
Ring-opening polymerisation (ROP) of large ring lactones is of great interest as a consequence of the properties that these materials exhibit, such as high tensile strength.¹⁻⁵ However, high molecular weight polymers produced from macrocyclic lactones were difficult to achieve until the turn of the century as a consequence of inorganic catalysts relying heavily on the enthalpy of breaking ring-strain to drive polymerization.⁶⁻⁸ Whilst this method is ideal for smaller (4-6 ring) lactones with high ring-strain, 14-16 ring lactones are sufficiently large to not exhibit strain and are thus commonly hard to polymerise using such catalysts.

Recent studies have shown that a range of species are able to polymerize the 16-membered cyclic lactone, ω -pentadecalactone (PDL). Poly(pentadecalactone) (PPDL) contains a long 14-carbon length chain per repeat unit, which gives the polymer a highly hydrophobic nature leading to tensile properties similar to that of low density poly(ethylene) (LDPE).^{13, 14} Furthermore, the recurring ester group of the chain makes the polymer susceptible to degradation in hydrolytic conditions.^{15, 16} Amongst the species reported to mediate this entropy-driven process are yttrium, zinc and aluminium catalysts,^{7, 9} as well as organocatalysts and enzymes.^{1, 10-12, 17, 18}

Social and economic pressures have pushed studies toward finding 'greener', less environmentally damaging processes of material production. Currently, ROP catalysts are often dependent on rigorously dry and inert environments, the

implementation of which increases the cost and time of the total process. The presence of water in particular can be problematic for end-group fidelity and transesterification side reactions, leading to polymers of high dispersity and diverse properties.¹⁹ Organic and enzymatic catalysts both initiate ROP from any present water; however organometallic catalysts can be tailored through ligand variation to negate the effects of water although are commonly deactivated under such conditions. Polymerisations would therefore be performed in inert atmospheres, the degassing of which can be time consuming and costly depending on the environment (*i.e.* Ar or N_2) or quantity of degas cycles. The ideal catalyst for use in a commercially viable process would therefore not initiate from water, have a high throughput before poisoning and be produced from renewable or inexpensive, commercially available compounds. 'Immortal' ring-opening catalysts as pioneered by Carpentier, Guillaume and coworkers meet such demands through acting as 'true' catalysts allowing low quantities of catalyst with respect to monomer, ignoring any impurity present in the reaction mixture and maintaining a high monomer turnover number.^{7, 8, 20, 21} Whilst pentadecalactone has been shown to be catalyzed by the small range of catalysts described above, so far none have been shown to polymerize in the presence of water without water initiation and water-based transesterification side reactions taking place.

A recent report has shown the ability of the metallorganic catalyst, magnesium 2,6-di-tert-butyl-4-methylphenoxide ($\text{Mg}(\text{BHT})_2(\text{THF})_2$), to polymerize the ROP of ϵ -caprolactone



Scheme 1 Polymerization of pentadecalactone (PDL) with benzyl alcohol (BnOH) initiator.

(ϵ CL) under “air” conditions, *i.e.* the reagents used were not dried prior to use in an oxygen-rich (air) environment.²² This study investigates the ‘immortal’ ring-opening polymerization of PDL using $\text{Mg}(\text{BHT})_2(\text{THF})_2$. Furthermore, for the first time the successful polymerization of PDL is shown to occur in atmospheric conditions, without drying reagents beforehand and still maintaining high end-group fidelity (Scheme 1).

The synthesis of $\text{Mg}(\text{BHT})_2(\text{THF})_2$ was replicated in line with the previous report from the Ittel group.²³ Briefly, under an argon environment, $n\text{Bu}_2\text{Mg}$ was reacted with 2 molar equivalents of BHT in toluene. The solvent was removed and pentane was added in excess, followed by 2 molar equivalents of tetrahydrofuran. Following the reaction, all solvents were again removed and the white solid was dried under vacuum overnight before being stored in a glovebox. $\text{Mg}(\text{BHT})_2(\text{THF})_2$ has been studied as a catalyst for the ROP of ϵ CL.²² PDL is a much larger (16-membered) cyclic molecule compared to ϵ CL (7-membered cyclic molecule) with a lower ring-strain that results from its greater flexibility. Thus, polymerization is driven through the entropic gain of rotation from ring-opening rather than ring-strain enthalpy, resulting in longer reaction times to reach full conversion. The catalytic activity of $\text{Mg}(\text{BHT})_2(\text{THF})_2$ in the ROP of PDL, using benzyl alcohol as an initiator, was studied (Table 1). The reactions were generally undertaken in 75 wt.% toluene at 80 °C in order to maintain the poorly soluble monomer and polymer in solution. Monomer conversion was monitored during the polymerization using ^1H NMR spectroscopy by monitoring the disappearance of the monomer $\text{CH}_2\text{OC}=\text{O}$ resonance ($\delta = 4.15$ ppm) and appearance of the polymer $\text{CH}_2\text{OC}=\text{O}$ resonance ($\delta = 4.05$ ppm) in agreement with previous literature.²⁴ The viscosity of the solution noticeably increased throughout the reaction. The reaction was quenched using acidified methanol (5% 1 M HCl), dissolved into chloroform and precipitated in excess methanol. Analysis of the resultant polymer by Gel Permeation Chromatography (GPC) demonstrated increasing molar mass in line with increased targeted degrees of polymerization. Notably, the dispersity of these polymers was approximately 2 which indicated that significant transesterification occurred alongside ROP during the polymerization process. PDL polymerization kinetics followed through ^1H NMR spectroscopy presented consumption of PDL throughout the polymerization indicative of first order kinetics, maintaining the number of active chains and conversion was maintained throughout the reaction, displaying

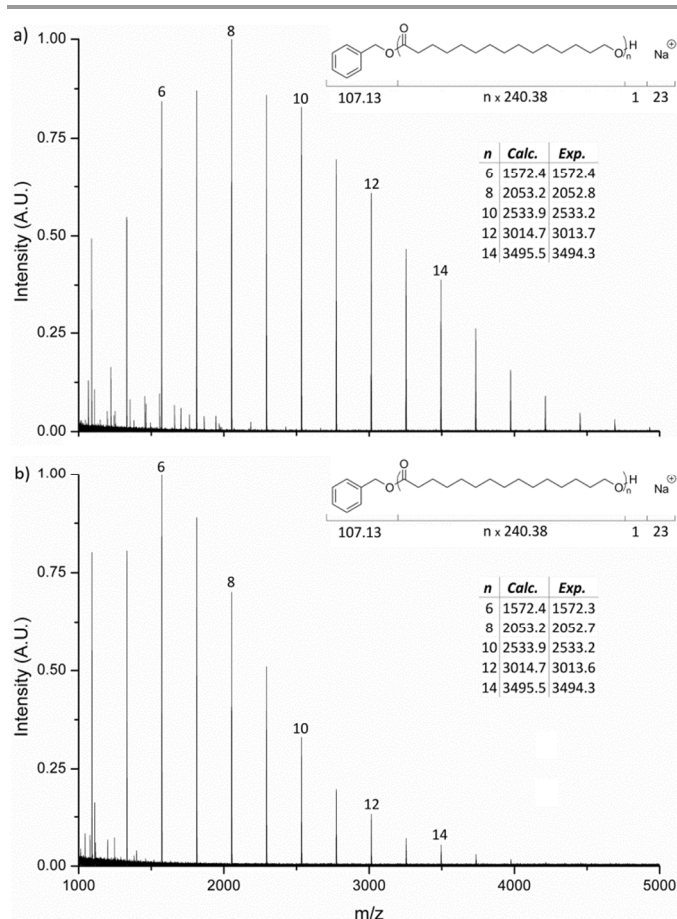


Figure 1 a) MALDI-TOF of DP10 PPDL produced in a dry argon environment b) MALDI-TOF of DP10 PPDL produced in 'air' conditions

no solvation effects decreasing the rate. Furthermore, steady growth of the polymer was observed with M_n increasing proportionally to monomer conversion.

Further polymerizations were performed without prior drying or degassing of monomer, initiator or solvent. These polymerizations showed control similar to those in which these components had been dried, with comparable yield, dispersity (\bar{D}_M) and theoretical molecular weight based on monomer conversion (Table 1). The end-group fidelity of these reactions was quantified through MALDI-TOF mass spectrometry (Figure 1). A single distribution was observed, attributable to benzyl alcohol initiation, indicating that no initiation from water had

Table 1 Synthesis of PPDL using 1 eq. $\text{Mg}(\text{BHT})_2(\text{THF})_2$

Monomer	[M]:[I]	Time (h)	Monomer Conversion ^d (%)	M_p^e	M_n^e	M_w^e	\bar{D}_M^e
PDL	10:1	6	99	11900	6600	12700	1.94
PDL	25:1	6	94	26600	11100	26000	2.34
PDL	50:1	6	94	47900	16500	48100	2.91
PDL	100:1	15	95	99700	33300	84300	2.53
PDL ^a	10:1	18	92	2000	2500	4000	1.58
PDL ^a	50:1	6	95	54100	17400	57300	3.29
PDL ^{a,b}	50:1	6	95	45500	9000	41900	4.66
PDL ^{a,c}	50:1	6	94	48500	14300	47000	3.29

^aIn 'air' conditions. All polymerizations conducted using 75 wt.% toluene at 80 °C, except ^b in bulk at 100 °C and ^c using 75 wt.% hexane at 80 °C. ^dDetermined by ^1H NMR Spectroscopy. ^e Determined by Gel Permeation Chromatography.

Table 2 'Immortal' ring-opening polymerization results for varied $\text{Mg}(\text{BHT})_2(\text{THF})_2$ concentrations polymerizing PDL and ϵCL .^a

Monomer	[M]:[I]:[cat]	[M]:[I]	Time (h)	Monomer Conversion ^b (%)	M_p^c	M_n^c	M_w^c	D_M^c
PDL	100:1:1	100:1	15	95	99700	33300	84300	2.53
PDL	200:1:1	200:1	19	82	195400	89100	176500	1.98
PDL	200:10:1	20:1	19	99	20800	9900	20900	2.11
PDL	1000:10:1	100:1	48	36	42100	17300	41500	2.39
PDL	10000:100:1	100:1	24	0	-	-	-	-
ϵCL	100:1:1	100:1	0.5	99	38300	23800	41600	1.75
ϵCL	1000:10:1	100:1	0.5	99	39600	27400	43400	1.60
ϵCL	5000:10:1	500:1	24	89	25800	18200	30900	1.70
ϵCL	10000:100:1	100:1	24	0	-	-	-	-

^a All polymerizations conducted in dry conditions using 75 wt.% toluene. ^b Determined by ^1H NMR Spectroscopy. ^c Determined by Gel Permeation Chromatography.

occurred. Low molecular weight cyclic species were also detected by GPC analysis of the crude polymers. Following deconvolution of the chromatograms with an idealized Gaussian fit, the cyclic oligomer fraction was able to be estimated at about 12% of all polymer species. The cyclic species were easily removed through precipitation in methanol. It can thus be assumed the catalyst is selectively initiating the ROP with benzyl alcohol in preference to water.

The conditions under which this ROP was able to be conducted could be extended. To this end, the replacement of toluene with a more hydrophobic solvent was investigated. ROP of PDL in hexanes yielded comparable results to those observed with toluene despite the lack of solubility of the polymer in hexanes even at elevated temperatures (Table 1, entry 8). In a further experiment, bulk polymerisation was investigated at 100 °C, the further elevated temperature was required to maintain the monomer and polymer in the melt phase. While polymerisation was successful a significant change in the molecular weight distribution was observed such that a significant shift to a bimodal distribution of polymer and cyclic oligomers was observed, likely to be the result of poor accessibility to the propagating chain end.

In order to investigate the 'immortal' ring-opening polymerization (iROP) behaviour of $\text{Mg}(\text{BHT})_2(\text{THF})_2$ under inert conditions, the catalyst loading was decreased by an order of magnitude in a sequence of reactions until no observable polymerization occurred. It was observed that a monomer-to-catalyst molar ratio of 200:1 underwent successful polymerization with a target degree of polymerization (DP) of 200 being reached (Table 2). The quantity of impurities with respect to catalyst is proposed to lead to the complete loss of catalytic activity with polymerizations of initiator-to-catalyst molar ratio of 100:1, with no monomer conversion being observed after 24 h. The results infer 'truer' catalytic behaviour in the polymerization which pertain to the degree of active chains being greater than the quantity of catalyst; hence the chain can activate and deactivate reversibly by chain transfer, requiring low catalyst loading. Very recently, a catalyst study from the Duchateau group has also shown that immortal ROP of PDL is possible with a range of aluminium, zinc and calcium species.¹⁷ Herein, we have demonstrated that $\text{Mg}(\text{BHT})_2(\text{THF})_2$ enables the synthesis of relatively high molecular weight PPDL, perhaps on account of

lower degrees of transesterification under the conditions employed.

The 'immortal' catalytic ability of $\text{Mg}(\text{BHT})_2(\text{THF})_2$ in the ROP of ϵCL initiated from benzyl alcohol with a monomer-to-initiator ratio of 100:1 was also explored. The quantity of $\text{Mg}(\text{BHT})_2(\text{THF})_2$ used was systematically decreased in line with the study of PDL ROP (Table 2). $\text{Mg}(\text{BHT})_2(\text{THF})_2$ was shown to mediate the ROP of ϵCL at a reduced molar ratio with no loss of catalytic activity. Poly(caprolactone) (PCL) was produced with DPs greater than 500 at reduced catalyst loading ([I]:[cat.] being 10:1) with comparable dispersities. However, similarly to PDL polymerization with an initiator-to-catalyst molar ratio of 100:1, polymerization does not occur as a consequence of catalyst deactivation.

Conclusions

Magnesium 2,6-di-tert-butyl-4-methylphenoxide ($\text{Mg}(\text{BHT})_2(\text{THF})_2$) has been successfully demonstrated to catalyze ω -pentadecalactone (PDL) through 'immortal' ring-opening polymerization (iROP) for the first time. Polymers produced exhibited no water initiation when no drying techniques were used to prepare the reagent. The iROP of both PDL and ϵ -caprolactone (ϵCL) were also shown to be successful for catalyst:monomer ratios above 1:10.

Notes and references

^a Department of Chemistry, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, UK.

^b Infineum UK Ltd., Milton Hill, Abingdon, OX13 6BB, UK.

^c Infineum USA, 1900 East Linden Avenue, Linden, New Jersey, 07036, USA.

EPSRC are acknowledged for support through a CASE DTA studentship to J.A.W. The work was also supported by Infineum UK Ltd as part of its commitment to fundamental chemical research. A.P.D. is grateful to the Royal Society for the award of an Industrial Fellowship.

Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/c000000x/

- M. L. Focarete, M. Scandola, A. Kumar and R. A. Gross, *J. Polym. Sci., Part B: Polym. Phys.*, 2001, 39, 1721-1729.
- Z. Jiang, H. Azim, R. A. Gross, M. L. Focarete and M. Scandola, *Biomacromolecules*, 2007, 8, 2262-2269.

3. B. Lebedev and A. Yevstropov, *Makromol. Chem.*, 1984, 185, 1235-1253.
4. M. de Geus, I. van der Meulen, B. Goderis, K. van Hecke, M. Dorschu, H. van der Werff, C. E. Koning and A. Heise, *Polym. Chem.*, 2010, 1, 525-533.
5. N. Simpson, M. Takwa, K. Hult, M. Johansson, M. Martinelle and E. Malmström, *Macromolecules*, 2008, 41, 3613-3619.
6. A. P. Dove, *Chem. Commun. (Cambridge, U. K.)*, 2008, 6446-6470.
7. N. Ajellal, J.-F. Carpentier, C. Guillaume, S. M. Guillaume, M. Helou, V. Poirier, Y. Sarazin and A. Trifonov, *Dalton Trans.*, 2010, 39, 8363-8376.
8. S. M. Guillaume and J.-F. Carpentier, *Catal. Sci. Tech.*, 2012, 2, 898-906.
9. I. van der Meulen, E. Gubbels, S. Huijser, R. Sablong, C. E. Koning, A. Heise and R. Duchateau, *Macromolecules*, 2011, 44, 4301-4305.
10. M. Bouyahyi, M. P. F. Pepels, A. Heise and R. Duchateau, *Macromolecules*, 2012, 45, 3356-3366.
11. H. Uyama, H. Kikuchi, K. Takeya and S. Kobayashi, *Acta Polym.*, 1996, 47, 357-360.
12. A. Kumar, B. Kalra, A. Dekhterman and R. A. Gross, *Macromolecules*, 2000, 33, 6303-6309.
13. J. Cai, C. Liu, M. Cai, J. Zhu, F. Zuo, B. S. Hsiao and R. A. Gross, *Polymer*, 2010, 51, 1088-1099.
14. G. Ceccorulli, M. Scandola, A. Kumar, B. Kalra and R. A. Gross, *Biomacromolecules*, 2005, 6, 902-907.
15. I. van der Meulen, M. de Geus, H. Anthéunis, R. Deumens, E. A. J. Joosten, C. E. Koning and A. Heise, *Biomacromolecules*, 2008, 9, 3404-3410.
16. J. Zotzmann, M. Behl, Y. Feng and A. Lendlein, *Adv. Funct. Mater.*, 2010, 20, 3583-3594.
17. M. Bouyahyi and R. Duchateau, *Macromolecules*, 2014, 47, 517-524.
18. L. Jasinka-Walc, M. R. Hansen, D. V. Dudenko, A. Rozanski, M. Bouyahyi, M. Wagner, R. Graf and R. Duchateau, *Polym. Chem.*, 2014, DOI: 10.1039/c3py01754k
19. S. Namekawa, S. Suda, H. Uyama and S. Kobayashi, *Int. J. Biol. Macromol.*, 1999, 25, 145-151.
20. T. L. Yu, C. C. Wu, C. C. Chen, B. H. Huang, J. C. Wu and C. C. Lin, *Polymer*, 2005, 46, 5909-5917.
21. T. Aida, *Prog. Polym. Sci.*, 1994, 19, 469-528.
22. H.-J. Fang, P.-S. Lai, J.-Y. Chen, S. C. N. Hsu, W.-D. Peng, S.-W. Ou, Y.-C. Lai, Y.-J. Chen, H. Chung, Y. Chen, T.-C. Huang, B.-S. Wu and H.-Y. Chen, *J. Polym. Sci., Part A: Polym. Chem.*, 2012, 50, 2697-2704.
23. J. Calabrese, M. A. Cushing and S. D. Ittel, *Inorg. Chem.*, 1988, 27, 867-870.
24. M. Eriksson, L. Fogelstrom, K. Hult, E. Malmstrom, M. Johansson, S. Trey and M. Martinelle, *Biomacromolecules*, 2009, 10, 3108-3113.