

Fundamental Understanding of Microwave Assisted Ring-Opening Polymerisation and Co-Polymerisation



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Declaration

Except where specific reference has been made to other sources, the work presented in this thesis is the original work of the author. It has not been submitted, in whole, or in part, for any other degree or qualification.

Signed.....

Date.....

Edward Taylor Greenhalgh

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Abstract

The work presented in the thesis attempted to gain in-depth understanding of the effect that the microwave energy has on various facets of the ring-opening polymerisation of cyclic esters with a view to synthesising novel bio-degradable homopolymers, branched structures and copolymers.

Chapter 1 introduces the various synthetic polymer procedures and lists possible final product architectures. The main technique that is used throughout this thesis, ring-opening polymerisation, is discussed in great detail. The various targeted linear aliphatic polyesters are introduced. Finally, the fundamental theory behind microwave dielectric heating is discussed.

Chapter 2 outlines the various characterisation techniques that are used to analyse the various synthesised materials throughout the work in this thesis. The polymerisation techniques used, particularly using the microwave reactor, is also discussed.

In Chapter 3, the effect that microwave heating has upon the homopolymerisation of poly(ϵ -caprolactone) is investigated. Detailed analysis of the dielectric properties of the reagents and accurate temperature monitoring is applied at various stages of the reaction mechanism to compare and contrast the effect of microwave and conventional heating.

Chapter 4 describes the impact that microwave energy has upon the copolymerisation reactions when a second cyclic ester is introduced, D/L-lactide. Various procedures are utilised in an attempt to synthesise bio-degradable block copolymers with interesting mechanical properties and degradation rates. The dielectric properties of the reagents and their polymer structures are used to rationalise any experimental observations.

The work presented in Chapter 5 investigates the synthesis of branched polymers using a di-lactone branching agent, composed to two joined ϵ -CL units. Various analytical techniques are employed to guarantee successful branching. The effect of microwave energy is scrutinised, with a view to creating faster rates of reaction and altering the final product structure using direct dielectric heating.

Finally, Chapter 6 provides the overall conclusions obtained from the work presented in this thesis, before providing possible routes of subsequent study for further research into this area.

Abbreviations

<i>b</i> -PCL	Branched Poly(ϵ -Caprolactone)
bis-MPA	2,2-bis(hydroxymethyl)propanoic acid
BnOH	Benzyl Alcohol
BOD	4,4'-Bioxepanyl-7,7'-dione
CCS	Core Cross-Linked Star
$\bar{D}$	Dispersity
DCM	Dichloromethane
DLLA	D/L-Lactide
dn/dc	Differential Refractive Index
DP	Degree of Polymerisation
DSC	Differential Scanning Calorimetry
ϵ'	Dielectric Constant
ϵ''	Dielectric Loss
FO	Fibre-Optic
FCH	Flash Conventional Heating
GC	Gas Chromatography
GPC	Gel Permeation Chromatography
HPLC	High-Pressure Liquid Chromatography
<i>hb</i> -PCL	Hyperbranched Poly(ϵ -Caprolactone)
IR	Infrared
LLA	L-Lactide
k^{app}	Apparent Rate of Polymerisation
k_{ct}	Rate of Chain Transfer
k_{deact}	Rate of Deactivation
k_{i}	Rate of Initiation

k_p	Rate of Propagation
MALDI-TOF	Matrix Assisted Laser Desorption-Ionisation Time of Flight
MALLS	Multi-Angle Laser Light Scattering
M_n	Number Average Molecular Weight
M_p	Peak Molecular Weight
MS	Mass Spectrometry
M_w	Weight Average Molecular Weight
N_i	Number of Individual Polymer Chains
NMR	Nuclear Magnetic Resonance
PDI	Polydispersity Index
PCL	Poly(ϵ -Caprolactone)
PLA	Poly(Lactic Acid)
PLA- <i>co</i> -PCL	Poly(Lactic Acid- <i>co</i> - ϵ -Caprolactone) Copolymer
ppm	Parts per Million
PS	Poly(Styrene)
RI	Refractive Index
ROMBP	Ring-Opening Multibranching Polymerisation
ROP	Ring-Opening Polymerisation
SCVP	Self-Condensing Vinyl Polymerisation
SEC	Size Exclusion Chromatography
Sn(Oct) ₂	Tin 2-Ethylhexanoate (Stannous Octoate)
Tan δ	Loss Tangent
T_g	Glass Transition Temperature
THF	Tetrahydrofuran
T_m	Melting Temperature
W_i	Weight of an Individual Polymer Chain
ϵ -CL	ϵ -Caprolactone
ΔG	Gibbs Free Energy
τ	Relaxation Time

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1 Introduction

The aim of this chapter is to introduce and explain the relevant topics that are discussed throughout this thesis. General polymer structures and synthetic techniques are detailed first, before the ring-opening polymerisation mechanism is examined along with relevant literature work. Biodegradable aliphatic polyesters are introduced, particularly poly(lactic acid) and poly(ϵ -caprolactone). Finally, this chapter details the fundamentals of microwave energy before examining the use of microwave heating as a method of conducting polymerisation reactions.

1.1 Introduction to Polymers

A polymer is a large molecule constructed from many small repeating units joined together by covalent bonds. The polymer, also known as a macromolecule possesses significantly different properties than the repeating units, which are called monomers.¹

Polymeric structures are present in nature; DNA and proteins are examples of biologically derived polymers. Synthetic polymers have been widely studied and utilised for over a century, with nylon and poly(ethylene) being two of the

most well known examples. The chemical and physical properties of a polymer depend on a wide range of factors, such as monomer properties and sequencing. Therefore the possibility of tailoring a polymer to meet the end use requirements has created a wide range of polymer applications; from consumer products (plastics, adhesives, paints etc) to biomedical purposes (drug delivery, implants) and many more.²⁻⁹

1.1.1 Structures

The monomer units in a polymer can be arranged in a wide variety of forms (Figure 1.1), leading to differing physical properties, such as density, rigidity, viscosity.¹⁰⁻¹⁸

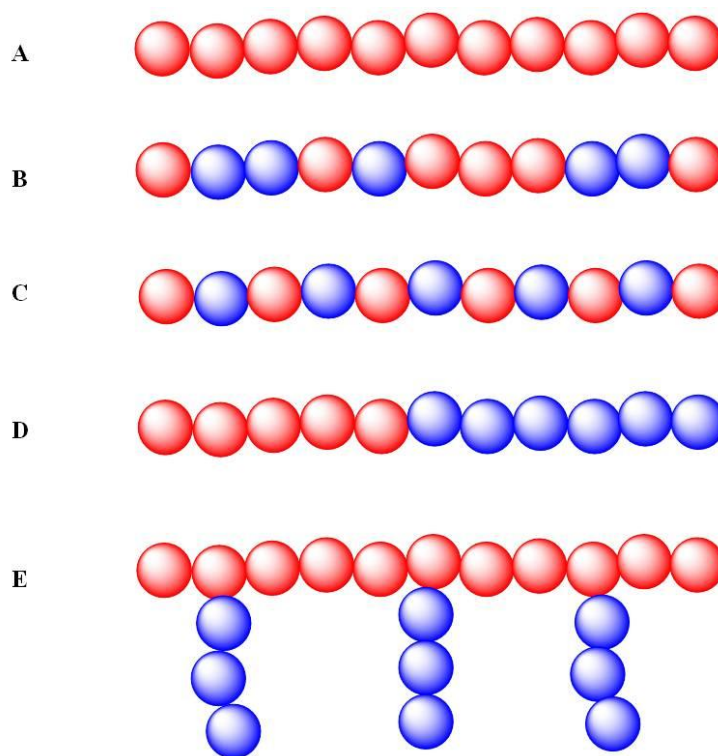


Figure 1.1: Examples of possible architectures of homopolymers and copolymers composed of two different monomers. A = homopolymer; B = random/statistical copolymer; C = alternating copolymer; D = block copolymer; E = graft copolymer.

The simplest possible composition is the linear homopolymer (Figure 1.1 A). When a second monomer is simultaneously incorporated, copolymer formation may occur depending on the monomer reactivity ratio and relative molar concentration. If the distribution of monomers A and B in the copolymer backbone is based on the statistical probability of one monomer being incorporated at any particular time, a statistical copolymer is produced (Figure 1.1, B). This probability is mainly governed by monomer reactivity. A random copolymer is formed when monomer reactivity does not control incorporation levels; instead the mole fraction determines the statistical probability of reaction. Gradient copolymers, also known as tapered copolymers, are intermediates between statistical and block copolymers. An alternating

polymer is formed (Figure 1.1, C) when each monomer has a higher affinity to react with the other monomer, rather than itself, resulting in a perfectly alternating backbone. The properties of statistical and alternating copolymers are an amalgam of the respective homopolymers.¹⁹

To obtain copolymers that contain both properties from each polymeric segments, block or graft copolymers must be formed.^{1, 20} Block copolymer formation (Figure 1.1, D) arises from sequential monomer addition after complete homopolymerisation of the first monomer. Graft copolymers (Figure 1.1, E) are created when pendent unreacted moieties are located within the initial homopolymer chain, which later reacts with the subsequent secondary monomer chains.²¹⁻²⁴ Since block and graft copolymers are two distinct homopolymers joined covalently, the overall product maintains properties of each homopolymer.^{8, 25, 26}

One method of creating branched polymer is *via* the utilisation of multifunctional monomers.²⁷ They can provide interesting mechanical and rheological properties. For example, they exhibit lower viscosity than a linear polymer of similar molecular weight due to a decreased hydrodynamic radius.²⁸⁻³¹ Grafted copolymer can be considered a type of branched macromolecule. Figure 1.2 provides examples of others.

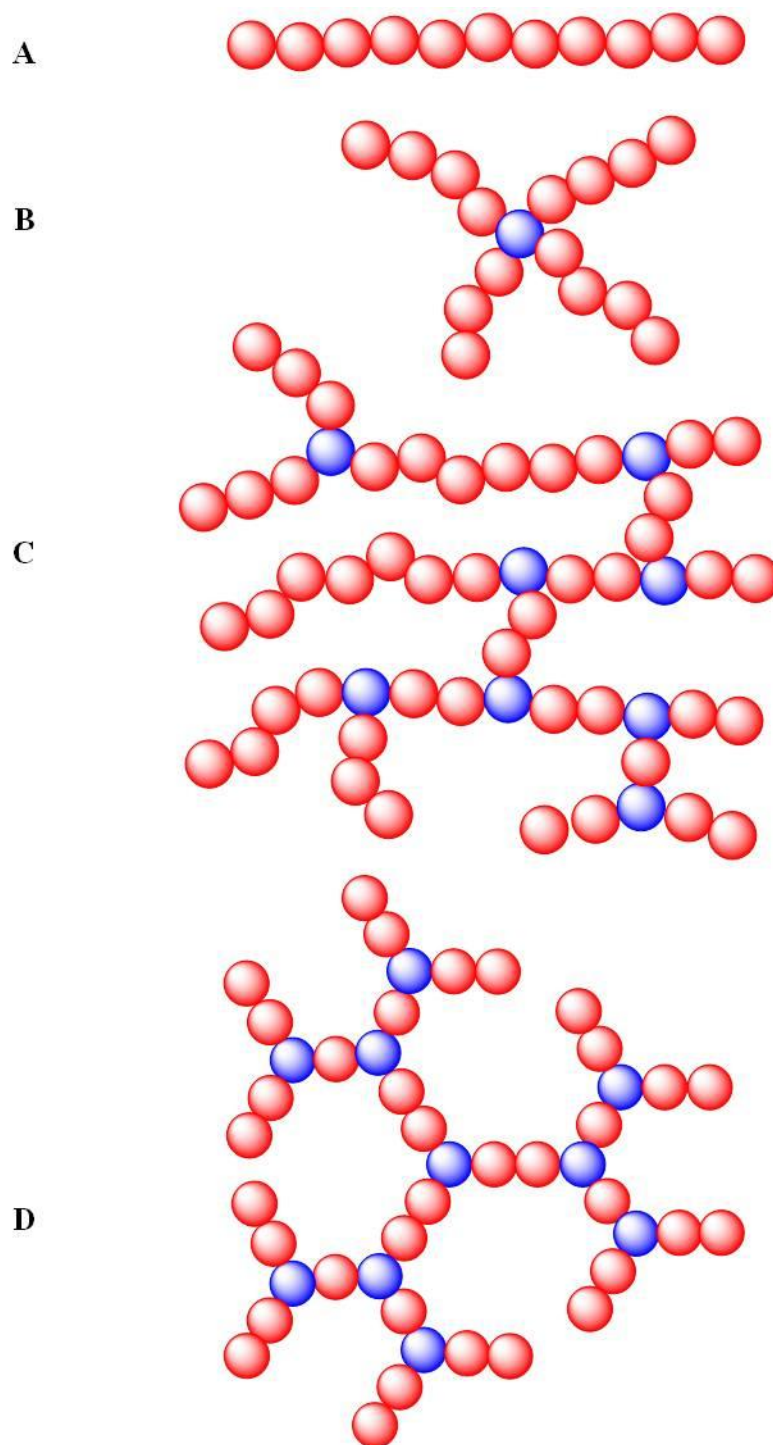


Figure 1.2: Examples of possible architectures of polymers. A = linear; B = star; C = hyperbranched; D = dendrimer.

A star polymer contains ‘arms’ that emanate from a central hub (Figure 1.2, B).²⁸ They are either formed *via* a core-first mechanism, where

linear arms grow from a multi-functional molecule at the centre.³²⁻³⁴ An arm first method is an alternative technique, where linear chains containing a functional group at the end react, forming the star structure. These structures are of interest due to reduced viscosity and potential for small molecule storage.^{9, 24, 32-34}

Dendrimers (Figure 1.2, D) are a class of perfectly ordered branched polymers that, along with lower viscosity, also contain ‘micro-environments’ in the core and a shell containing a very high concentration of functional groups.^{28, 35, 36} However, dendrimers are notoriously difficult to synthesise, on a timescale of hours to weeks required for the multi-step process where each layer of monomer is added sequentially.²⁸

Hyperbranched polymers (Figure 1.2, C) are a cheap and fast alternative to dendrimers, often created in a one-pot synthesis on a reaction timescale of a few hours, rather than weeks.^{28, 37-41} However, they have a much more statistical nature with less control and a lower degree of branching than dendrimers. Despite this, hyperbranched polymers have many potential applications for drug delivery, resins, coatings and dispersants, among others.⁴⁰ Hyperbranched polymers have been observed to have much lower viscosity than their linear analogues, both in solution and in their molten state, due to the globular structure caused by the branched architecture.²⁸ This also leads to higher reactivity and enhanced solubility due to the elevated concentration of functional end groups.^{17, 38, 42} Various methods to synthesis highly branched polymers are known, using both step and chain growth procedures.⁴¹ This will be discussed in greater detail in the introduction to Chapter 5.

1.2 Polymerisation Techniques

The technique for synthesising polymers tends to fall into one of two categories depending on the mechanism of the polymerisation reaction: either step-growth or chain-growth polymerisation.¹

Step-growth polymerisation uses multi-functional monomers that react with each other in discrete steps. When the small units react to form solely the polymeric product, it is known as addition polymerisation. If a small molecular is also produced along with the polymer, the mechanism is known as condensation polymerisation. The monomer is consumed early in the reaction, forming dimers, trimers and other oligomeric structures. The same reaction mechanism exists throughout the process as there are no initiation or termination stages.

Chain-growth polymers are formed *via* the successive addition of monomers to a growing polymer chain (this mechanism can also be called addition polymerisation). Monomer is consumed slowly in the reaction, but high molecular weight chains are afforded quickly. Chain-growth polymerisation can be broken down into three stages: initiation, propagation and termination.

- 1) Initiation involves an initiator forming the true initiation species (in what is often referred to as the ‘pre-initiation step’) and the subsequent reaction with the first monomer.

- 2) The process of adding monomer to the active species is known as the propagation step. This represents the majority of the polymerisation process. Only the active species is able to react with the monomer units.
- 3) Toward the end of the polymerisation, when monomer levels drop, the active centres often terminate; either by combining together or being removed from the end of the polymer chain.

There are four different types active centre in chain-growth polymerisation: free radical, anionic, cationic or an organo-metallic complex. The latter is the method utilised in this project, and will be discussed in greater detail later in this chapter (Section 1.2.2.5).

1.2.1 Controlled Polymerisation

There is an important category of chain-growth polymerisation where a large amount of control over polymer growth is exerted, which is described as ‘living’, ‘controlled’, ‘quasi-living’ or ‘pseudo-living’ polymerisation.¹ In this body of work it will be referred to as controlled polymerisation.

The important features of living/controlled polymerisation are:

- 1) Rapid and efficient initiation stage.
- 2) Relatively slow rate propagation.
- 3) Fast equilibrium of active centres between dormant and active polymer chains.

- 4) Almost complete elimination of termination reactions
- 5) Linear growth of molecular weight with conversion.
- 6) Relatively small molecular weight distribution.

A fast initiation means that the concentration of the active sites will remain constant and independent of conversion, and will be equal to the initial initiator concentration. The fact that propagation will not occur before complete initiation will ensure that for most living polymerisations, high molecular weight chains will not form early in the reaction, relative to the other chains. This produces polymers with a very low dispersity ($\bar{D}$). Slow propagation, coupled with the fast shuttling equilibrium of the active centres between dormant and growing chains, guarantees a uniform growth of all the polymeric chains, hence the ‘controlled’ label of the reaction.

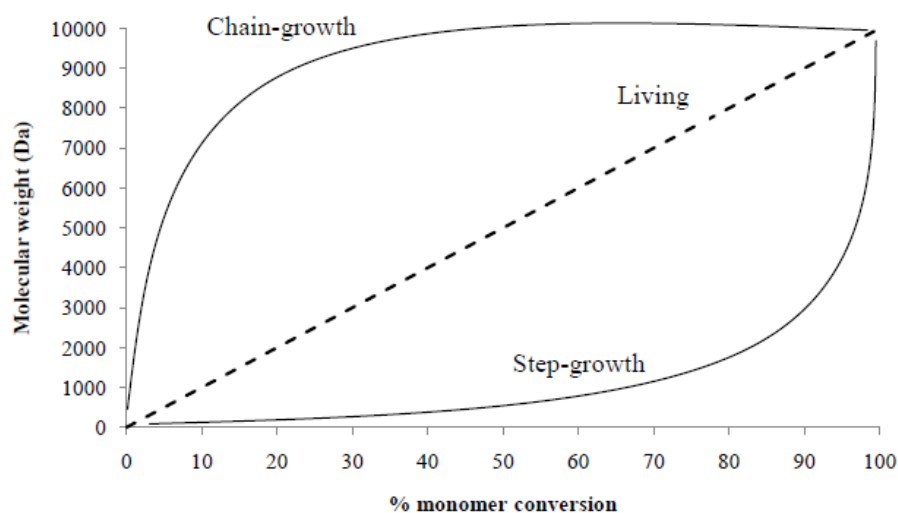


Figure 1.3: Plot of molecular weight vs conversion for chain-growth, step-growth and living polymerisations.

As the termination step is subdued, the active species remain present throughout the reaction, which will only end when all the monomer has been consumed; consequently this form of polymerisation is known as ‘living’. Further addition of subsequent monomer should lead to a continuation of polymerisation, with the possibility of block copolymer formation if a secondary monomer is added. The fact that not all termination reactions are completely nullified has led to the terms ‘quasi-living’ and ‘pseudo-living’ being used.⁴³

The most widely used living/controlled polymerisation techniques are living anionic, living cationic, living free radical and living ring-opening polymerisation (ROP).⁴³ As ROP is the method used in this thesis, an in-depth study of the ROP mechanism and current literature is conducted in the following section.

1.2.2 Ring-Opening Polymerisation

ROP is a type of chain growth polymerisation technique, where cyclic monomers undergo ring cleavage upon reaction with an initiator species. The newly ring opened moiety becomes the active species and is the propagation site at the terminus of the growing polymer chain.⁴³

Figure 1.4 represents the general diagram for the ROP mechanism, where a cyclic monomer reacts with an initiator to become a macromolecule of m amount of repeating units derived from monomer.

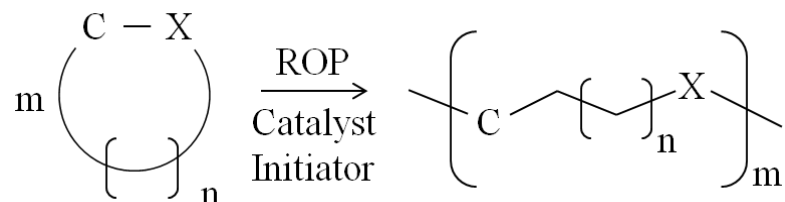


Figure 1.4: Generalised ROP scheme.

A wide variety of cyclic monomers are known to undergo ROP to form high molecular weight polymers, with a large amount of work examining compounds containing a heteroatom in the ring, such as oxygen, nitrogen, sulfur and phosphorous.⁴³ The heteroatom provides the target point for nucleophilic and electrophilic attack. Some examples of cyclic monomers that undergo ROP are provided in Figure 1.5.

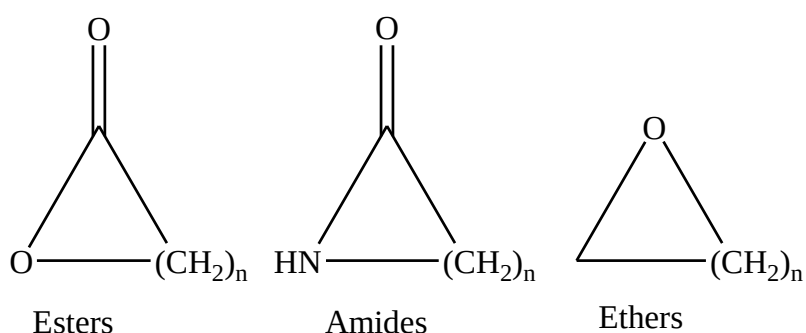


Figure 1.5: Cyclic monomers.

Mechanistic and thermodynamic factors control the polymerisability of cyclic monomers.⁴³ Some common examples of structures unable to undergo ROP are

benzene and cyclohexane. The lack of ring strain on these compounds means that the more thermodynamically stable state is the ring form, rather than the linear macromolecular structure. Cyclic monomers with 3, 4 and 8 membered rings show highly negative free energy (ΔG) of polymerisation and this means that ROP is highly likely to occur.

However, 5 and 7 membered ring monomers often have relatively low ΔG values, and are thus less susceptible to polymerise. Cyclic monomers with 6 atoms generally do not undergo ROP. However, an addition of a heteroatom can facilitate ROP, for example cyclohexanone will not undergo ROP, but lactide will.

Lactones and lactides are exclusively studied in this thesis. A detailed analysis of their respective mechanisms and final polymer properties are examined later in this chapter.

1.2.2.1 General ROP Mechanism

The general mechanism of ROP can be broken down into separate stages, much like in chain growth polymerisation. Figure 1.6 denotes the initiation, propagation, termination and segment transfer mechanisms present in ROP.⁴³

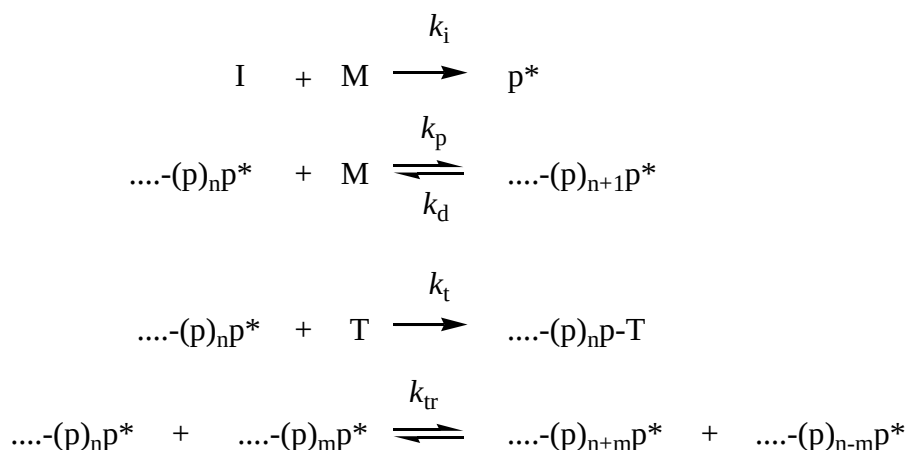


Figure 1.6: Various stages of ROP mechanism.⁴³ I is the initiating species. M is the monomer and p represents the opened monomer in the polymer chain. p* is the active propagating species. T is the terminating species. k_i , k_p , k_d , k_t and k_{tr} are the rate constants for the initiation, propagation, depropagation, termination and transesterification respectively.

To begin ROP, the first monomer unit must react with an initiator. However there is often the need for a pre-initiation reaction. This is where either the initiator or monomer (or both) need to react with a separate entity, thus producing the true initiation reagent. When the reagents are prepared for reaction, the first monomer unit undergoes ROP *via* reaction with the true initiator.

After the first cyclic monomer has been cleaved, it becomes the active centre where further monomer units can react during the next stage of reaction, the propagation period. This addition of new cyclic monomer units to the growing polymer chain will happen rapidly, without side reactions.

A transfer mechanism can also be present. This is where the active centre is capable of leaving growing polymer chains and forming new chains. If this is a rapid process, this can be advantageous as it ensures that the polymer chains grow at similar rates and with a narrow distribution of sizes. However, when

this step is slow and the active centres do not react between chains of similar sizes, a process called transesterification can dominate. This often occurs at low monomer concentration and can disrupt control over the polymer products.

The general mechanism for termination is provided in Figure 1.6. The termination stage is a major issue with reactions where the active species can be consumed, for example when two radical species combine, killing both. However when a metal catalyst acts as an active site, termination reactions are much less significant. Hence, ROP can act as a controlled polymerisation with the rate of $k_t = 0$.

1.2.2.2 Kinetic Criteria for Controlled ROP

A thorough understanding of the kinetic studies during ROP can determine the level of control exhibited over the polymerisation.⁴⁴ The ROP reaction equations in Figure 1.6 can be used to analyse the controlled nature of ROP. If it is assumed that initiation is sufficiently fast ($k_i \gg k_p$), then the DP does not have an effect on rate constants and all side reactions are ignored $k_t k_i = 0$.³⁵

Therefore, if only the fast initiation and reversible propagation reactions are present during the ROP, the rate constant of propagation (k_p) can be represented using the first order rate constant as:

$$R_p = - \frac{d[M]}{dt} = k_p \sum [p^*][M] - k_d \sum [p^*]$$

Equation 1.1

However, as $k_p \gg k_d$, then $k_d \sum [p^*]$ becomes negligible and can be ignored. Also the concentration of active centres remains constant throughout the reaction (independent of the monomer concentration). Therefore, the equation can be simplified to:

$$- \frac{d[M]}{dt} = k_p \sum [p^*]$$

Equation 1.2

Using the first-order rate law:

$$\ln[A] = -k_t + \ln[A]_o$$

Equation 1.3

After integration of Equation 1.2, this leads to the semi logarithmic dependence of $[M]$ to reaction time as there is fast and efficient initiation $\sum [p^*] = [I]_o$

$$\ln \frac{[M]_o}{[M]} = k_p \sum [p^*] t = k_p [I]_o t$$

Equation 1.4

Therefore the plot of $\ln [M]_o/[M]$ against time should be linear for controlled ROP.

For a growing polymer chain, assuming $k_i \gg k_p$, the DP at any time should be equal to the product of conversion and theoretical DP.

$$DP_n = \frac{[M]_o - [M]}{[I]_o}$$

Equation 1.5

After multiplying Equation 1.5 by $[M]_o/[M]_o$ and rearranging gives:

$$DP_n = \frac{[M]_o}{[I]_o} \times \frac{[M]_o - [M]}{[M]_o}$$

Equation 1.6

Therefore controlled ROP is further confirmed if the plot of DP_n (M_n) against monomer conversion ($[M]_o - [M] / [M]_o$) is linear.

1.2.2.3 Methods of ROP

The two main classes of ROP that are used to form linear aliphatic polyesters are either ionic or coordination, depending on the initiator and catalyst mechanism and process.⁴³ The processes use a wide range of initiators and catalysts, which have different roles. The initiator transfers an active site and becomes incorporated into the macromolecule. The catalyst promotes ROP whilst it does not react irreversibly.

The anionic mechanism uses alkali metal alkoxides and carboxylates as the catalyst/initiator species. The monomers undergo nucleophilic attack by the negatively charged initiator species. The propagating species is the negatively charged growing polymer chain.⁴³

In cationic ROP, electrophilic reagents are used; initiators are protic acids and strong organic acids used with Lewis acid catalysts. The heteroatom in the ring forms a formal bond with the Lewis acid in the initiation step, forming a cationic centre. A monomer will then react with the cation *via* the lone pair of the heteroatom, cleaving the ring. However, in recent years these methods for forming linear aliphatic polyesters have become less popular due to loss of control and side reactions.⁴³ The ionic active site has a high level of reactivity and a chain transfer mechanism can disrupt control of molecular weight growth.

1.2.2.4 Coordination-Insertion

The most common method of ROP involves the use of metal alkoxides and metal carboxylates as the initiator/catalyst mixture in a process called coordination/insertion (C/I).^{45, 46} This is a type of activated monomer approach, where the cyclic monomer is prepared for ROP *via* coordination to a metal (Figure 1.7) before being inserted into the metal alkoxide bond. This process is known to have short reaction times. It provides polymers with high molecular weight and with a high level of control over the architecture of the product.

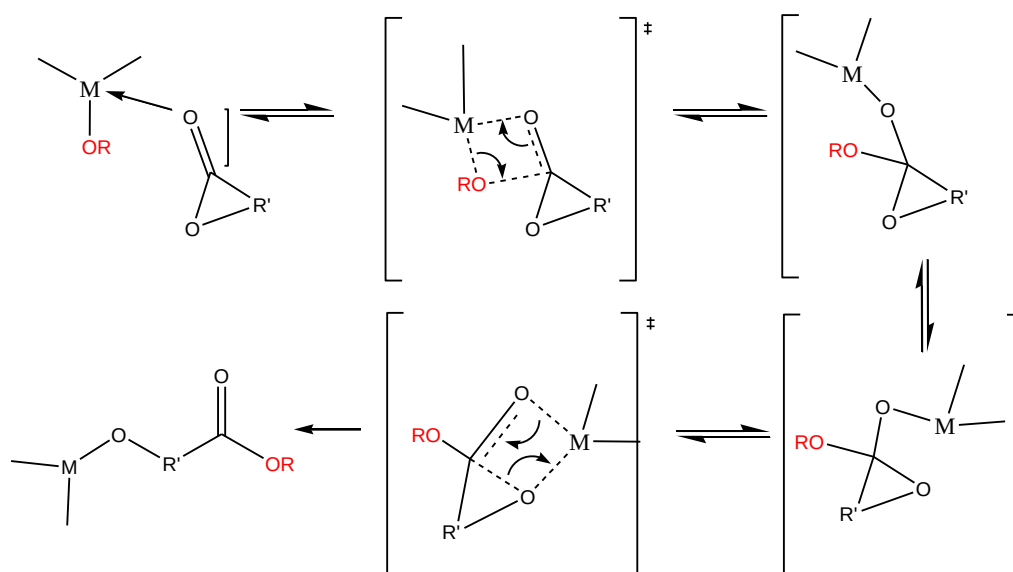


Figure 1.7: Coordination / Insertion Mechanism for ROP.

The first stage of the C/I mechanism is the coordination of the monomer to the metal. The lone pair of electrons, from the heteroatom in the cyclic ester, forms a dative bond by donating the lone pair to a vacant orbital in the Lewis acidic metal. This alters the polarisability of the heteroatom, which makes the carbon next to the heteroatom more susceptible to nucleophilic attack by the ligand, forming a new ring. This unstable ring causes the acyl bond to cleave, thus opening the monomer. The ligand leaves the metal and there is a simultaneous formation of a new bond between the heteroatom of the monomer to the metal. Therefore the monomer is now located between the metal and the ligand, hence the ‘insertion’ label. The metal remains at the end of the growing chain, able to coordinate to a new monomer.

A wide range of metal compounds are used for the coordination/insertion mechanism. The metals act as Lewis acids, thus must have free p, d or f orbitals capable of accepting the lone pair from the heteroatom in the cyclic ester, thus making the monomer able to undergo cleavage. To separate this mechanism from others, the catalyst must be stable in the absence of the monomer, i.e. not possess a formal charge. As the initiator species is used as a starting point in the polymer chain, the coordination/insertion method allows for potential end group functionality. For example, selecting a multi-armed initiator species could allow for facile formation of star polymers.¹⁷

A major benefit of the coordination/insertion mechanism is that controlled polymerisation is possible.⁴⁷⁻⁵⁰ Theoretically there is no termination step, as the catalyst is not consumed at any stage and is always present on the end of the polymer chain. This means that the number of active sites remain constant, independent of DP. Therefore there will be a linear progression of molecular weight with monomer conversion. Molecular weight can be targeted by the monomer to initiator ratio.

1.2.2.5 Metal Catalysts

A wide range of metal catalysts have been studied, for example iron, zinc, yttrium and some lanthanide based systems.^{43, 51-53} However, the most widely studied are aluminium and tin.^{47, 51} Aluminium alkoxide species are known to catalyse full monomer conversion in a few minutes and at room temperature

whilst exhibiting control over the ROP.⁵⁴ Aluminium alkoxides are known to act as both initiator and catalyst, i.e. aluminium iso-propoxide. But a significant issue affecting the use of aluminium is the fact that the catalytic species resides in the final product and aluminium can cause chronic neurological conditions, such as Alzheimer's.⁴³ Thus, aluminium based catalysts will never be used in biomedical devices.

1.2.2.6 Tin Catalyst

Tin (II) and tin (IV) alkoxides are widely used as efficient ROP initiator/catalyst using the coordination/insertion mechanism, the most popular being tin (II) ethyl-hexanoate, also known as stannous octoate ($\text{Sn}(\text{Oct})_2$). Tin can easily act as a Lewis acid, due to its energetically favourable empty d-orbitals that are caused by sp^3d^2 hybridisation at the metal centre. The d-orbitals can readily react with a protic compound, (e.g. alcohols, amines, thiols) to create the alkoxide/thiolate species. This is known as pre-initiation, as the metal alkoxide is the true catalytic species. Thus $\text{Sn}(\text{Oct})_2$ is referred to as the pre-catalyst, as shown in Figure 1.8.

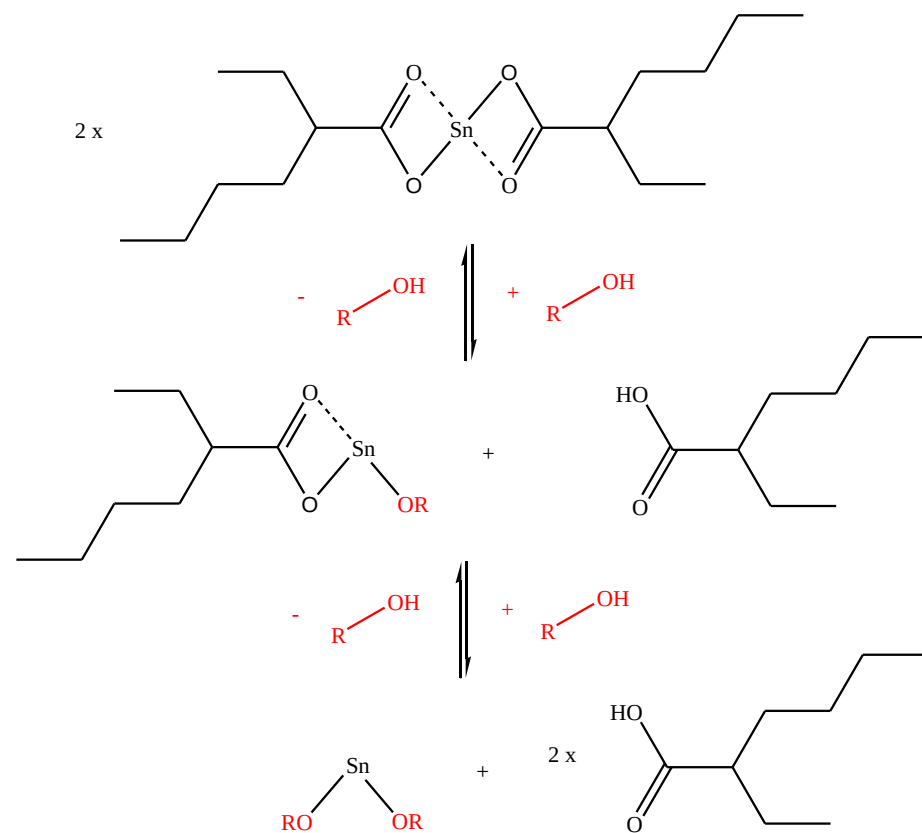


Figure 1.8: Mechanism for true catalyst $\text{Sn}(\text{OR})_4$ formation step via the reaction of $\text{Sn}(\text{Oct})_2$ with one or two initiating species (ROH).

It has been proved that $\text{Sn}(\text{Oct})_2$ initiate or catalyse ROP without the presence of the co-initiator.⁵⁵ It is unclear whether both octanoate ligands must be replaced with alkoxide, or whether ROP can occur with one ligand remaining on the tin. $\text{Sn}(\text{Oct})_2$ tends to be the only catalyst used in industry for the ROP of many cyclic esters.⁴³ Not only does it afford high molecular weight polymers with a narrow dispersity, it is cheap, readily available, highly catalytic, but most significantly it is the only catalyst that has been approved by the Federal Drugs Administration for food contact in packaging.⁵⁶

Tin alkoxide species tend to be less reactive than other metals (i.e. aluminium) and thus higher temperatures are required (80 – 150 °C) over a longer period of time (12- 24 hours). A major disadvantage with $\text{Sn}(\text{Oct})_2$ (and other tin based catalysts) is the prominence of side reactions.⁵⁷ In particular, transesterification reactions occur at the elevated temperatures and longer reaction times are required. This leads to either an intermolecular or an intramolecular transesterification reaction. This causes a broadening of $\bar{M}$ and a loss of the controlled nature of ROP. In copolymerisation reactions, this backbiting can lead to less control over macromolecular architecture caused by the randomisation of the block copolymer segments.⁵⁸ The nature of the polymer can affect backbiting, with flexible polymers, such as PCL, particularly susceptible.

1.3 Biodegradable, Bio-renewable and Biocompatible Polymers

There is a huge market for polymers produced from green processes that can be broken down to bio-renewable components.^{4-6, 21, 59, 60} Common materials that are used to synthesis these bio-plastics are starches, cellulose and biopolymers.^{2, 21} The main areas of applications for these products are food packaging, insulation, dining utensils and packaging materials.^{21, 59, 61}

1.3.1 Linear Aliphatic Polyesters

Linear aliphatic polyesters contain an ester group in the polymer backbone, which is a site for hydrolytic attack. Therefore these polymers are classed as biodegradable polymers as they can be broken down by hydrolysis by water, as shown in Figure 1.9.

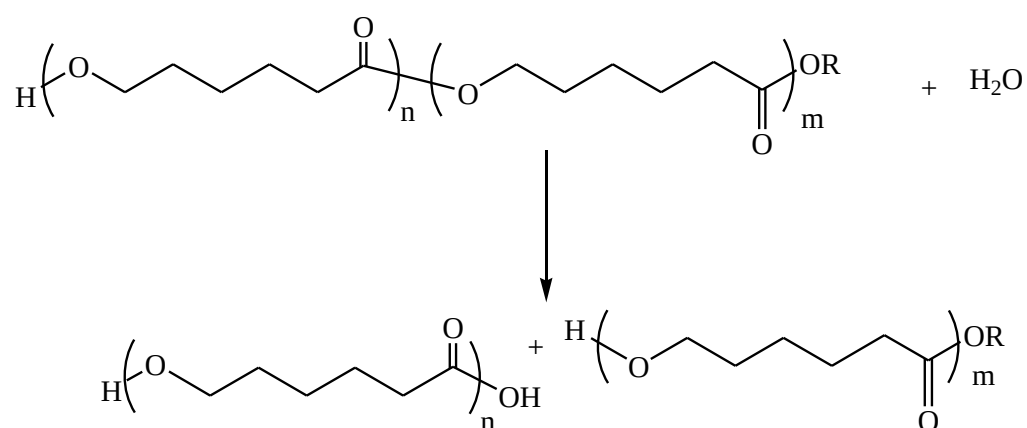


Figure 1.9: Hydrolysis of the ester linkages by water.

1.3.2 PCL

Poly(ϵ -caprolactone) PCL is an aliphatic polyester constructed from hexanoate repeat units, the general ROP equation is shown in Figure 1.10. PCL is semi-crystalline and hydrophobic.⁶² It is soluble in a wide range of organic solvents and is miscible with many other polymers. It is biodegradable on a timescale of several months to a few years depending on the conditions, as it undergoes hydrolytic cleavage of the ester linkages in the PCL backbone.

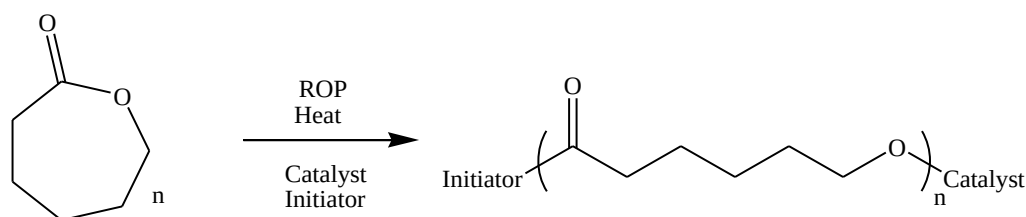


Figure 1.10: Structure of ϵ -CL and PCL.

PCL has a wide range of applications, e.g. packaging, long term drug delivery systems, scaffolds in tissue engineering.^{9, 21, 62-64} It is an interesting polymer that is widely used due to its appealing properties, such as superior rheological and viscoelastic properties, biocompatibility, controlled degradation rates, miscibility with other polymers, and the potential to be produced from a renewable resource. ϵ -CL is prepared industrially via the Bayer-Villiger oxidation of cyclohexanone by peracetic acid.⁶²

1.3.2.1 PCL formation

There are two main methods for the synthesis of PCL: condensation polymerisation and ROP. The condensation method requires long reaction times, high temperatures and must be conducted under vacuum to remove water to drive the reaction to completion. Hence ROP is the widely preferred method to synthesis PCL.

1.3.2.2 ROP of ϵ -CL mechanism

ϵ -CL, much like the other lactones discussed earlier in Section 1.2.2.3, is able to undergo ROP *via* anionic, cationic, activated-monomer and coordination/insertion ROP mechanisms.^{44, 65-67} As a coordination/insertion mechanism using a tin catalyst is used in this thesis, an in-depth mechanistic and current literature study of the ROP of PCL using tin catalyst ($\text{Sn}(\text{Oct})_2$) will be discussed in more detail.

1.3.2.3 Coordination/Insertion formation of PCL with Tin catalyst

The coordination/insertion method is the most common form of ROP for the synthesis of PCL. It can be referred to as 'pseudo-ionic' ROP; however there is no formal negative charge present in the process. The proposed mechanism

includes the coordination of the monomer to the catalyst before ring cleavage and insertion into the metal ligand bond, as shown in Figure 1.11.

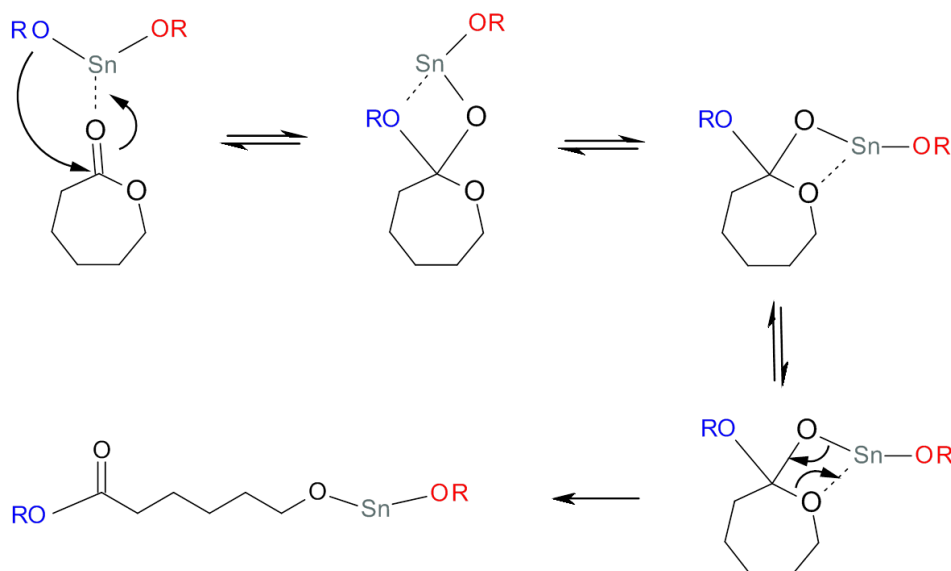


Figure 1.11: ROP mechanism for PCL with Sn alkoxide catalyst.

There has been some debate about the mechanism by which the active tin species initiates the ROP. In the ‘directly catalytic type’ mechanism, it is proposed that $\text{Sn}(\text{Oct})_2$ coordinates directly to the monomer and the hydroxyl on the alcohol then undergoes nucleophilic attack on the carbonyl carbon.⁵¹

The currently accepted method, however, is the ‘monomer insertion type’.⁶⁸

Kowalski *et al.* were the first to show that the catalyst also acts as co-initiator.⁶⁹

The $\text{Sn}(\text{Oct})_2$ reacts with the alcohol initiator and this new initiator causes polymerisation through the insertion of a monomer into the catalyst-alkoxide bond, as shown in Figure 1.11.

Kowalski *et al.* found that, as with many polymerisation mechanisms, there is more than one part to the initiation step.⁷⁰ The primary part to the reaction involves the $\text{Sn}(\text{Oct})_2$ reacting with the BnOH . After further reaction with a hydroxyl group, bi-functional tin is bonded to two BnOH groups. This produces the stannous alkoxide activated species. There is some discussion over whether the ethyl hexanoate moieties remain bonded to the tin; however it is currently believed that the two molecules of octanoic acid are released.⁷¹

The second part to the initiation step (Figure 1.11) involves the active initiating species reacting with the first monomer unit by coordinating to the carboxyl oxygen, accepting one of the oxygen's lone pair into an empty *d*-orbital. After the formation of this dative bond, one of the BnOH units forms a covalent bond with the carbonyl carbon *via* nucleophilic attack, breaking the carbon-oxygen double bond. The bond between the tin and the alcohol is cleaved allowing the tin to bond with the oxygen in the ring, forming a 4 membered ring. This is very unstable and collapses, causing the acyl-oxygen bond in the ring to be cleaved, opening the ring.

Storey *et al.* studied the initiation mechanism and found that this insertion of the monomer into the bond between the metal and the initiating group produces the first actively propagating unit, which contains the initiating group, the linear monomer unit and the stannous active centre.⁷¹ The propagation step involves monomer units reacting with the tin in the same way, as shown in Figure 1.11.

1.3.2.4 Effect of Excess Alcohol on ROP of ϵ -CL

If there is an excess initiator concentration, i.e. more than twice the molar concentration of the tin octanoate, the alcohol species will react with the growing chain to cap it. It will donate a proton in exchange for the stannous alkoxide, deactivating the growing chain.⁴⁴ This ‘free’ stannous species will then be able to initiate another growing chain, as shown in Figure 1.12.

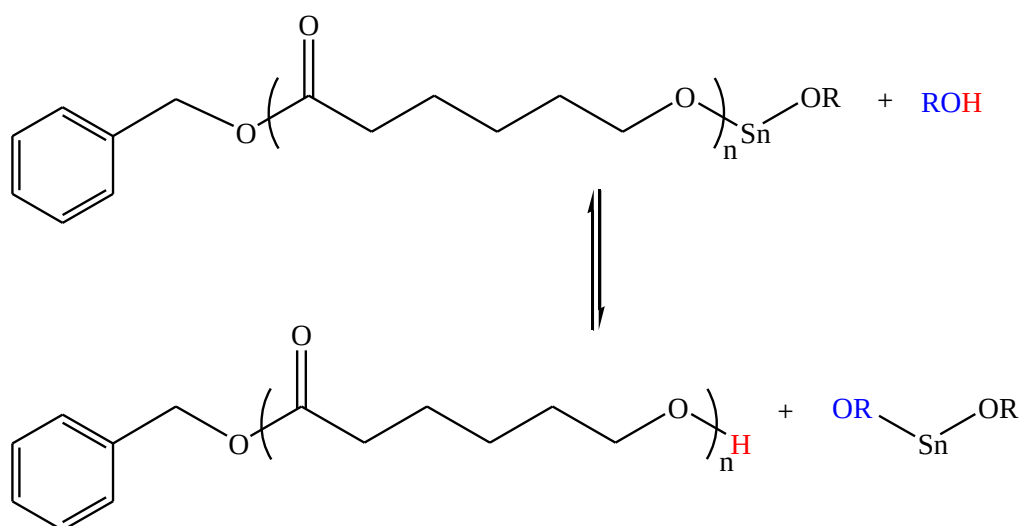


Figure 1.12: Formation of dormant chains during the ROP of PCL catalysed by $\text{Sn}(\text{Oct})_2$.

The dormant chain is able to be reactivated at a later stage after reaction with an active site. Thus excess alcohol acts as a chain transfer agent. This rapid exchange between active and dormant species is a vital factor of controlled polymerisation.

1.3.2.5 Proof of Controlled Character of ROP of ϵ -CL

The ROP of PCL using a $\text{Sn}(\text{Oct})_2$ has been proven to be a controlled process.^{35, 44, 46, 55, 68, 70, 72, 73} Kowalski *et al.*⁷⁰ showed that the number of active sites remained constant throughout the reaction and the number was independent of DP, thus the plot the plot of M_n against monomer conversion ($[\text{M}]_0 - [\text{M}] / [\text{M}]_0$) is linear. When more initiator was added, the number of active sites increased, raising the rate of polymerisation. As the reaction of the $\text{Sn}(\text{Oct})_2$ with the initiator is in equilibrium, increasing the amount of initiator pushes the equilibrium to the right, thus forcing the creation of more active species. This equilibrium is known to be present throughout the reaction.

As with other controlled polymerisation methods, there is no termination step in this mechanism.⁷⁴ Therefore the reaction will only stop when all the monomer has been polymerised. Only when more monomer is added will the active species continue to propagate. Addition of a different monomer could thus potentially result in block copolymers.⁷⁵

1.3.2.6 Potential Side Reactions

Possible problems related to control of the reaction mechanism can be caused by side reactions, such as deactivation of growing chains or transesterification reactions.⁴³ In general, hydroxyl containing compounds are the main factor which can affect the controlled polymerisation mechanism. Both BnOH and

water can act as initiator due to the presence of hydroxyl group in their structure (Figure 1.13).

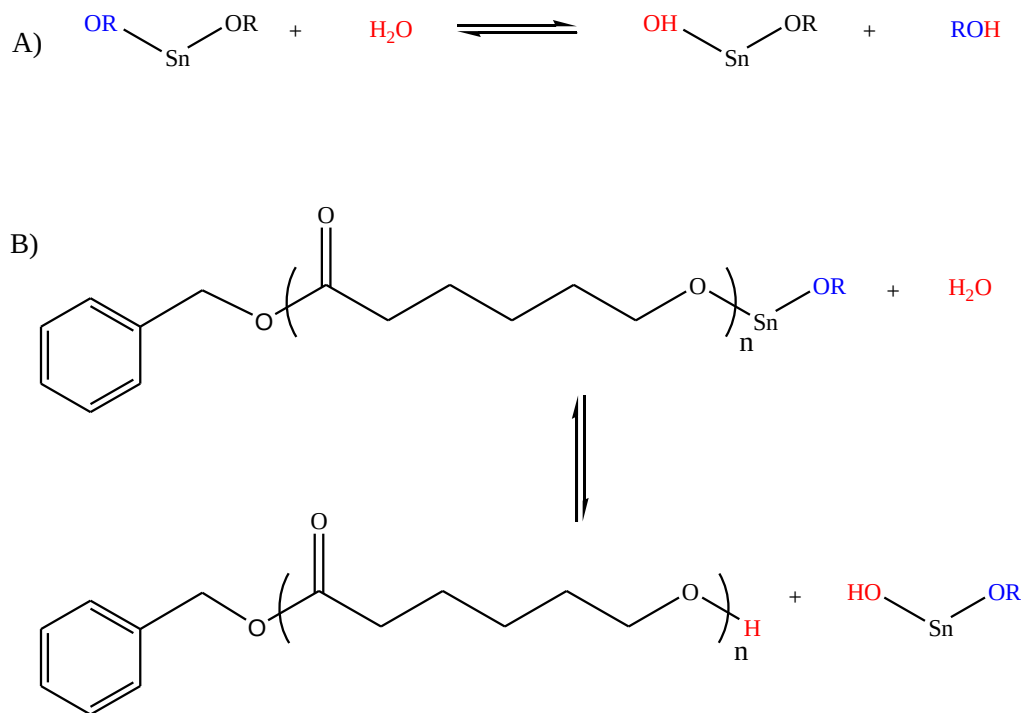


Figure 1.13: Hydroxyl containing molecules (A) blocking formation of Tin Alkoxide true catalytic species in the Initiation step. (B) Hydroxyl containing molecules acting as a transfer agent causing the formation of dormant PCL chains.

The presence of superfluous hydroxyl containing moieties, i.e. water molecules, as impurities in any of the starting materials can compete with BnOH to react with the Sn(Oct)₂. The Sn(Oct)₂ tends to react with water molecules instead of BnOH, retarding the formation of the tin alkoxide active centres. Water molecules can deactivate the active BnOH and act as more stable but less reactive initiator in the reaction. This can occur in the initiation or propagation steps (Figure 1.13). This will result in a deviation from the theoretical degree of polymerisation and a broadening of Đ. Unfortunately, Sn(Oct)₂ is

hygroscopic, therefore there is no advantage to distilling off any adventitious water prior to the ROP reaction.

Transesterification reactions are known to occur for the ROP of PCL using a $\text{Sn}(\text{Oct})_2$ catalyst, particularly at the high temperatures ($80 - 150^\circ\text{C}$) and long reaction times are required to force the reaction to full conversion. Both intermolecular and intramolecular transesterification reactions can occur (Figure 1.14 and Figure 1.15 respectively).

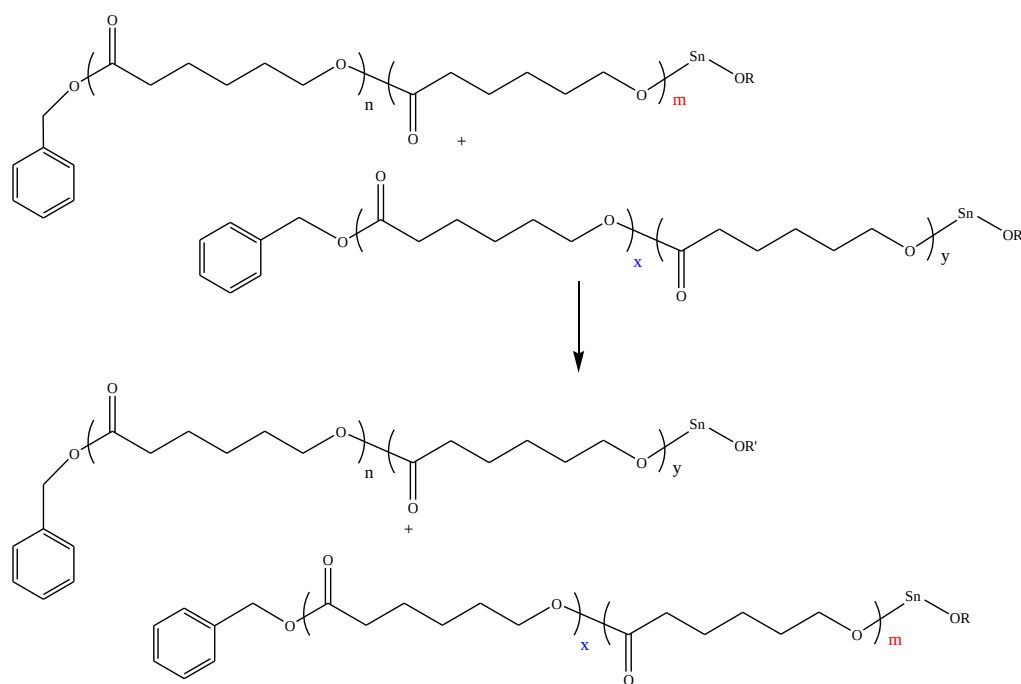


Figure 1.14: Intermolecular transesterification reactions catalysed by $\text{Sn}(\text{OR})_2$ during the ROP of ϵ -CL.

Intermolecular reactions are caused when an active centre of one chain reacts with an ester linkage in a separate PCL chain. Intramolecular transesterification reactions result in the formation of large rings, when a PCL chain ‘backbites’ and reacts with itself (Figure 1.15).

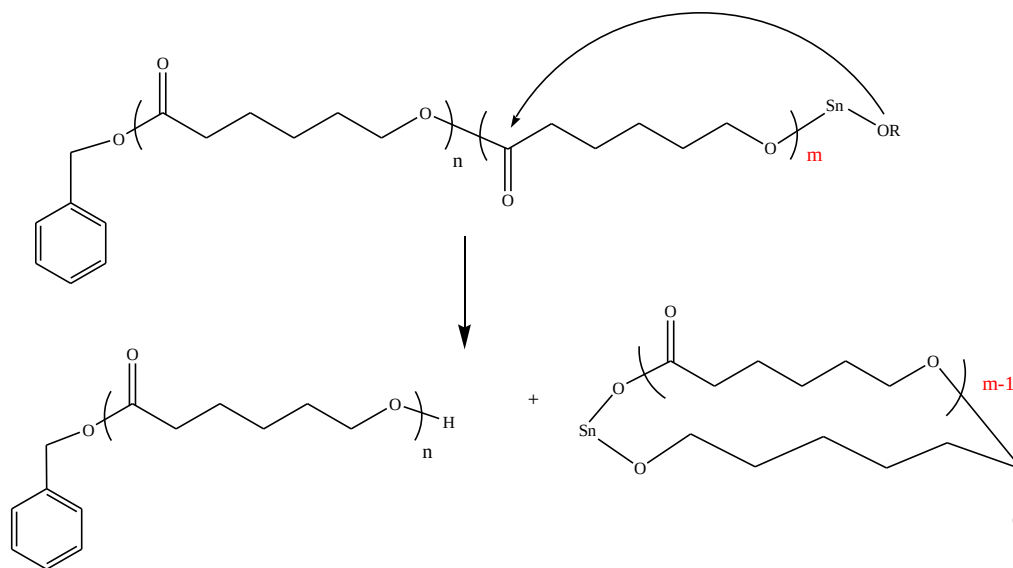


Figure 1.15: Intramolecular transesterification reactions catalysed by $\text{Sn}(\text{Oct})_2$ during the ROP of PCL.

These reactions tend to occur at the end of the reaction, when monomer levels are low, causing a widening of $\bar{M}$ and loss of control over molecular weight growth. Thus, reducing reaction time is a key method to reduce the impact of transesterification reactions and thus maintain control. The use of microwave heating to efficiently heat reagents and shorten the time required to ensure complete ROP of ϵ -CL is a therefore a significant part of this thesis.

1.3.3 PLA

Poly(lactic acid) (PLA) is an aliphatic polyester that has undergone a large amount of research due to its interesting biodegradable, bio-renewable and biocompatible properties.^{61, 76-78}

Lactic acid is easily obtained by fermentation of renewable resources such as corn and sugar beets.⁷⁹ PLA can be produced *via* two methods from lactic acid: condensation of the lactic acid monomers and ROP of a di-lactic acid ring.⁸⁰ The quickest is *via* a condensation polymerisation reaction giving a low molecular weight pre-polymer, which is then treated with coupling agents to afford the high molecular weight PLA. The alternative path proceeds *via* a lactide moiety. After the condensation reaction of the lactic acid, the pre-polymer is depolymerised forming a six membered di-ester ring which undergoes ring-opening polymerisation producing PLA.³

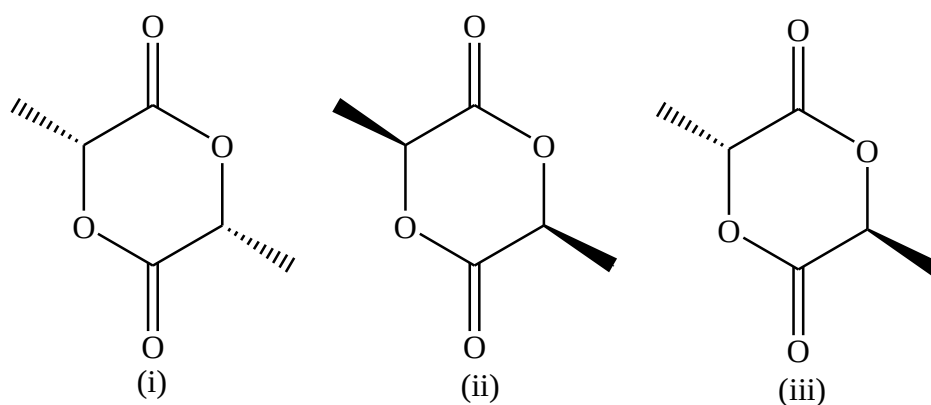


Figure 1.16: D-lactide (i), L-lactide (ii) and *meso*-lactide (iii).

When the low molecular weight PLA is depolymerised, three different forms of lactide are produced, L-lactide, D-lactide and *meso*-lactide, also known as D/L lactide (DLLA), as illustrated in Figure 1.16. The amount of each enantiomer is dependent on the lactic acid isomer feedstock, temperature of reaction and catalyst used.⁸¹

1.3.3.1 Ring-Opening Polymerisation of D/L Lactide Using Tin Catalysts

DLLA can be polymerised to PLA (Figure 1.17) through cationic and anionic ring opening mechanisms, but the most widely used method for industrial production of PLA is coordination-insertion polymerisation, especially using $\text{Sn}(\text{Oct})_2$.^{35, 50, 59, 74, 82-85}

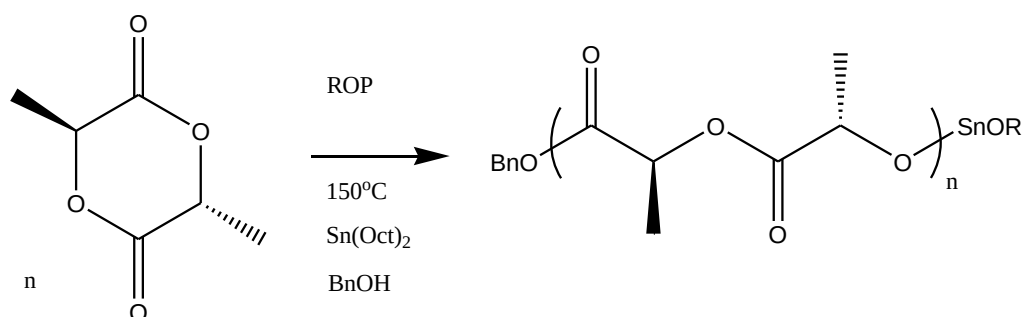


Figure 1.17: Reaction scheme for the ROP of DLLA with tin catalyst and BnOH alcohol.

This mechanism for the ROP of DLLA (Figure 1.18) is analogous with the one previously discussed with regard to the ROP of ϵ -CL (Figure 1.11).

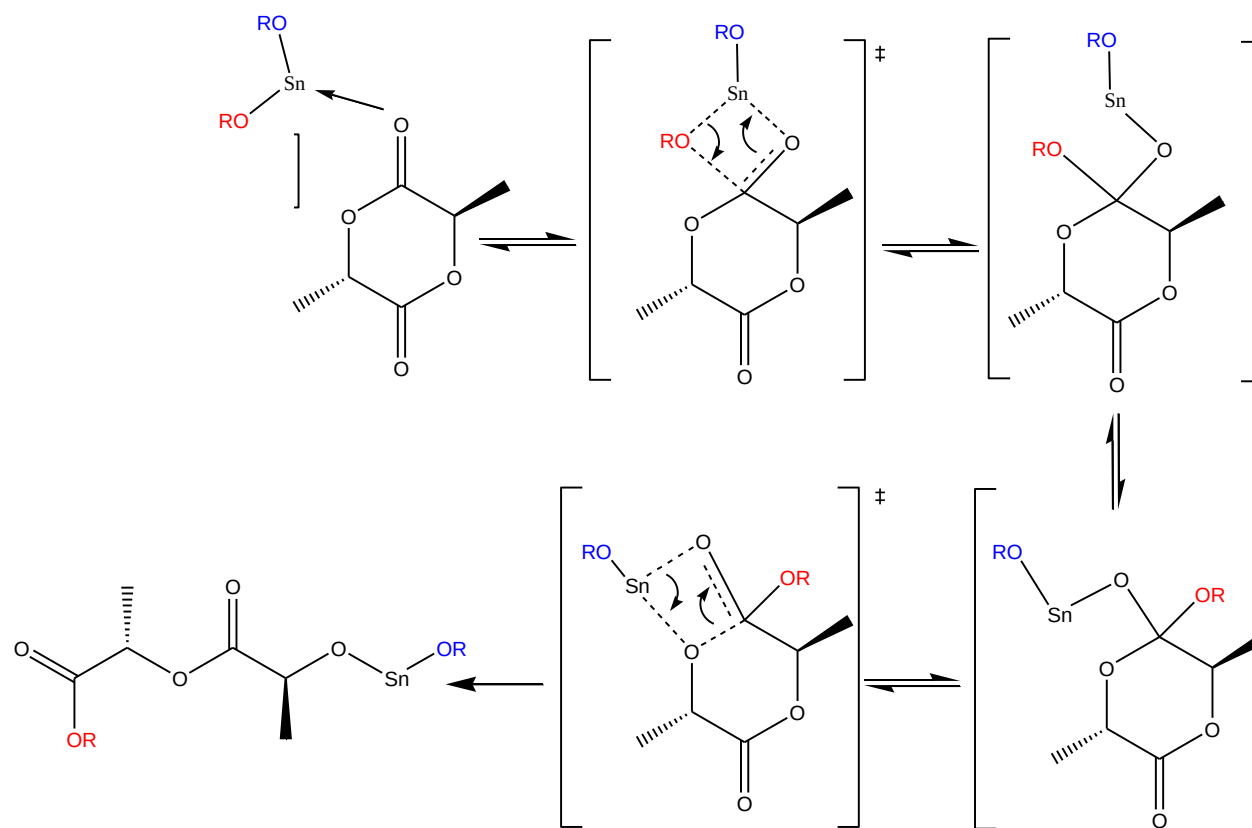


Figure 1.18 : ROP mechanism for synthesis of PLA with $\text{Sn}(\text{Oct})_2$ catalyst.

Figure 1.18 is a diagram of the three step process of ROP for DLLA; starting with the lone pair of electrons on the carboxylic oxygen coordinating to the Lewis acidic metal centre forming a dative bond.³ The DLLA is then inserted into one of the metal alkoxide bonds by nucleophilic addition by one of the alkoxy groups onto the carbonyl carbon. The final step is the ring opening *via* cleavage of the acyl oxygen bond.

From a thermodynamic perspective, DLLA is one of the few six membered rings to have a negative and relatively high standard state polymerisation enthalpy ($\Delta H_p = -23 \text{ kJ mol}^{-1}$).⁶⁶ The polymerisation entropy has been calculated to be $\Delta S_p = -13.0 \text{ J mol}^{-1} \text{ K}^{-1}$. This has been explained by the large ring strain placed on the planar conformation by the two ester groups. However this process is slightly reversible at high temperatures and leads to an increase in monomer concentration when the system is at equilibrium. The kinetics of the reaction has been shown to be first order in relation to monomer and catalyst concentration.⁵⁰

ROP of DLLA can be seen as controlled polymerisation as long as there is fast and efficient initiation and termination steps can be limited.^{67, 86} This leads to control over the reaction with low $\bar{D}$ values and theoretical molecular weights close to observed sizes. The number of active sites remain constant throughout the reaction, thus the targeted molecular weight of the polymerisation is controlled by the amount of initiator present at the start of the reaction and the monomer conversion. Therefore the plots of $\ln [M]_0/[M]$ against time and M_n against monomer conversion ($[M]_0 - [M] / [M]_0$) should be linear to provide evidence for the controlled characteristic of the ROP of DLLA.⁴⁸

The control established over the polymerisation of DLLA using the $\text{Sn}(\text{Oct})_2$ coordination-insertion method is affected by the amount of transesterification reactions. These unwanted side reactions lessen the control over molecular weight growths and increase Đ.⁵⁰ $\text{Sn}(\text{Oct})_2$ catalysed ROP is very susceptible to transesterification reactions even from the start of the polymerisation. Different factors affect this side reaction with varying impacts. Elevated temperatures have been shown to be the most important cause of esterification, followed by the ratio between monomer to catalyst. Increased reaction time also worsens the amount of control as degradation reactions will start occurring.⁴

1.4 Microwave

The study into the application of microwave technology in chemical synthesis has grown exponentially in recent years.⁸⁷⁻⁹⁹ Microwave heating (MWH) has been shown to accelerate and improve a vast range of synthetic reactions.^{78, 100-102} There have been reports of improved rate of reaction, better selectivity, reduced side products and even less need for organic solvents.^{87, 88, 103-107} Studies have shown that energy efficiency can be improved using MWH over conventional heating (CH) by reducing reaction times and improving yields.^{87, 103, 107-109} This chapter will introduce MWH and explain some of the important properties of dielectric heating.

1.4.1 Fundamentals

Microwave irradiation is a type of electromagnetic irradiation that is found between IR and radiofrequency, at 0.3 – 300 GHz.¹⁰⁸ This relates to approximately 1mm to 1 m in wavelength. Most microwave energy is at the frequency of 2.45 GHz. The energy at this frequency (0.0016 eV) is not strong enough to break a chemical bond. Therefore, unlike photochemistry, MWH does not directly induce a reaction. It only heats the mixture through friction, known as dielectric heating.

1.4.2 Dielectric Heating

Microwave dielectric heating is the mechanism for materials to heat *via* microwave irradiation. Microwave dielectric heating is dependent on the efficiency of a specific material to absorb microwave energy and convert it into heat.¹⁰⁸ Electromagnetic radiation, such as microwaves, is composed of an electronic and a magnetic component. These waves propagate perpendicular to each other and are always in phase with each other, with the electronic component being more important to interactions between the material and the irradiation.

Any material can be heated by electromagnetic energy, as long as it is neither a perfect conductor nor insulator. For the work contained in this thesis, the main mechanism for dielectric heating is dipolar polarisation. For a material to

undergo dipolar polarisation, it must have a dipole moment. The dipole aligns itself with the oscillating electric field, which causes friction between the molecules as they attempt to arrange in line to the field. The molecular friction generates energy which is distributed to adjacent molecules through dielectric loss. The distributed energy becomes heat. The ability of the dipoles in the material to align with the oscillating wave affects the heating efficiency. If the wave changes direction too quickly, the dipole will not be able to align, thus will not rotate and no friction will occur. If it is too slow, all molecules will be in phase with the field, which will mean that they do not ‘rub’ against each other.¹⁰⁵

Therefore the dipolar polarisation mechanism works by transferring electromagnetic field energy into the material in the form of electrical energy. This is converted into kinetic energy as the molecules containing dipoles align with the oscillating field. The molecular friction causes heat which is dissipated to adjacent molecules thus heating the bulk material.¹⁰⁸

1.4.3 Dielectric Properties

A material’s dielectric properties determine its heating characteristics when experiencing microwave irradiation.¹⁰⁵ The loss tangent ($\tan \delta$) represents a materials ability to absorb electromagnetic irradiation and convert it into heat.

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

Equation 1.7 ϵ'' is the dielectric loss and ϵ' is the dielectric constant. ϵ'' is the efficiency at which the electrochromagnetic energy is absorbed and converted into heat. ϵ' is an indication of the polarisability of a particular molecule.

Therefore a high $\tan \delta$ is indicative of a material that is able to efficiently absorb and convert the microwave energy into heat. In general, a material is conceived to be high microwave absorbing with $\tan \delta$ value of > 0.5 , medium 0.1-0.5 or low < 0.1 .¹⁰⁵ At 2.45 GHz, water has a relatively low $\tan \delta$ value of 0.12 despite its high dielectric constant whilst ethanol has a high loss tangent of 0.94.

Dielectric properties are temperature and frequency dependent. The frequency for the optimum dielectric heating of water is at 18 GHz.¹⁰⁸ At low frequency, ϵ' will be at its highest value, but will decrease at increasing frequency. This is because at low frequency, the electron cloud will be able to shift the most, causing the largest dipole and hence increase the molecule's polarisability. Therefore increasing frequency causes the molecules to struggle to achieve high polarisability and the ϵ' value decreases.

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + \omega^2 \tau^2}$$

Equation 1.8: Dielectric constant ϵ' with τ the relaxation time; ϵ_{∞} and ϵ_s are the frequencies $\ll \tau^{-1}$ and $\gg \tau^{-1}$ respectively and ω is the angular frequency.

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty})\omega\tau}{1 + \omega^2 \tau^2}$$

Equation 1.9: Loss factor ϵ'' .

The maxima for ϵ'' is achieved when ϵ' has dropped to half of its value. The largest value for $\tan \delta$ is at slightly higher frequency than the ϵ'' maxima. For the majority of materials (including water), the maxima $\tan \delta$ value is achieved at much higher frequency than the standard operating frequency of 2.45 GHz.

The effect of temperature can significantly affect a materials dielectric property.¹⁰⁵ The relaxation time (τ), the time taken for all the molecules in a material to return to their randomised equilibrium state after the removal of an external current, affects both ϵ' and ϵ'' (as shown in Equation 1.8 and Equation 1.9). For a spherical molecule, τ can be expressed using the Debye equation as:

$$\tau = 4\pi r^3 \eta / kT$$

Equation 1.10. Relaxation time (τ) of a spherical molecule in a viscous system; where r is the radius, η is the viscosity and T is temperature with the rate constant k .

Equation 1.10 shows that for polymeric systems, the monomer and polymer will exhibit very different dielectric properties. As a polymer is constructed of hundreds to thousands of monomer units, the size and viscosity is significantly larger. The intermolecular forces for the polymer will hinder the ability of the individual dipoles to rotate and align with the oscillating field.

Equation 1.10 also presents the importance of temperature on the dielectric properties. As temperature increases, τ decreases as the molecules will have more energy to rotate. Therefore, the maximum $\tan \delta$ value will increase with increasing temperature. As discussed earlier, the $\tan \delta$ maxima is often higher than the operating frequency. This means that when such a material (i.e. water) is heated using MWH, as it becomes hotter, its ϵ'' maxima shifts to higher

frequency (away from the operating frequency) and therefore is less susceptible to the microwave energy. This has an important practical implication where, as materials get hotter, they are less efficient at converting microwave energy to heat, thus reducing the risk of a thermal runaway and potential hazardous reaction conditions.

However, if a material has an ϵ'' maxima lower than the operating frequency, (e.g. ethanol), then heating the material will shift the ϵ'' to a higher frequency that is closer to the frequency of the electromagnetic energy. Therefore, understanding the dielectric properties of the various components of a polymerisation reaction is important to fully understand the effect that MWH will produce. Polymerisation reactions are very different from simple organic reactions, due to vastly changing bulk properties, as many small monomer units join together to form large polymer macromolecules.^{93, 104, 109}

1.4.3.1 Dielectric Property Measurements

The method used in this thesis for calculating the dielectric properties of the materials studied was the cavity perturbation technique. It is a highly accurate method for small samples with relatively low $\tan \delta$ values.¹¹⁰ It works by introducing a sample into a cavity and measuring the effect this has on the properties of the cavity. Depending on the sample's size, electromagnetic properties and position in the cavity, the cavity field distribution and resonance frequency will change. The electromagnetic properties of the sample are

calculated from the change in the electromagnetic properties of the cavity. The equipment allows for calculating the dielectric properties at 2.45 GHz.

1.4.4 Microwave Effects

When comparing MWH with CH, many authors have found faster rates of reaction, higher yields, better control and purity of products.^{108, 112-118} Many have attributed these enhancements to the mechanism whereby MWH heats a sample, compared to a traditional oil bath for CH.

Oil baths and other CH methods use conduction and convection to transport heat from outside the reaction vessel. This process is often slow and inefficient (depending on the vessel size, design and mixing ability). Energy is wasted heating the vessel walls, which are often hotter than the reagents as an inverted temperature gradient develops. MWH is able to directly impart energy to the molecules in the reaction mixture, thus allowing for simultaneous heating for the entire sample. Reaction vessels are often microwave transparent, so the bulk temperature is higher than its surroundings. This means that MWH is often efficient at heating a sample and less energy exhaustive.¹¹¹

The ability of MWH to volumetrically heat a sample faster than CH is known as a thermal microwave effect. It is generally accepted that this is the main explanation for the benefits observed in MWH. However, there are other microwave effects that have been the subject of debate which some authors use

to explain observed improvements using MWH.^{78, 112-118} The main microwave effects can be grouped into thermal microwave effect, specific microwave effect and non-thermal effect.¹⁰⁸ As discussed, the thermal effect is the most widely held view for enhanced rates. It is also referred to as the kinetic effect; where high temperatures are reached faster due to the direct interaction of the polar molecule to the electric field leading to volumetric heating.

Specific microwave effects are caused by the unique nature of dielectric heating and cannot be replicated in CH. For example, the super heating of organic solvents (up to 100 °C above their boiling points) in a sealed vessel using high powered microwave reactors.¹¹⁹ The ability of MWH to uniformly heat a sample has been shown to remove the inverted temperature gradient, or ‘wall effect’. An important specific microwave effect for heterogeneous systems is the possibility of specific heating of a certain reagent. In a reaction mixture containing various substances with varying dielectric properties, MWH affords the ability to target a reagent that is known to have particularly high dielectric properties if it is surrounded by a less polar or more viscous medium. This can lead to microscopic hot spots, especially around catalytic sites.¹⁰⁸

Non-thermal, or a-thermal, microwave effects are highly controversial and are related to the microwave energy having a direct effect on the orientation of the molecules, such as the lowering of the activation energy.¹⁰⁸ These are notoriously difficult to prove due the short life-times involved and the problems encountered when attempting to isolate and analyse the intermediate products affected by MWH.

1.4.5 Temperature Monitoring

The precision of the temperature monitoring is paramount when making comparisons between different systems. It is now believed that many of the initial papers discussing enhanced rates in MWH may have been inadvertently quoting inaccurate temperatures, leading to potential errors in their conclusions.^{97, 99, 111, 120}

Most MWH reactors are programmed to control the input power to target a pre-set temperature *via* a temperature feedback control. This requires constant and accurate temperature monitoring. The most common method of temperature monitoring, particularly among the early popular CEM reactors, is *via* a calibrated external infrared (IR) sensor. This is built into the cavity and constantly records the temperature of the vessel wall. The fact that the coldest part of the cavity will be the reaction vessel highlights the inadequacy of using an external IR sensor as the temperature probe.

Recently, research groups have started using fibre-optic probes (FO) located inside the reaction medium as a more accurate temperature sensor.¹²⁰ The high cost and fragile nature of the FO probes are barriers to widespread use. Unlike metal-based thermocouples, FO probes are not affected by the electromagnetic waves and thus do not need shielding. The majority of FO probes use a semiconductor crystal (often gallium arsenide) attached to the end of a FO probe. The size of the band gap in the crystal is temperature dependent. A light

is passed through the probe, and the light is absorbed at differing wavelengths depending on the temperature.

1.5 References

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2 Experimental Procedures and Characterisation Techniques

This chapter details the experimental and characterisation techniques used in this thesis. The experimental procedures are separated into two main methods; either heating in a conventional oil bath (CH) or with the use of electromagnetic energy in a microwave (MWH). The methods used to synthesise the various linear, homopolymer, copolymer and branched polymers are given.

The second part of this chapter explains the various techniques used to analyse the products during the research listed in this thesis. Samples were analysed at various stages during reactions, in order to compare and contrast the effect of heating method on the rates of polymerisation and the control of the reaction. The final copolymer and branched polymer products were analysed to determine molecular weight, composition, thermal and structural properties.

2.1 Equipment

2.1.1 CEM-Discover Microwave Reactor

A CEM-Discover reactor (Figure 2.1) was used for all the microwave experiments in this thesis and was purchased from CEM Microwave Technology Ltd. It is a single-mode cavity, i.e. the electromagnetic waves created by the magnetron pass along a waveguide ensuring a homogenous energy field in the cavity. This guarantees efficient and uniform dielectric heating. The reactor provided a frequency of 2.45 GHz. The open vessel mode was selected.



Figure 2.1 CEM-Discover Reactor

The CEM-Discover reactor was used with a maximum power input of 300 W and functions with continuous irradiation through self-tuning at a pre-programmed temperature. The set parameters for the CEM reactor were for a 10 minute ramp time, where maximum power (300 W) was irradiated to get the temperature to the set value. The CEM was set on Standard Irradiation setting, when the set temperature was reached, small amounts of power were used (~15 W) to keep the temperature steady for the duration of the reaction, according to the internal temperature feedback from the Infrared (IR) sensor.

Temperature was monitored using an IR sensor and a Fibre Optic (FO) probe. The IR sensor (Neoptic Inc.) measured the surface of the reaction vessel. The FO probe was placed directly into the reaction medium and used a gallium arsenide semiconductor crystal attached to the end of the FO probe. The size of the band gap in the crystal is temperature dependent. A light is passed through the probe, and the light is absorbed at differing wavelengths depending on the temperature. Stirring was achieved with a magnetic stirrer bar placed in the reaction medium which was rotated by the CEM-Discover motor at 300 rotations per minute (rpm). The CEM-Discover was connected to a computer where Chem Driver Version 2.6 was used to control reaction parameters and record power and temperature data.

2.2 ROP Procedures

2.2.1 One-Pot Reaction

ϵ -CL (6.25g, 54.8 mmol) or DLLA (7.9g, 54.8 mmol) was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μ L, 0.63 mmol) and Sn(Oct)₂ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ¹H-NMR and GPC. When the reaction had finished, it was quenched with liquid N₂ and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed by GPC and the thermal properties monitored by DSC.

2.2.2 One-Pot Two-Step Copolymerisation Reaction

The first monomer species (ϵ -CL (6.25g, 54.8 mmol) or DLLA (7.9g, 54.8 mmol)) was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μ L, 0.63 mmol) and Sn(Oct)₂ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular

intervals for monitoring *via* ^1H -NMR and GPC. The conversion was calculated by comparing the monomer and polymer peak integrals from the ^1H NMR spectrum. When the reaction had been calculated to have reached the target conversion, the second monomer was added directly to the reaction vessel and left to polymerise to high conversion. The second monomer was heated to reaction temperature prior to addition. When the reaction had finished, it was quenched with liquid N_2 and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed by GPC and the thermal properties monitored by DSC.

2.2.3 Two-Pot Two-Step Copolymerisation Reaction

The first monomer species was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μL , 0.63 mmol) and $\text{Sn}(\text{Oct})_2$ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ^1H -NMR and GPC. When the reaction had been calculated to have reached the target conversion, the reaction was quenched with liquid N_2 and dissolved in ~ 50 mL of dichloromethane. It was purified by drop wise addition of the polymer solution into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The purified polymer

prepared in the first step was placed into a 50 mL glass test tube. The second monomer was added and the test tube was returned to the oil bath/CEM-Discover reactor and the reaction was continued to high monomer conversion. When the second monomer has reached high conversion, the reaction was quenched with liquid N₂ and dissolved in ~50 mL of dichloromethane. Purification was achieved by drop wise addition into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed with GPC and the thermal properties monitored by DSC.

2.3 Characterisation Techniques

2.3.1 NMR

Nuclear Magnetic Resonance (NMR) analysis provides an excellent insight into the chemical, structural and electronic properties of molecules. In a typical ¹H NMR experiment the sample is dissolved in deuterated solvent and placed in a high magnetic field. The nuclei are excited by pulses of radio frequency and when they relax they emit energy, which is recorded. The frequency of the emitted energy will be highly dependent on the number, type and special arrangement of other atoms in the immediate vicinity. All ¹H NMR spectra for this thesis were recorded in CDCl₃ using a Bruker DPX 300 spectrometer operating at 300 MHz. Samples underwent 64 scans to improve the signal to noise ratio and were referenced to CHCl₃ at 7.26 ppm.

2.3.2 GPC

Since the molecular weight and molecular weight distribution of a polymer has a direct impact on its overall physical and chemical properties, an accurate method of deducing a polymer's molecular weight and molecular weight distribution is of paramount importance to a polymer chemist. The most important characterisation technique for this process is Gel Permeation Chromatography (GPC), also known as Size Exclusion Chromatography (SEC). GPC works by separating the sample according to size before analysing with a detector.

The separation process involves dissolving the polymer sample in an appropriate solvent before being passed through a column packed with an inert porous material. This separates the polymer into various molecular weight fractions according to the polymer's hydrodynamic volume. The inert material contains a wide range of pore sizes. The smaller sized polymer particles are able to migrate deeper into more of the pores than larger particles. This causes smaller molecules to take longer time to flow through the column. Indeed, larger molecules are eluted first.

The separation in the columns produces a molecular weight distribution, represented by various numerical molecular weight averages. The equations for the most widely used, M_n and M_w , alongside $\bar{D}$ are given in the Equation 2.1.

$$M_n = \frac{\sum n_i N_i}{\sum n_i}$$

$$M_w = \frac{\sum n_i N_i^2}{\sum n_i N_i}$$

$$\mathfrak{D} = \frac{M_w}{M_n}$$

Equation 2.1: Determination of: M_n is the number average molecular weight and M_w is the weight average molecular weight where n_i is the number of molecules at N_i molecular weight. The dispersity index ($\mathfrak{D}$) is a measure of the breadth of distribution of molecular weights in a single polymer sample.

The GPC machine used in this thesis was the PL-GPC 120, Polymer Labs using THF as the solvent over two columns (30 cm, PolarGel-M) in series packed with cross-linked poly(styrene) at a flow rate of 1 mL min⁻¹, with poly(styrene) standards used for calibration. The polymer samples were dissolved at a concentration of approximately 3 mg mL⁻¹. The two detection methods used were RI and MALLS.

2.3.2.1 RI Detector

The most widely used method of detection in GPC is the Refractive Index (RI) detector. RI works by monitoring the refractive index of the eluent passing through the system and comparing differences between pure solvent and solvent containing the polymer sample. Increased levels of concentration of polymer lead to greater refraction being measured, allowing for the molecular

weight distribution curve to be built, as response from the detector is proportional to the concentration of sample in the solvent.

The RI detector, operating computer and the auto sampler were connected *via* a Data Capture Unit (PL DataStream, Polymer Laboratories), which synchronises the sample injection to the recording of the data, allowing for sample retention time to be recorded exactly. The polymer sample can then be compared to the poly(styrene) standards for calibration (EasiCal PS-2 PS Standards, sample range: 580 – 377400 g mol⁻¹, Agilent Technologies).

2.3.2.2 MALLS

In a GPC system, the Multi-Angle Laser Light Scattering (MALLS) detector is often located sequentially after the RI detector and is another method for determining molecular weight and particle size of a polymer sample. Unlike RI, MALLS does not require the use of an external calibrate; instead MALLS directly targets the polymer molecule. It is considered an absolute technique for the characterisation of molecular weight.

MALLS works by exposing the polymer sample to polarised laser light, which scatters depending on the polarisability of the polymer, with high polarisability leading to increased scattering. The polarisability is represented by measuring the effect the polymer concentration has upon the refractive index of the solution. This relationship is referred to at the dn/dc value, or the differential

rate index. The dn/dc value needs to be calculated for each polymer as it is used when calculating the intensity of scattered light, which is directly proportional to the molecular weight of the sample. The dn/dc value is taken from the gradient of the straight line when plotting the refractive index against various known polymer concentrations.

MALLS is sensitive to concentration and molecular weight, as both have an impact on the amount of light scattering. This is due to the fact that atoms that are in phase (covalently bonded) become coherent and thus the emitted light is at higher intensity. The increased intensity has not been caused by elevated concentration, therefore the size of the molecule has caused the increase. The Zimm equation (Equation 2.2) is used to elucidate molecular weight of the polymer from the scattered light.¹

$$\frac{KC}{R_{\theta}} = \frac{1}{mP_{\theta}} + 2A_2C$$

Equation 2.2: Zimm Equation. K is a light scattering constant based on the dn/dc value; C is the polymer concentration, R_{θ} is excess Raleigh ratio, the difference between the polymer solution and the eluent at angle θ ; M is the weight averaged solute molar mass; P_{θ} is the form scattering factor, the angular dependence of the scattered light which is related to the polymer root mean square (rms) radius; A_2 is the virial expansion coefficient.

2.3.3 DSC

Differential scanning Calorimetry (DSC) is a thermal analysis technique that probes various thermal transitions of the polymer, such as melting (T_m), glass transitions (T_g) and crystallisation values. DSC measures and compares the

heat flow required to heat the sample and a reference in a controlled temperature program.

Change of heat flow to polymer samples is governed by an exothermic or endothermic process. As melting is an endothermic process, it requires an increased heat flow to maintain the desired heating rate. The opposite is true for crystallisation, which requires less heat flow to sample. A step change is observed at the glass transition temperature as the heat capacity increases over the transition due the elevated molecular motion.

DSC analysis for this thesis was conducted on a DSC Q2000 (TA Instruments) machine using aluminium pans. A small amount of sample (typically 3-5 mg) was loaded into the pan and sealed, with an empty identical pan used as the reference. The experiments were run under N₂ with a flow rate of 50 ml min⁻¹. The sample was heated at 10 °C min⁻¹ to 80 °C where it was allowed to equilibrate for 5 minutes. The sample was quickly cooled at 50 °C min⁻¹ to -90 °C where it was held for 5 minutes, before being heated back up to 80 °C and 10 °C min⁻¹. This cycle was run three times, with the T_g, T_m and crystallisation values taken from the average of the second and third cycles.

2.3.4 GC-MS

Gas Chromatography-Mass Spectrometry (GC-MS) is a method used to separate and analyse liquid mixtures into the various components. A sample is

injected into the GC column where it is heated and carried through by an inert carrier gas. The long column allows for separation of the various components due to their differing interactions with the stationary phase.

As the samples elute out of the column they are transferred into the MS instrument. Here they are ionised and accelerated towards the detector, which leads to accurate analysis of the eluting molecule.

The GC-MS instrument used in this thesis was a VG / Micromass / Waters AutoSpec in the EI⁺ ionisation mode. The BP1 column had the dimensions 15 m x 0.25mm x 0.25µm. Helium was used as the carrier gas at 100 KPa. The GC oven was programmed for heating at 50 °C (3 min) to 300 °C (20 min) at 6 °C min⁻¹. The injector temperature was 250 °C and the inlet temperature was 200 °C. Typically a sample size of 50 mg was dissolved in 1 ml of chloroform.

2.4 Reference

1. B. H. Zimm, *Journal of Chemical Physics*, 1948, **16**, 1093-1099.

3 Investigation into the Effect of Microwave Energy on the Ring-Opening Polymerisation of ϵ -Caprolactone

The work presented in this chapter investigates the effect that microwave energy (MWH) has upon the ring-opening polymerisation (ROP) of ϵ -caprolactone (ϵ -CL) by directly comparing it with conventional oil bath heating (CH). Consequently, the controlled nature of the ROP of ϵ -CL in MWH was assessed.

In so doing, the true nature of the ‘microwave-effects’ reported in prior literature work was investigated. Previous work had quoted significant rate increases and other improvements within a range of reaction systems by using MWH. However, in most of the prior literature, the method of temperature monitoring was *via* an external Infrared sensor (IR). Recently it has been speculated that this was prone to record an incorrect bulk temperature. The current work aimed to exploit a fibre-optic probe (FO) placed directly into the reaction medium, thus recording the true temperature, to investigate the magnitude of the effect this has upon the validity of MWH and CH comparisons.

Thus a series of experiments were conducted to examine the impact of reaction conditions on the disparity in recorded IR and FO temperatures, with a view to

explaining the root causes behind these literature ‘microwave effects’ and also to ensure that future work in this thesis does not build on any misjudgements.

For the first time, an FO sensor placed into the bulk ROP of ϵ -CL mixture was able to quantify and qualify any differences that MWH and CH have on the ROP of ϵ -CL. Thus this in-depth knowledge of the temperature dependence of the various reaction compounds was used to justify observations. To further explain these changes, assessments have also been made on the influence of the reaction component dielectric properties, the changing physical nature of the bulk and the changing reagent ratio that occurs during the ROP of ϵ -CL.

Crucially the FO allowed for comparisons between the heating methods at reactions conducted at identical temperatures. In particular, the early stages of the reaction, i.e. the induction and initiation periods were studied and increased rates were found in MWH polymerisation. The propagation period was also analysed and it was found the MWH had less of an advantage over CH than during the earlier stages.

3.1 Introduction

The use of ROP to synthesis a wide range of polyesters is an important area of both scientific and industrial research.¹⁻⁹ One of the polyesters most widely used and studied is PCL.

PCL is a semi-crystalline and hydrophobic aliphatic polyester constructed from hexanoate repeat units derived from the cyclic monomer ϵ -CL (Figure 3.1). It is biodegradable, biocompatible, soluble in a wide range of organic solvents and miscible in many other polymers. The timescale for the biodegradation of PCL ranges from several months to a few years, depending on the crystallinity of the polymer and the degradation conditions, as it undergoes hydrolytic cleavage of the ester linkages in the PCL backbone.⁸

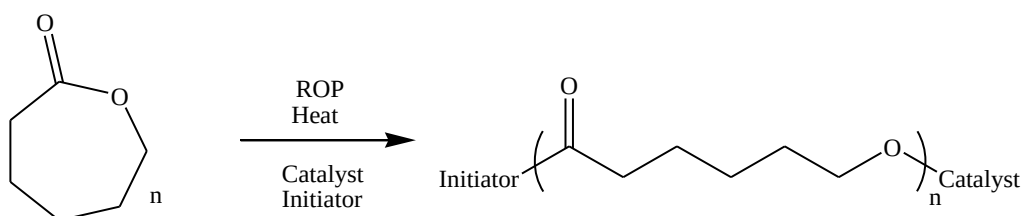


Figure 3.1: Structure of PCL formed via the ROP of ϵ -CL.

PCL has a wide range of applications, e.g. packaging, long term drug delivery systems, scaffolds in tissue engineering.^{8, 10, 11} It has been used in industry due to its appealing properties, such as superior rheological and viscoelastic properties, biocompatibility, controlled degradation rates, miscibility with other polymers, and the potential to be produced from a renewable resource.⁸

3.1.1 ROP of ϵ -CL with MWH

Interest in microwave assisted ROP of ϵ -caprolactone has increased sharply in recent years,¹²⁻³¹ with research undertaken into varying the experiment procedure, for example catalysts, solvents and microwave apparatus. It has

been widely accepted that the mechanism discerned for a thermally heated polymerisation applies equally to a microwave heated polymerisation.

ϵ -CL is polar and can therefore absorb microwave energy as it has a relatively high $\tan \delta$ value of 0.35 at room temperature,²⁹ which means it is efficient at converting electromagnetic energy to heat. This $\tan \delta$ value is much higher than that of water (0.123) but much lower than ethanol (0.941). A wide range of catalyst systems have been used for the ROP of ϵ -CL with MWH; such as titanium,³² lanthanides,¹⁵ zinc,^{14, 18} acidic,^{17, 20, 33} lipase,^{34, 35} ionic liquids²³ and tin.^{13, 14, 16, 24, 36}

One of the first examples of the use of MWH on the ROP of ϵ -CL was published in 1996. Albert *et al.*³² found no advantage using MWH over CH for the ROP of ϵ -CL catalysed by a titanium tetrabutylate catalyst. Conversion, molecular weight and viscosity measurements were similar for both heating methods at comparative stages of the reactions. Barbier-Baudery *et al.*¹⁵ synthesised PCL with MWH using non-toxic lanthanide based catalysts (Samarium and Yttrium). Temperatures of 200 – 230 °C were used to produce PCL with molecular weight in the region of 3,000 to 16,000 g mol⁻¹ in a “green” process. There was little difference between the products and reaction times from the two heating methods.

Zinc catalysed ROP of ϵ -CL investigated by Sivalingam *et al.*¹⁸ in 2003. The ROP kinetics were studied for bulk ϵ -CL reactions irradiated with pulses of 350 W for 30 seconds. The temperature-dependent rate coefficients were used to calculate the activation energies for the CH and MWH zinc catalysed

reactions. The activation energy was found to be much lower in the MWH ($5.7 \text{ kcal mol}^{-1}$) case compared with the CH equivalent ($13.4 \text{ kcal mol}^{-1}$). Liao *et al.*²³ also used a zinc catalyst, but conducted the ROP of ϵ -CL in the presence of 30 wt % ionic liquid in a multi-mode domestic microwave. $28,500 \text{ g mol}^{-1}$ PCL was obtained after 30 minutes due to the high heating efficiency of ionic liquids in MWH.

A metal-free approach was conducted by Yu and Liu using a benzoic acid-initiated ROP of ϵ -CL in a multi-mode microwave oven.²⁰ Higher rates of propagation were observed in MWH than CH at $200 - 240^\circ\text{C}$ with $4,000 \text{ g mol}^{-1} M_w$ PCL produced. However, it was proposed that MWH inhibited the formation of active centres at the initial stages of the reaction whilst it also appeared to encourage PCL degradation at temperatures above 230°C .

Ritter *et al.*³¹ have investigated the MWH ROP of ϵ -CL using a lipase catalyst in different solvents at reflux. They found that altering the nature of the solvent can influence the level of effect of the MWH. Reactions performed in non-polar toluene and benzene exhibited a decreased rate when compared to CH reactions, whereas in refluxed diethyl ether, a more polar solvent, the rate of polymerisation was increased. Ritter and Kerep³⁵ used a lipase catalyst and 2-mercaptoethanol as the initiator and found the MWH reaction afforded higher yields and less formation of side products than in CH.

3.1.2 ROP of ϵ -CL with MWH using $\text{Sn}(\text{Oct})_2$ Catalyst

The extensive mechanism and kinetics studies that have been conducted on the ROP of ϵ -CL by the $\text{Sn}(\text{Oct})_2$ catalyst and the approval of the Federal Drugs Administration³⁷ (for the use of $\text{Sn}(\text{Oct})_2$ for food packaging plastic) has meant that the MWH ROP of ϵ -CL is often tin catalysed.³⁸⁻⁴⁰ Initial research often reported observing increased reaction rates when the reaction was heated using MWH, but recently much work has tried to determine the exact cause of these advances, i.e. if these improvements were due to thermal or non-thermal MWH effects.^{22, 24, 30}

Liao *et al.*¹⁴ were one of the first groups to study the effect of MWH on $\text{Sn}(\text{Oct})_2$ catalysed ROP of ϵ -CL. They have shown that the reaction time can be reduced from 24 hours using CH to under 30 minutes using the MWH when irradiating with 680 W. When only 0.1 % mole ratio of $\text{Sn}(\text{Oct})_2$ was used, a high yield of PCL was obtained (> 90 %, 30 minutes, 180 °C). A follow up paper from the same group studied the heating rate of ϵ -CL with high levels of MWH energy.¹⁶ High temperatures were reached (343 °C after 5 minutes) when 680 W was used, resulting in PCL of 123,000 g mol⁻¹ M_w at 95 % yield. Fang *et al.*¹³ conducted experiments in a variable frequency microwave for 2 hours with $\text{Sn}(\text{Oct})_2$ and an alcohol based initiator (1,4-butanediol) over a temperature range of 150-200 °C. It was found that CH gave slower reaction rates (e.g. at 180 °C, CH: 16-18 hours, > 90 % of PCL; MWH: 2 hours, > 90 %). However, the enhanced reaction rates observed with MWH were not supported with mechanistic explanations. McCarthy and Koroskenyi also

published a paper on the MWH ROP of ϵ -CL in 2002,⁴¹ in which it was reported that faster rates were achieved when using MWH without providing an explanation for the observed improvements. At 390 W and $\text{Sn}(\text{Oct})_2$ concentration below 2 %, complete monomer conversion was achieved in 8 minutes with $40,000 \text{ g mol}^{-1} M_w$.

The paper by Sinnwell *et al.*³³ was one of the early works to move away from reporting on the empirical observations, about the shorter reaction times and faster rates achieved in MWH over CH, but investigated the controlled nature of ROP of ϵ -CL when using MWH, by adding methacrylic acid and acrylic acid macroinitiators. Reactions were conducted at 90 minutes in bulk with $\text{Sn}(\text{Oct})_2$. The molecular weights of the PCL were controlled by the initial concentration of the acidic units, thus proving that MWH does not alter the controlled nature of the ROP of ϵ -CL. It is interesting to note that no significant improved rate of reaction was observed compared with classical CH methods.

In an attempt to establish the cause of enhanced rates in MWH, Liao *et al.*²² compared MWH with CH and flash conventional heating (FCH). FCH was found to have an apparent rate constant of polymerisation (k^{app}) value 5 times larger than calculated from the MWH equivalent reaction. Although the kinetics were faster in the FCH case faster than the MWH equivalent, MWH was reported to exhibit greater control over the controlled nature of the ROP. Thus, the reaction in FCH was concluded had a much lower concentration of active sites than the corresponding MWH case. It appears that MWH was able to encourage full initiation before the propagation reaction dominated. This

meant that MWH was able to produce an observed M_n close to theoretical M_n value, and the $\bar{D}$ was lower (1.21 in MWH : 1.73 in FCH after 6 minutes). Following on from that paper, Liao *et al.*²⁴ compared FCH and MWH reactions at varying temperatures from 160 – 230 °C with a view to investigating the presence of non-thermal MWH effects on $\text{Sn}(\text{Oct})_2$ catalysed ROP of ϵ -CL. The analysis of the k^{app} values from the FCH reactions found they followed the Arrhenius law, i.e. as temperature increased, k^{app} increased. However the MWH k^{app} values plotted an unusual trend. The k^{app} value at 180 °C was significantly higher than the other reactions conducted at much higher temperatures. The authors concluded that this extremely high k^{app} value could only be rationalised by a non-thermal MWH effect at this temperature, although no hypothesis of the nature of the non-thermal effect was proposed.

3.1.3 Accurate temperature monitoring

The presence (or absence) of non-thermal MWH effects has been an area of controversy and contention in the field of microwave chemistry. Previous claims, such as the paper by Liao *et al.*²⁴, that have claimed a non-thermal MWH effect have been heavily scrutinised. The majority of recent papers cite the temperature monitoring as a possible source of misleading MWH effects.^{30,}

42-47

A key work by Kappe *et al.*⁴³ in 2008 was the first paper to revisit non-thermal MWH effects of chemical reactions. They studied the effect of MWH on four

synthetic transformations and drew comparisons with CH equivalent reactions. For an accurate temperature measurement of the MWH reactions, a multiple FO probe system was employed alongside the normal IR sensor. By using the FO probes, they discovered large differences between the assumed temperature (gained from IR) and the true internal temperature (FO). They concluded that there were no non-thermal MWH effects; all observations were only caused by thermal effects. Robinson *et al.*⁴² took this research further by using electromagnetic simulations to provide fundamental explanations and quantitative analysis of the experimentally observed MWH effects. They showed the impact of various reaction and reagent conditions on the experimental observations that were previously misinterpreted as MWH specific and non-thermal effects. The different methods of temperature monitoring (IR vs FO) highlighted significant temperature gradients that can be caused by solvent volume, solvent type, stirring rate, the material and dimensions of the reactor vessel.

The Robinson paper, however, only studied simple homogenous one-solvent systems. Kwak *et al.*⁴⁴ were the first to apply this deeper understanding of MWH reaction technology and temperature monitoring to a more complicated polymerisation system. They found that the k^{app} values for the radical polymerisation of methyl methacrylate were essentially the same for reactions heated by both MWH and CH methods. They concluded that previous enhancements were caused by the MWH reactions being at higher internal temperature than expected due to imprecise temperature monitoring *via* the IR sensor.

The first comprehensive study into the existence of a non-thermal MWH effect in ROP was first conducted by Grande *et al.*⁴⁵ They utilised the FO to gain an accurate internal temperature monitoring of the ROP of D/L-lactide (DLLA) reactions conducted in toluene. Reactions were conducted at various temperatures (120 °C, 130 °C and 140 °C) in both MWH and CH apparatus. The method of heating did not alter the reaction kinetics and the calculated k^{app} values were independent of the heating method employed. However, as all the reactions were conducted in toluene, which is a solvent with poor dielectric properties, the impact of MWH energy could have potentially been excessively nullified.

Recent work by Kappe *et al.*³⁰ studied ROP in the MWH in bulk (i.e. without the presence of a solvent). They purposely did not run the reaction in solvent as to highlight the importance of accurate internal temperature monitoring of the viscous ROP of ϵ -CL at 180 °C. By using a FO probe and an external IR sensor simultaneous with a camera filming the reaction in real time, the paper analysed the effect of stirring and errors in temperature monitoring. They observed that when the MWH reactor was calibrated to input power through a feedback from the IR temperature reading, the true FO internal temperature increased when the viscosity of the ROP reaction increased. The IR sensor was noted to record the relatively cool external reaction vessel wall temperature, whilst the FO probe simultaneously documented the internal temperature rising due to the “efficient in-core volumetric heating”. The paper, in direct contrast to the Liu paper in 2007,²⁴ could not establish any non-thermal MWH effects.

Therefore, recently, it has become widely acknowledged that when analysing and investigating the MWH effect, the use of a FO probe to accurately measure the true internal reaction temperature is essential. The work presented in this chapter will take the previous work by Kappe³⁰ on the MWH effect on the ROP of ϵ -CL to a further level of understanding and investigation. Whereas Kappe only studied reactions at one temperature (180 °C), this work reports the impact of a wide range of temperatures (130 – 180 °C) whilst breaking down the ROP of ϵ -CL into the various mechanistic stages; induction, initiation, propagation and termination. The in-depth understanding of the dielectric properties of the various ROP of ϵ -CL reaction components provided further understanding and analysis of the true effect of MWH energy on the ROP of ϵ -CL.

3.2 Experimental

3.2.1 Materials

ϵ -Caprolactone (99%) was purchased from Acros Organics and used without further purification. Anhydrous benzyl alcohol (99 %) and tin 2-ethyl hexanoate (99 %) were purchased from Sigma Aldrich.

3.2.2 One-Pot Reaction

ϵ -CL (6.25 g, 54.8 mmol) was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μ L, 0.63 mmol) and Sn(Oct)₂ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ¹H NMR and GPC. When the reaction had finished, it was quenched with liquid N₂ and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed by GPC and the thermal properties monitored by DSC.

3.2.3 Monomer Conversion

The samples were analysed by ¹H NMR to determine the conversion and M_n values and degree of polymerisation (DP). Figure 3.2 presents a typical ¹H NMR spectrum.

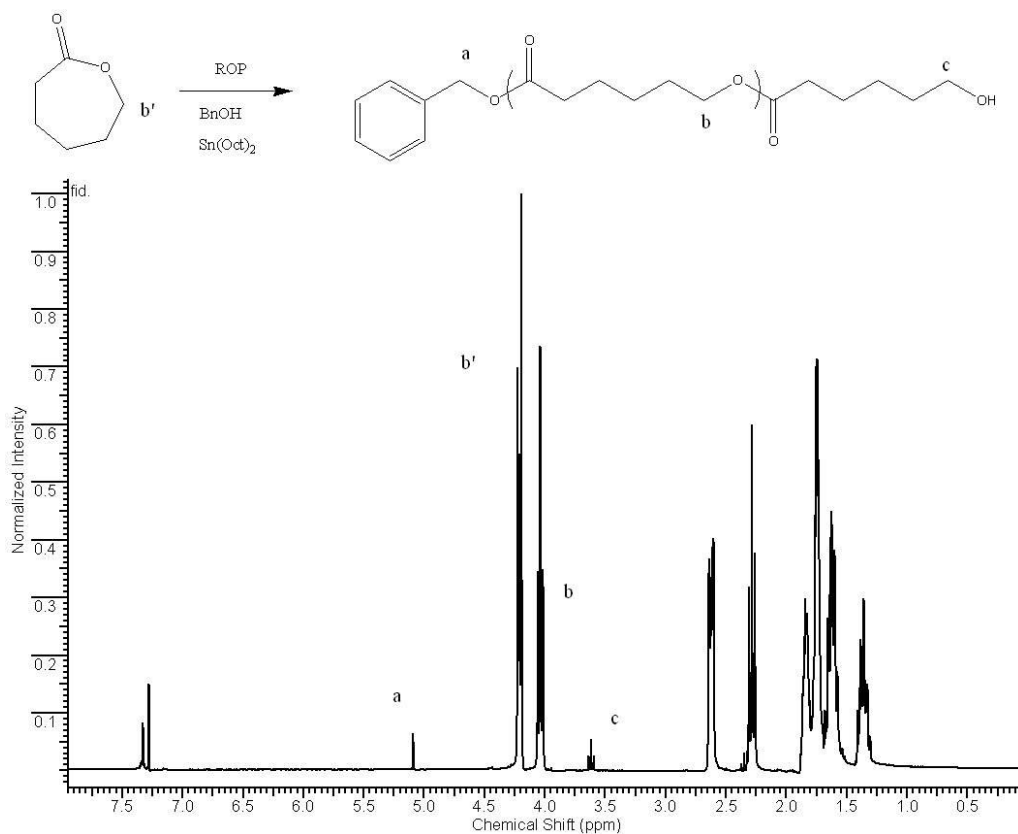


Figure 3.2: ^1H NMR spectrum of PCL measured in CDCl_3 .

Monomer conversion was calculated by comparing the integral of the proton resonance of the methylene adjacent to the oxygen on the carbonyl group of the monomer ($\delta = 4.24$ ppm) and polymer ($\delta = 4.07$ ppm) using the following equation:

$$\text{conversion (\%)} = \frac{\text{integral value of } b}{\text{integral value of } b + b'} \times 100$$

The M_n was calculated by multiplying the ϵ -CL molecular weight (114.14 g mol^{-1}) by the DP.

3.3 Results and Discussion

This work analyses the effects that MWH has upon the ROP of ϵ -CL, specifically when used with a BnOH initiator and Sn(Oct)₂ catalyst combination. There is a large body of published work which has reported superior results when using MWH, such as improved rates of reaction and higher quality of product.^{22, 24, 31, 33, 41} The initial section of this study details a rigorous comparison of the reaction characteristic observed for this controlled ROP growth of PCL when heated using both MWH and CH methods. The data generated from this work is then used to provide explanation for the root causes of the differences generated by the heating mechanism used.

3.3.1 ROP Experiments in MWH and CH

In order to embark upon this study, a series of reactions were undertaken following the same experimental procedure as in previous work comparing MWH and CH. Therefore, the only experimental difference in these experiments was the method of heating the reaction. Based on the results of a previous study into the ROP of ϵ -CL, a reaction temperature of 150 °C was chosen because it gave the optimum balance between reaction rate and retaining control.⁴⁸ At this stage in the study, the reaction was allowed to proceed until full monomer conversion and the monomer was pre-heated under vacuum prior to reaction to remove water. Entrained water has the potential to be a competitive initiating species as it contains a hydroxyl moiety.⁴⁹ All

reactions were conducted following the procedure detailed in the experimental section (Section 3.2.2) in a 50 ml test tube and in the bulk, i.e. without solvent, to nullify any solvent effect on the reactions. The target DP for these experiments was 87 with the reagent ratio of $[\epsilon\text{-CL}]_{87} : [\text{BnOH}]_1 : [\text{Sn}(\text{Oct})_2]_{0.02}$. The plots of $L_n ([M_0]/[M])$ against reaction times generated from these experiments are shown in Figure 3.3.

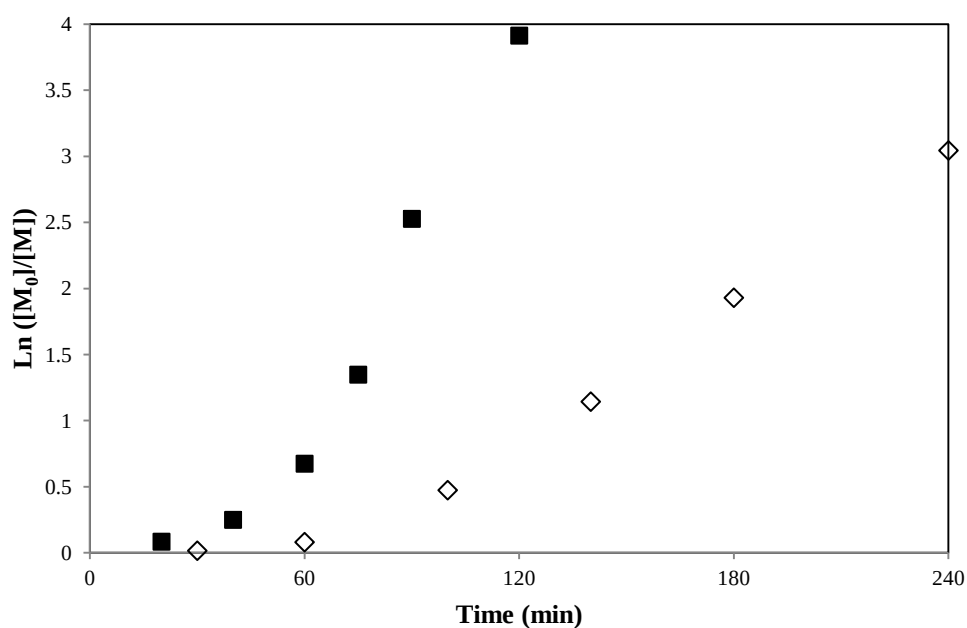


Figure 3.3 Kinetic plots of $L_n ([M_0]/[M])$ versus reaction time for the ROP of ϵ -CL at 150 °C using MWH (■) and CH (◇).

The plots for both heating methods do not follow a true living polymerisation (as described in Section 1.2.2.2). It is clear that there was a delay before any polymerisation occurs (during an induction period) and a linear polymer growth plot was not observed until 60 minutes of MWH reaction and after 100 minutes of heating *via* CH. After the initiation period for both heating methods, a controlled polymerisation was evident for both heating methods due to the

linear growth during propagation. Hence, this implies that a constant level of active sites was available during the entire polymerisation. This lack of termination of the active sites provides evidence that controlled ROP of ϵ -CL was possible with both heating methods. Although there was a difference in actual rate of reaction observed and onset of the ROP propagation (which will be discussed in greater detail later in Section 3.5.5.1), the overall reaction paths/mechanisms were very similar. As has been previously been reported, an initiation period in both MWH and CH was observed. However, the length of initiation period for MWH and CH was found to be different, approximately 15 and 25 minutes respectively.

The linear growth of M_n when plotted against monomer conversion was also observed to follow the theoretical growth patterns expected from a controlled polymerisation for both MWH and CH (Figure 3.4).

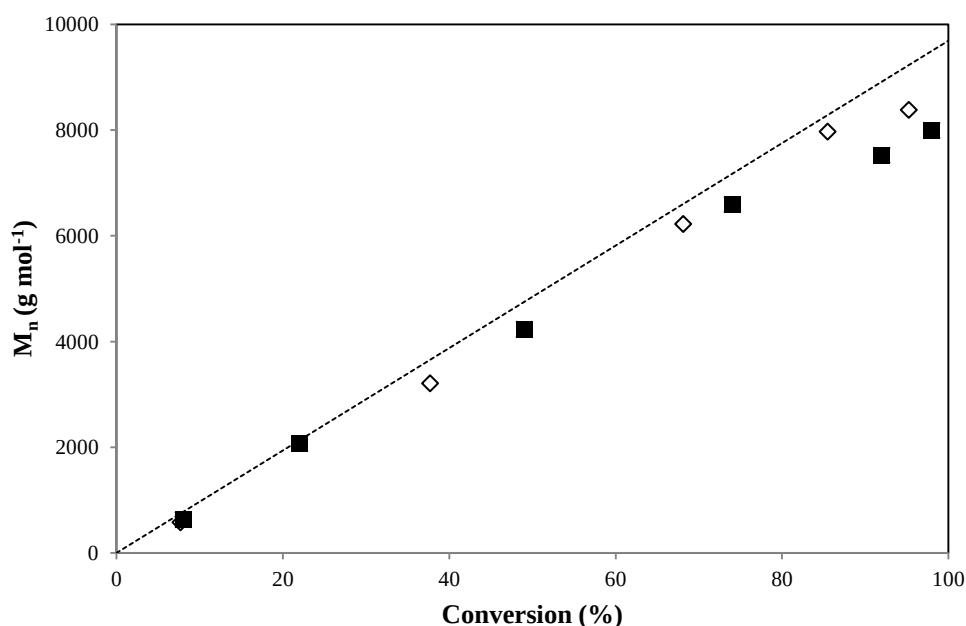


Figure 3.4 Dependence of molar mass (M_n) on monomer conversion (the dashed line represents the theoretical variation of M_n with conversion) for the ROP of ϵ -CL at 150 °C using MWH (■) and CH (◇).

The linearity of the plots was indicative that a controlled ROP mechanism operated with both heating systems. The fact both reactions tended to have slightly lower molecular mass than the theoretical value at their respective conversions was an indication that small amounts of superfluous hydroxy containing compounds were present, i.e. H_2O . These impurities can have an effect on the molecular weight for both heating methods by acting as an additional initiating species. These experiments also demonstrated that, at high monomer conversion (i.e. >80 %), both plots deviated away from the theoretical predicted value. This was the point in the reaction where transesterification side reactions dominate over the propagation reaction as described in the introduction (see Section 1.3.2.6). This appeared to be more prominent with MWH, where to the final deviation appears to be greater. This will be studied in greater depth later in this chapter (see Section 3.3.4.5).

The comparison of the evolution of $\bar{D}$ values against monomer conversion (Figure 3.5) during the reactions provided more evidence that MWH produces controlled growth of PCL.

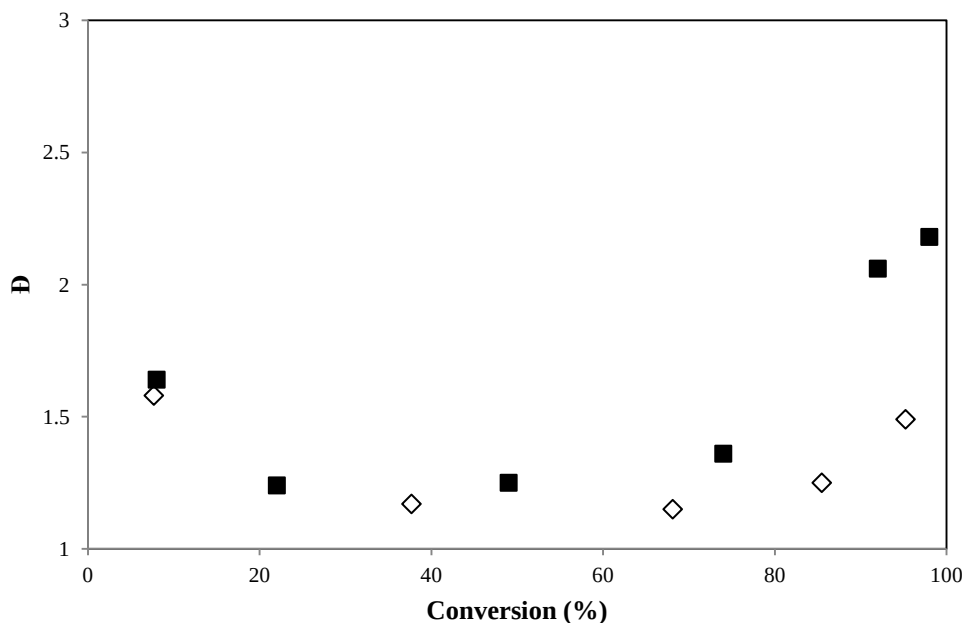


Figure 3.5 Evolution of dispersity on monomer conversion for the ROP of ϵ -CL at 150 °C using MWH (■) and CH (◇).

Analysis of this data supported the previous conclusions, that both heating methods exhibited good control over the kinetics. During the majority of both reactions, the $\bar{D}$ was between 1.2 - 1.4. As the polymer chains grew, both heating methods exhibiting similar mechanisms with efficient transfer and constant amount of active centres during the propagation stage. However, at low monomer conversion the $\bar{D}$ was relatively high, above 1.5 for both MWH and CH. This was because during the induction and initiation stage there are a number of pre-propagation processes were on-going: the pre-catalyst was involved in the formation of the active species reactions and the first

coordination of a monomer to the true catalytic species. Therefore, only a few PCL chains of varying lengths were starting to be formed.

Additionally, at high monomer conversion, the $\bar{D}$ values rose at the same level as the molecular weight deviations from theoretical M_n were noticed in Figure 3.4. This was an indication of the effect of the transesterification reactions that dominated when the active centre was unable to react with the last few remaining monomer units and thus unwanted side reactions occurred, resulting in the loss of control over the ROP. Again these seemed to be more pronounced in the MWH case, where the final $\bar{D}$ values were higher in MWH as they go above 2.0. As has been shown in previously reported studies, MWH can produce controlled ROP of ϵ -CL using a $\text{Sn}(\text{Oct})_2$ and BnOH catalyst/initiator system.⁵⁰ A comparison of the kinetic plots of monomer depletion against reaction time for both MWH and CH is provided in Figure 3.6.

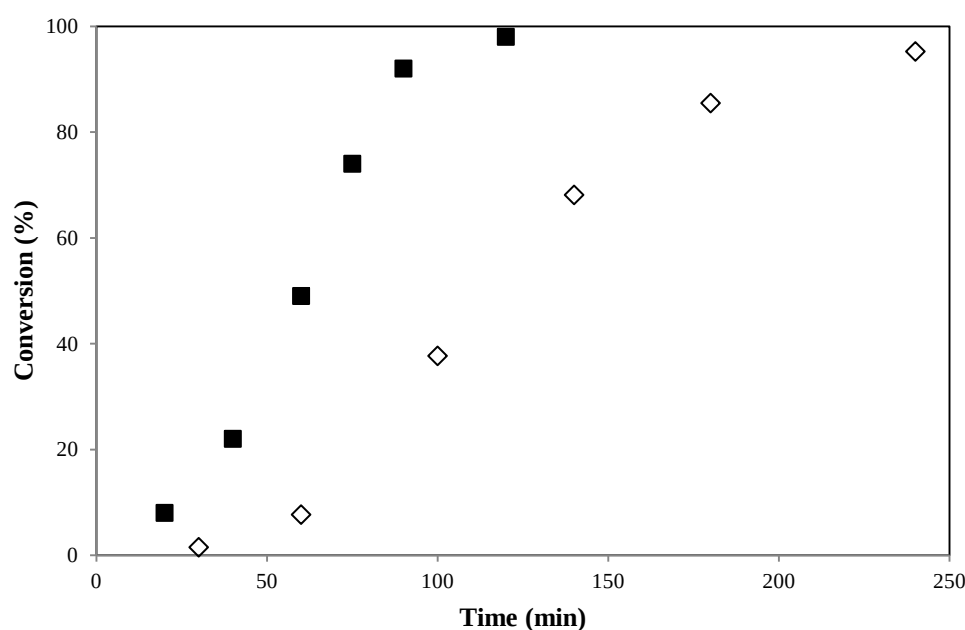


Figure 3.6 Kinetic plots of ϵ -CL conversion against time for ROP of ϵ -CL at 150 °C for MWH (■) and CH (◇).

As discussed above, this conversion profile is the expected profile which has been reported in the literature.⁵¹ It is clear from Figure 3.6 that both heating methods followed similar reaction profiles: no conversion can be observed initially, before a slow induction period during which the first monomer units react. Linear increase of conversion against time was noted during the majority of reaction during propagation until termination reactions dominate at low monomer levels. The key difference being that the reaction in the CH occurs over a longer reaction time period.

In this study, this reaction fingerprint was broken down into four separate stages representing the constituent components of the polymerisation mechanism (i.e. induction, initiation, propagation and termination) and each of the first three stages was rigorously analysed to explore what effect, if any,

MWH was imparting during each stage by direct comparison with the comparative CH reactions.

3.3.2 Summary of Microwave and Conventional Reaction

Profile Differences

Both MWH and CH were observed to have a period during which the reaction mixture is at reaction temperature but there is no polymer growth (Induction period). This been attributed to the period in which the pre-catalyst $\text{Sn}(\text{Oct})_2$ complex was being converted into the catalytically active species $\text{Sn}(\text{OBn})_2$ which contains the benzyl alcohol moieties as ligands. Following the induction, the reactions in both heating methods were observed to exhibit an initial shallow growth during initiation of the reaction, where there is minimal growth of PCL (Initiation Period). This was when the newly formed organometallic catalyst initially interacted with the first ϵ -CL and the ROP is being established forming dimer and trimer species.

The key difference observed between the two heating methods was that the combined induction and initiation period was approximately 10 minutes when using MWH compared with 25 minutes with CH. This difference has been proposed to be the result of selective microwave heating of specific components in the reaction mixture and forms one of the key areas which have been studied in greater detail later in this work (Section 3.3.5.1).

After these initial stages, the propagation periods in the reactions were evident in the steep growth in monomer conversion, when more ϵ -CL units were added to the growing PCL chains. The propagation period, when heated by MWH, occurred 20 minutes into the reaction and lasted for 70 minutes. In this period, the monomer conversion increased from 20 % to 90 %. The propagation period in CH lasted longer, from the 60 minute point until the 160 minute point, during which the ϵ -CL conversion increased from 10 % to 80 %.

These reactions were both conducted at 150 °C, yet full conversion was achieved much earlier in MWH (Figure 3.6) where 120 minutes were needed, half the time it took with CH (240 minutes). Rate constants can be calculated from the semi-logarithmic plots $L_n ([M_0]/[M])$ versus reaction time using the slopes of the first-order kinetic plots if the slopes were linear. As there was non-linear ROP growth, the apparent polymerisation rate constants (k^{app}) were unable to be determined from the first-order kinetic plots. Instead, the gradients of the linear portion of the slopes were used to determine the rate constant of propagation (k_p) for the heating methods, with $0.3873 \text{ Lmol}^{-1}\text{min}^{-1}$ calculated from MWH and $0.1408 \text{ Lmol}^{-1}\text{min}^{-1}$ with CH. The k_p for MWH was 2.75 faster than the CH reaction, which is consistent with previous work.¹³

Thus, the main differences observed in between the reactions conducted with the differencing heating methods were the shorted lag time at the start of the reaction, the increased rate of polymerisation and the reduced time needed to reach full conversion with MWH. These advantageous results in MWH have been reported previously in the literature alongside claims of a ‘microwave effect’.²⁴

The work in this study aims to establish the effect the MWH had on reaction rates when identical reaction conditions and temperatures are applied. Furthermore, the work detailed in this study will also lead to a greater mechanistic understanding of the effect of MWH on the various stages of the ROP.

3.3.3 Assessment and Comparison of Bulk ROP Reaction

Temperatures

Much work in the literature has involved simply the empirical identification and quantification of potential microwave effects.^{13, 21-24, 31} Consequently, a large number of papers have been published claiming various improvements and enhancements that have resulted from adopting MWH over CH. The root causes of many of these positives have often been left unexplained; rather they have just been grouped under a ‘microwave effect’ umbrella. More recent work has revisited these claims and applied a higher level of understanding related to the microwave technology and a greater level of rigour related to the analytical practices employed. As a result, an area of microwave chemistry experimental practice that has come under intense scrutiny is that of relying on temperature measurements that use an external IR sensor in a microwave reactor.

3.3.3.1 Use of Fibre-Optic Probe (FO)

It was reported in the Introduction to this chapter (Section 3.1.3) that a significant proportion of recent published work on MWH has targeted the temperature monitoring system to explain previous ‘microwave effects’.^{30, 42, 47, 52} The purpose of this work is to investigate, using a more sensitive heating feedback system, the effect of microwave heating on the bulk ROP of ϵ -CL. Consequently, a FO probe was placed directly into the reaction mixture to examine the complex polymerisation environment at the separate stages of the ROP, in an attempt to rationalise the increased rates with MWH.

3.3.3.2 Temperature Profile

A FO probe was placed directly into the polymerisation reaction conducted earlier in this chapter (Figure 3.3 in Section 3.3.1) for the ROP of ϵ -CL at 150 °C which was being conducted using a CEM Discover microwave reactor. Thus, this sensor provided an accurate temperature measurement of the internal reaction conditions. The FO probe was located in the centre of the reaction, above the magnetic stirrer but not such that it affected the agitation rate. The CEM’s internal IR sensor was also used in monitoring the reaction to allow a comparison to be made between the results generated from this study and those from the literature studies. The IR sensor generates its measurement by assessing the temperature of the external wall of the reaction vessel. Thus overlaying the temperature readings from the internal (FO) and external (IR)

temperature sensors, one is able to gain a further understanding of the microwave effect on the ROP of ϵ -CL and possibly quantify and qualify any perceived microwave effects. Figure 3.7 shows the power input and both the FO and IR temperature achieved. In this experiment the power control was operated *via* a feedback loop from the IR probe as had been conducted in comparative literature experiments.

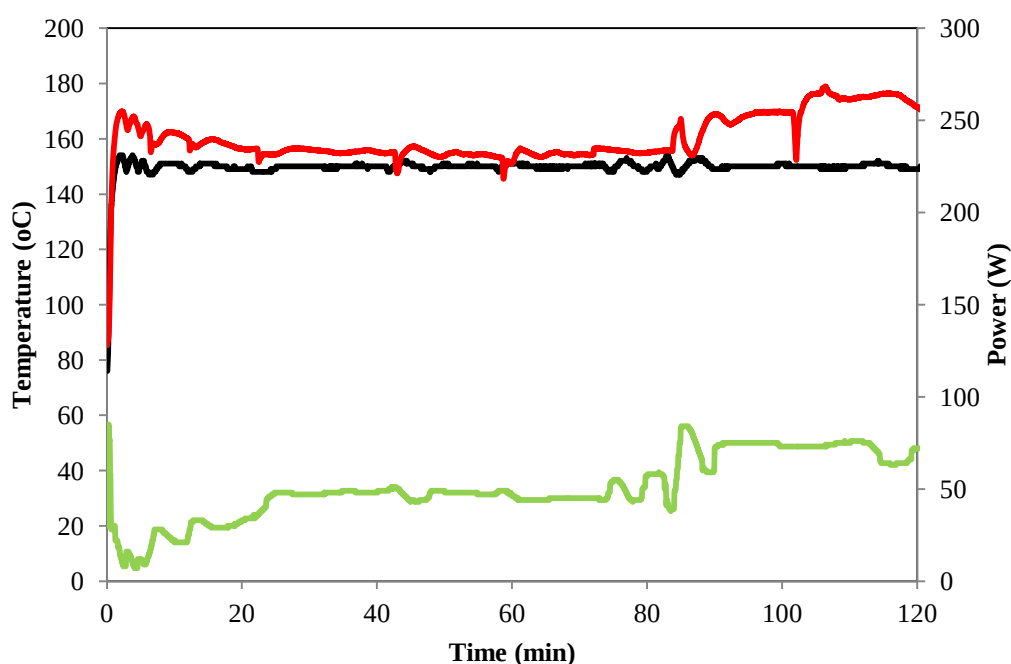


Figure 3.7 Power (green line), FO (red line) and IR (black line) temperature profiles during microwave heating of the ROP of ϵ -CL at 150 °C.

The input power was noted to be 80 W as the solution temperature was raised from 85 to 150 °C. After this the power levels drop to less than 20 W after one minute when the IR sensor has defined that the solution has reached its target temperature. The relatively high loss tangent value of ϵ -CL of 0.3 at 80 °C gives rise to the efficient volumetric heating of the bulk solution.²⁹

However, it was observed that the actual bulk temperature (FO reading) was significantly higher than that detected by the IR probe during this initial segment of the experiment. In the first 3 minutes of the reaction the FO data shows that there was a large temperature overshoot to 170 °C during the initial input of 60 W of microwave energy. Meanwhile, at this point in the reaction there was no evidence of such pronounced temperature overshoot from the IR sensor, which recorded the temperature at 150 °C. After reaching this set point, the IR temperature reading remained within a couple of degrees of this target for the majority of the reaction. The initial 20 °C disparity between the IR and FO readings occurs during the organo-metallic active catalyst formation reaction. Study of the dielectric properties of the polymerisation reagents indicate that at high temperature (i.e. above 130 °C), the loss tangent of the tin species increases and become similar to that of the ϵ -CL, and will thus be highly susceptible to the microwave energy.^{29, 48} A rigorous study into the cause of the 20 °C exotherm was conducted and the results are reported later in this chapter (Section 3.3.5.1).

After reaching this initial peak during the induction period, the power input dropped significantly and remained low during the initiation region, yet the bulk temperature remained 15 °C above the target temperature. The FO temperature only dropped below 160 °C after approximately 20 minutes and remained between 5 and 8 °C above the target temperature throughout the propagation period. This is important as the FO probe highlights potential inadequacies observed in the use of an IR sensor to follow the reaction kinetics. As the large majority work in the literature uses the IR sensor and quotes its

temperature when calculating rates of polymerisation, there is a risk that calculations of the k^{app} and other rate constants will be skewed in favour of MWH due to the misquoting of temperatures.

During propagation it was noted that 30 W of power was required to maintain a constant temperature. This can be rationalised by the decreasing dielectric properties of the ROP mixture with increasing lengths of PCL being formed. It has been shown that as the monomer is converted into polymer the dielectric constant for the reaction mixture will reduce in a predictable manner related to the loss of monomer. This is because the dielectric response of the polymer is much lower than that of the free ϵ -CL monomer.²⁹ This reduction in response has been attributed to the fact that the dipole movement in the polymer had become more restricted due to the steric bulk of the rest of the chain. Therefore MWH will be converted much less effectively into heat as the polymer chains grow. Any absorbance of MWH energy by the polymer chain has been attributed to the chain end species interacting with the electromagnetic field. This may still result in the slightly increase propagation rate in the MWH reactions. During the propagation period, the CEM raised the level of power which ensures a constant IR temperature of 150 °C and a true FO temperature of 158 °C.

Finally, the FO and IR temperatures were observed to again deviate by a significant amount after 80 minutes, which corresponds to over 80 % conversion from Figure 3.6. Whilst the IR reading remained at 150 °C, the FO probe recorded that the actual internal temperature was over 170 °C for 10 minutes before increasing up to 180 °C for the final 20 minutes of the reaction.

A diffusion effect and a potential MWH effect are possible explanations for the true internal temperature increase at the end of the ROP reaction. The increase in temperature is related to the increasing viscosity created by the presence of the long PCL chains. This viscosity build up may have resulted in poor heat transfer from the system at this point and/or it could have increased the level of intermolecular friction caused by the dipole moment inspired by the microwave energy, both could have caused temperature feedback and/or control issues for the CEM. Further internal heat increase has been attributed to the fact that the MWH experiments are promoting additional transesterification reactions to a greater degree than the CH method because the energy was being directly sent to the chain end; causing them to experience greater reactivity.

Therefore, the key conclusion from this section was that much of the prior literature work that have claimed an improved rate of reaction with MWH may have unknowingly misquoted the true temperature of reaction by adopting the IR sensor measurement as a true reflection of the bulk temperature. Thus, this could be the source of many observed ‘microwave effects’.

3.3.4 Detailed Study into Causes of Temperature Differences

Observed

The following section will analyse various experimental conditions and ‘non-microwave’ effects that lead to escalated reaction temperature differences between the IR and FO monitoring systems.

3.3.4.1 Volumetric Heating

Dielectric volumetric heating of a substance due to MWH has been known to deliver the ability to rapidly reach high temperatures. In this study it was this effect that was identified as the main cause of the observed rate enhancements and cycle time reduction in MWH experiments conducted and is purely a thermal effect. Previous studies have shown that ϵ -CL is highly susceptible to microwave energy with a significant $\tan \delta$ value, especially at room temperature.⁴⁸ Therefore the rate of ROP of ϵ -CL will be enhanced by the speed at which the ϵ -CL will reach the elevated target temperature with MWH when compared with CH.

Consequently, a series of experiments were conducted comparing the time taken to reach a target temperature (130, 140, 150, 160 and 170 °C) from 80 °C in MWH and CH for the ROP of ϵ -CL. The FO probe was utilised in the CEM and oil bath reactions and was used to ensure both accurate time and temperature recording were achieved and these results are shown in Figure 3.8.

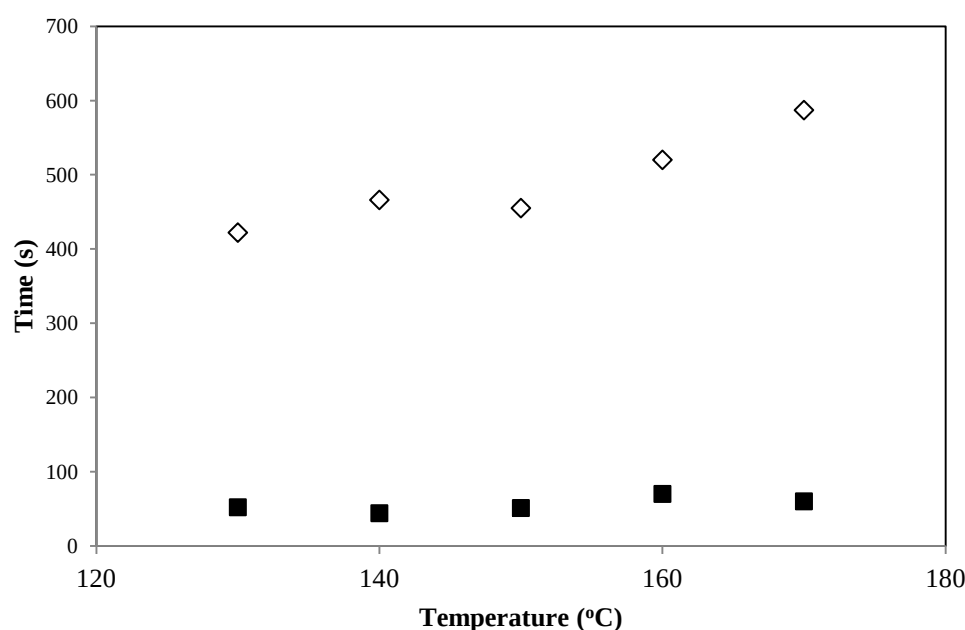


Figure 3.8 Time taken to reach target temperature over a range of temperatures when heating up ϵ -CL from 80°C in MWH (■) and CH (◇).

The results demonstrated that there was an order of magnitude difference between the times taken for the reagent to reach the target temperature depending on which heating method was adopted (see Figure 3.8). The time taken in MWH was under a minute for all temperatures, with 130 °C (52 seconds) reached in a very similar period of time as 170 °C (59 seconds). The time needed for ϵ -CL in the conventional oil bath to reach the elevated temperature was closer to 10 minutes. Furthermore, a prominent increase in the time required to reach a specific temperature was observed as the target was raised (i.e. 420 seconds for 130 °C whereas 590 seconds at 170 °C). This led to the disparity between MWH and CH times increasing as the higher temperatures are targeted, thus further exaggerating potential microwave effects when higher reaction temperatures are targeted. This highlights the importance of the potential efficiencies that can be gained from volumetric

heating effect on the ROP of ϵ -CL when compared to the conductive/convective mechanisms that are responsible for CH heating.

3.3.4.2 Average reaction Temperature

From the FO measurement (section 3.3.3) it was also observed that the temperature during the majority (particularly the propagation stage) of the ROP of ϵ -CL was approximately 10 °C above the assumed/target temperature (Figure 3.7). A series of experiments were carried out at various temperature ranges for both CH and MWH (Figure 3.9) to analyse the true average reaction temperature not only in the CEM MWH, but also the oil bath, which controls temperature *via* feedback from a thermocouple placed in the oil.

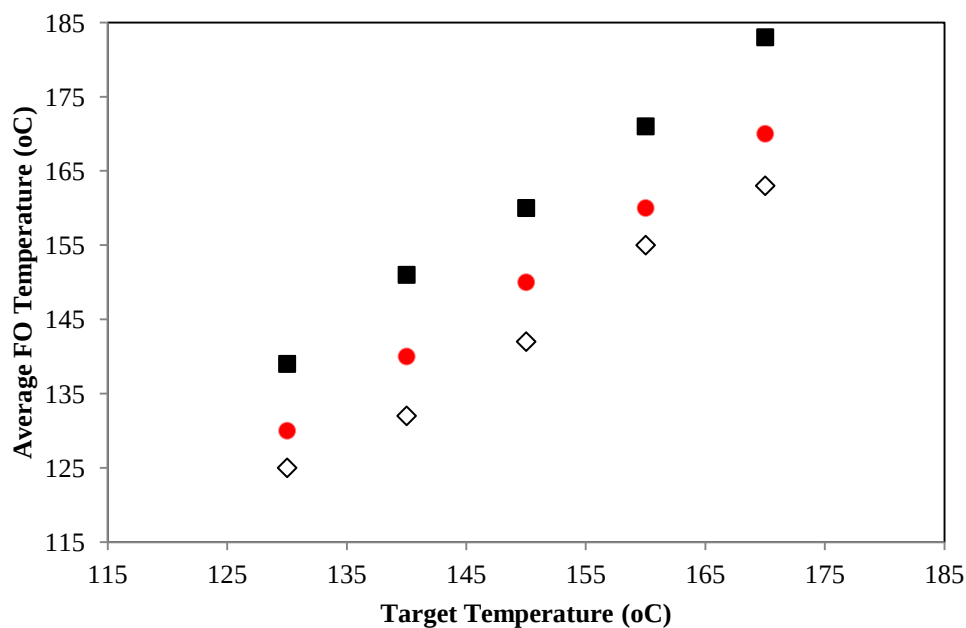


Figure 3.9 Average FO temperature during propagation period for the ROP of ϵ -CL at a range of temperatures in MWH (■) and CH (◇) against target temperature (●).

As expected, higher than targeted temperature was reached (Figure 3.9) in MWH for ROP of ϵ -CL reactions over a range of temperatures. The bulk reaction temperatures were approximately 10 °C higher than the set temperature. The reaction temperatures (Figure 3.9) in CH were found to be on average 5-7 °C below the target temperature. This was because energy can be lost in an oil bath to its surroundings (i.e. to the air above the reaction vessel) before the full heat can be transferred to the reaction mixture.

This shows that for the ROP of ϵ -CL, comparing MWH with CH reactions at identical temperatures was more complicated than previously expected. The inefficient temperature feedback in MWH caused reactions to be conducted at elevated temperatures whilst the opposite occurred with CH, where the bulk temperature was lower than the set oil bath temperature. This temperature disparity could also manifest itself when comparing k^{app} at ‘similar’ temperatures between CH and MWH. The MWH rate will be higher than the true value, and lower for CH, as the theoretical temperature will differ from the experimental one. This also highlights the importance for CH, as well as MWH, to report the internal FO temperature, not the external thermocouple (or IR in MWH).

3.3.4.3 Preheating Reagents

In MWH reactions, the slow temperature feedback between the IR sensor and the CEM power source has been noted to cause temperature anomalies (Figure

3.7). This phenomenon was only noticed when the FO probe was used to establish the true bulk temperature. To aid in future planning of experimental programs, a series of experiments were conducted to establish the amount of temperature overshoot in the ROP of ϵ -CL when MWH when the reagents were heated from room temperature (RT) or preheated to 80 °C prior to reaction; both of these experiments had 300 W of power introduced. Figure 3.10 contains the results of these experiments when the temperature profiles were followed by IR (A) and FO (B).

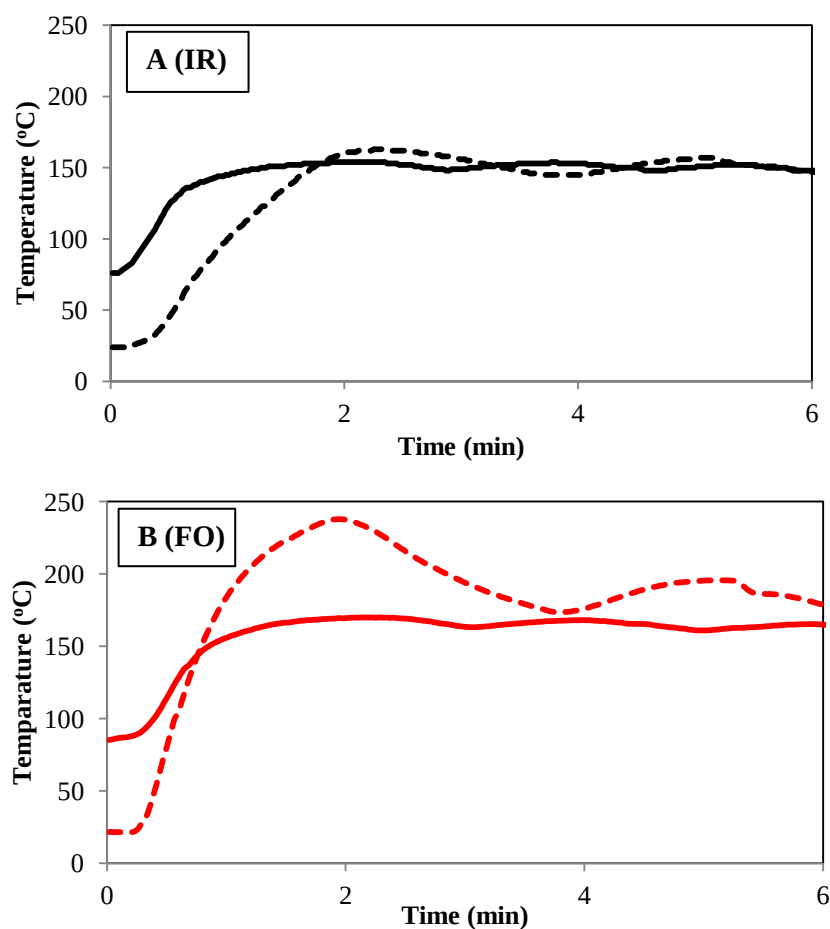


Figure 3.10 ROP of ϵ -CL by MWH. Reaction temperatures followed by IR (A) with preheated reagents (solid black line) and room temperature reagents (dashed black line). Reaction temperature followed by FO (B) with preheated reagents (red solid line) and room temperature reagents (red dashed line).

When the reagents were preheated to 80 °C prior to being combined and heated by microwave energy, it was observed that a temperature overshoot was present but that its size was significantly smaller than when the materials were heated from RT. Consequently there was a closer correlation between the IR and FO readings (the solid black line in A and the solid red line in B). Both temperature plots reach the target 150 °C in under a minute. Therefore one would use 150 °C when calculating k^{app} .

However, there was a large discrepancy observed when the reagents are heated from RT. The FO probe indicated a significant temperature overshoot (B, green line). In the RT case, the FO temperature, similar to the IR equivalent, peaked after 2 minutes; however this maximum was at 240 °C, a massive 90 °C overshoot. This difference was linked to the IR ineffectively reporting the true temperature, thus causing the CEM to continue to deliver 300 W, even though the actual bulk temperature was exceeding the target. This level of power input was reduced if the materials were already at 80 °C because the dielectric response of ϵ -CL has reduced from RT to 80 °C, thus it was less able to absorb energy. Therefore, when discussing the impact of MWH on the ROP of ϵ -CL, preheating reagents is another method to minimise accidental experimental error, and thus allowing for thorough investigation into the presence of potential microwave effects.

3.3.4.4 Reactor Vessel Placement

In the CEM microwave reactor, the placement of the reaction vessel has an impact upon the reliability of the recorded IR temperature. The mode of the cavity is directly in the centre, approximately 8cm above the bottom of the reactor. It is here that microwave energy is at its highest level of concentration, with substances undergoing their most efficient dielectric heating. Therefore, this is the optimum location for the reactor centre to obtain maximum efficiency of the MWH method. However, the IR sensor is located below the cavity, facing upwards onto the bottom of the reactor vessel. The optimum vessel placement with regards to the IR sensor is therefore at the bottom of the CEM cavity, thus producing the minimal distance for the IR to detect across.

The FO was used (Figure 3.11) to investigate the effect on bulk temperature when placing the vessel in the centre of the mode and at the bottom of the CEM cavity.

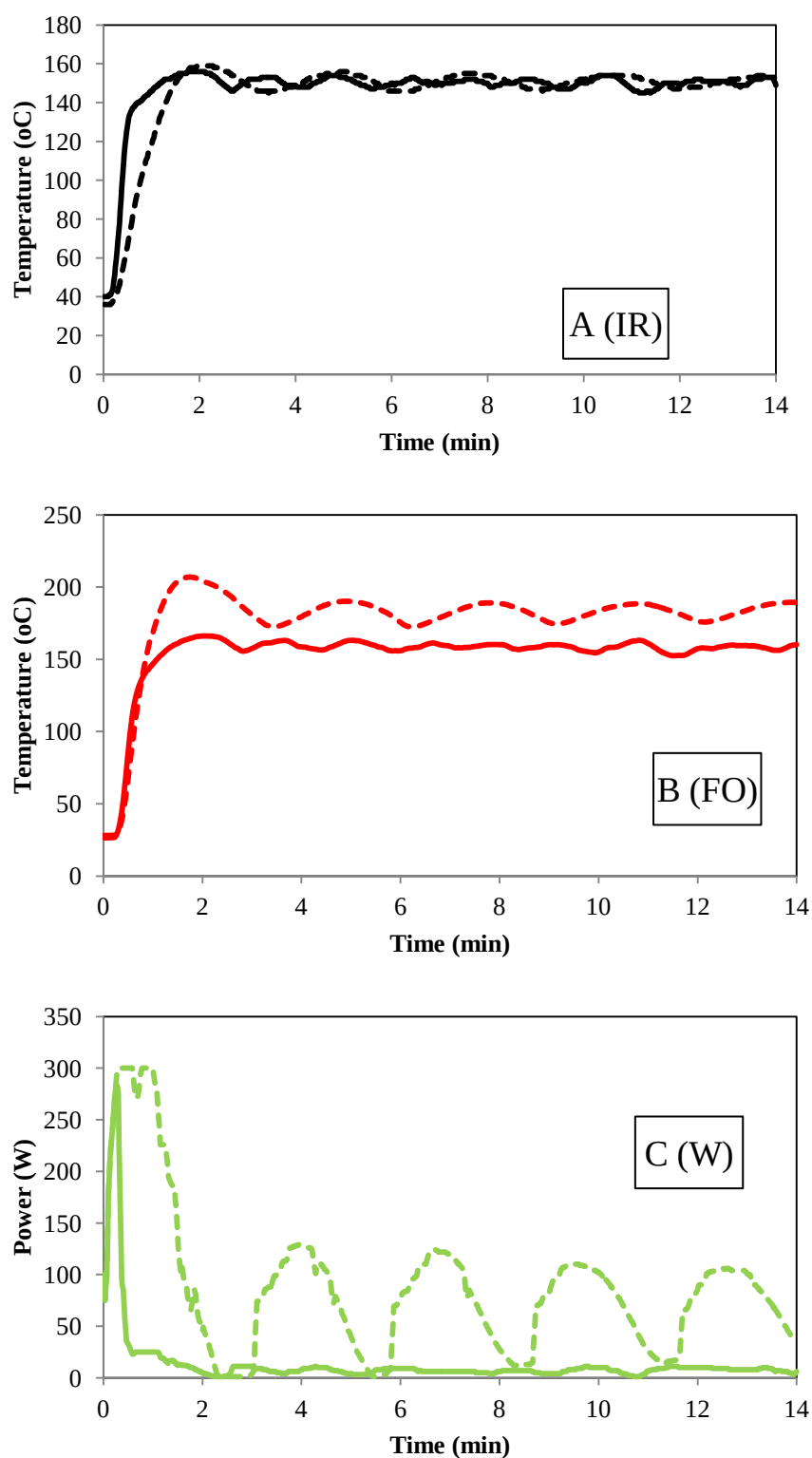


Figure 3.11 IR temperature (A), FO temperature (B) and CEM Power (C) for reactor vessels located at the bottom (solid line) and in the mode (dashed lines) of the CEM for the ROP of ϵ -CL.

The IR temperature profiles (Figure 3.11 A) for the two reactions are almost identical; both reactions reached the target temperature of 150 °C in less than 2 minutes with very little overshoot. According to the IR sensor, neither reaction exceeded 160 °C and only appeared to fluctuate a couple of degrees either side of the target 150 °C for the remainder of the reaction. Therefore, utilising solely the IR (as has been the case in much of the literature relating to MWH), one could assume that these two reactions followed the same temperature profiles.

However, the introduction of the FO highlighted the fact that the placement of the reactor vessel had a dramatic impact upon the true internal temperature for the ROP for PCL. It is clear from Figure 3.11 B that the two temperature profiles differed dramatically and thus these reactions were far from identical. The reaction at the bottom of the reactor, near to the IR (Figure 3.11 B; solid red line), reached the target 150 °C quickly and remains close to this temperature throughout the reaction, which was similar to the IR sensor readings. The power was initially high (300 W), but dropped to less than 5 W as the IR correctly fed back that the bulk temperature was stable at 150 °C.

The FO probe in the reaction undertaken in the centre of the mode of the cavity (B; red dashed line) clearly indicates that the IR sensor was unreliable when the 8 cm gap was introduced. Whereas the IR suggested that the bulk temperature never exceeded 160 °C, the FO reported that an overshoot of 60 °C occurred with an initial temperature of 210 °C being reached. This was caused by the maximum power (300 W) being inputted for much longer for the reaction in the mode (Figure 3.11; C). An additional 60 seconds of operation at

full power occurred before the IR recorded the temperature had reached the target and so reduced the energy input (Figure 3.11 C; solid green line). Additionally, the true internal temperature when in the centre of the mode was noted to exhibit significantly more fluctuation in temperature. This was also observed to be mirrored by the power profile for this reaction which indicated that during the reaction there were periods where up to 80 W was being introduced. This was also attributed to the fact that there was a significant lag between the temperature of the reaction vessel and the sensor reading when the two are 8 cm apart. Consequently, the true bulk temperature never dropped below 175 °C as large amounts of power (over 100 W) were used to maintain the IR temperature of 150 °C. The FO continued to show that this was an incorrect value, as the temperature lingered between 175 °C and 190 °C.

Therefore these experiments showed that the location of the reactor vessel played an important part in the misrepresentation of the true bulk temperature. Thus, the previous literature reports may have observed and quoted variable increased rates of reactions and other improvements in MWH because the true temperature may have been both different to that which they believed and varying between experiments due to the potential variance in the distance of the IR to the reactor vessel. From this point, all reactions in this report will be conducted at the bottom of the CEM cavity, in an attempt to minimise errors due to the IR temperature feedback mechanism.

3.3.4.5 Effect of Viscosity on Temperature Readings

It was observed during the end of the reaction (Figure 3.6) that the true internal temperature increased during the final stages of the reaction. Figure 3.12 shows the IR and FO temperature readings at the end of the ROP of ϵ -CL reaction, along with the CEM power input.

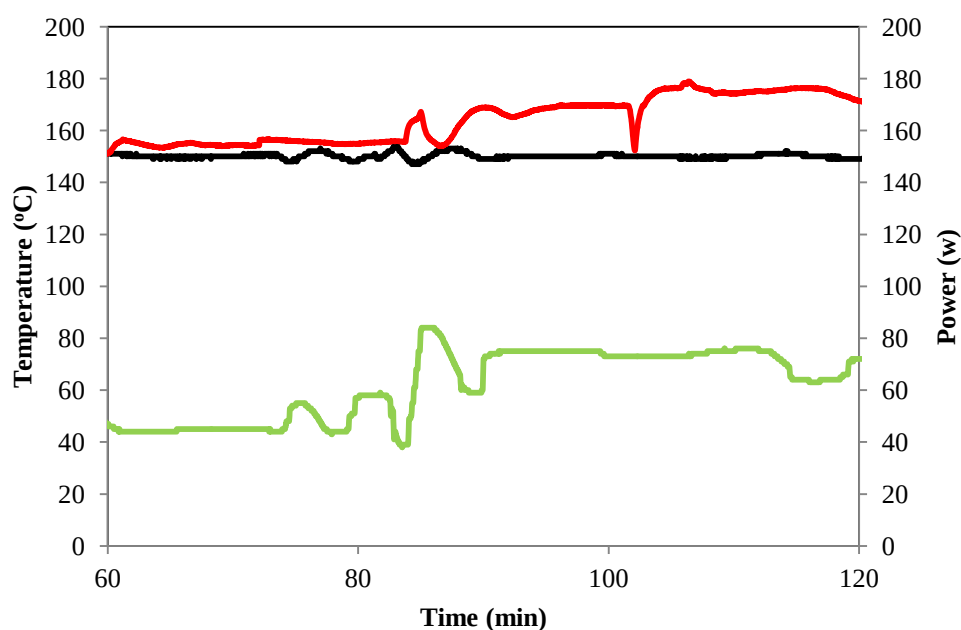


Figure 3.12 Power (green line) , FO (red line) and IR (black line) temperature profiles during the final stages of the MWH ROP of ϵ -CL at a target temperature of 150 °C.

After 80 minutes monomer conversion had reached 70 %, and the power level increased to over 80 W to maintain the IR temperature of 150 °C (Figure 3.12). These observations were linked to the increased viscosity that occurs when PCL chains are grown will affect the temperature of the reaction.

In this period of the reaction the monomer levels are very low, with PCL becoming the dominant (> 90%) component of the reaction mixture. Therefore,

the viscosity in the reactor vessel was greatly increased, whilst at the same instant the dielectric properties of the system were lowered. This was because the degrees of freedom around the active centres were also reduced severely and thus direct interaction of the dipoles with electromagnetic field would have been weakened. This would have caused inefficient energy heat transfer throughout the reaction medium, such that there would be an increase in what is termed the reflective power. This is the term used to describe the energy input which is not absorbed by the sample but is reflected around the cavity as a result. This will also result in inefficient heat transfer within the system resulting in localised hot spots in the cavity. In other words, the coolest part being the highly viscous polymer regions in the reactor vessel, whilst any remaining monomer will still be heated but due to the higher viscosity this will not be as evenly distributed in the earlier sections of the reaction which are more monomer rich. This will lead to difficulty in getting this hot spot heat to convect/conduct heat to the surface of the reaction vessel. Thus, as the IR measures the temperature at the wall (which was the coolest part) and the FO is placed into the bulk and thus more likely to detect the local temperature regions still being heated by the remaining microwavable susceptible monomer, it is proposed that the two temperature probes will record differing temperatures. This explained why the power levels increased during the final stage of the ROP reaction; there was little unreacted monomer still present that would have efficiently transformed the microwave power into heat, thus more energy was required.

The high viscosity in the MWH system could have had a detrimental effect on the controlled nature of the MWH ROP of ϵ -CL at the end of the reaction. As was observed in Figure 3.4, in the MWH reaction M_n deviated away from the $M_{n\text{ THEO}}$ at lower ϵ -CL conversion than in the CH equivalent. This was supported by the $\bar{D}$ data in Figure 3.5, where the MWH reaction values increased to almost 2.0 after 80 % monomer conversion, whilst the CH values remained below 1.4 at the same stage. The poor diffusion of the remaining ϵ -CL moieties at > 80 % conversion caused by the high viscosity could have explained this early loss of control in MWH. The loss of control over the controlled nature of the ROP would have occurred in MWH due to viscosity increasing, causing the rate of diffusion to drop, the true internal temperature increasing and as the active centres were unable to reach the remaining ϵ -CL units, the transesterification mechanism dominated. This process would have been much less pronounced in CH, due to uniform heating and better mixing. Therefore it is incorrect to conclude from the results in Section 3.3.1 that the controlled nature of ROP was lost at lower conversion than in CH, as the two reactions were no longer comparable, due to the difference in diffusion and true internal temperature. All future comparisons in this thesis will be made after ensuring identical reaction conditions for both heating methods.

Therefore the increasing viscosity of the ROP of ϵ -CL was observed to cause problems in temperature control. This means that analysing and comparing CH and MWH reactions is risky when trying to replicate reaction temperatures and conditions. Some increased rates of the ROP of ϵ -CL may have been the result of the increasing viscosity of the reaction mixture causing the CEM to overheat

the reaction due to the poor temperature feedback available using solely the IR sensor in the CEM.

3.3.5 Investigation into Microwave Effects on the ROP of ϵ -CL

This chapter has so far identified the effects that temperature measurement and reactor geometry can have upon the MWH reaction conditions and observations for the ROP of ϵ -CL. The remaining part of this chapter will break down the ROP reaction into its various components and study each one whilst eliminating previous temperature recording and reaction protocol errors, and study in great detail the effect of microwaves on ROP of ϵ -CL.

3.3.5.1 Induction Period

The induction period occurs first chronologically in the ROP of ϵ -CL and related to the section of the polymerisation mechanism in which the organo-metallic reactions occurs between $\text{Sn}(\text{Oct})_2$ and BnOH to form the true catalytic species. To investigate the true effect of microwaves upon this part of the ROP reaction, a comparison study between MWH reactions was undertaken using the FO probe.

The Induction stage is also the period in which the higher element of the initial temperature overshoot has been observed. Therefore, this temperature effect

was studied in greater depth to rationalise why the temperature reached a maximum of 170 °C after 130 seconds. Previous work by the NCIMP at Nottingham has reported that at room temperature, the $\tan \delta$ value of the monomer and alcohol are much greater than the tin precursor.⁴⁸ This means that the tin species will be the least efficient at converting microwave energy into heat. However, as the dielectric properties were analysed across a broad temperature range which included the target reaction temperature, it was found that the loss tangent of the monomer and alcohol decreased whilst the tin had an increased $\tan \delta$ at elevated temperatures. Above 140 °C, i.e. nearing the temperature the ROP reactions in this paper have been undertaken, the tin and monomer were the reagents most susceptible to microwave radiation with loss tangent values of 0.10 and 0.12 respectively.

Therefore by analysing the dielectric properties of the various reagents, it was concluded that the catalyst and monomer were the species likely to be preferentially/selectively heated at the higher temperatures and so led to a temperature overshoot. Therefore, a series of reactions were conducted with and without catalyst present to investigate this further (See Figure 3.13).

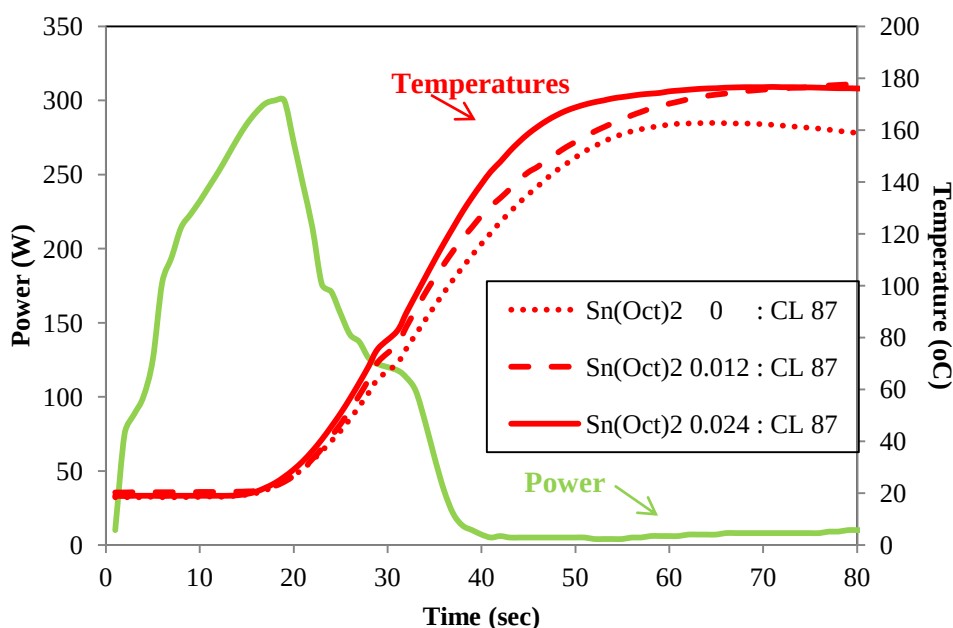


Figure 3.13 MWH heating profiles and typical power profile for Sn(Oct)₂: ϵ -CL solutions at pre-catalyst: monomer ratios of [0 : 87], [0.012 : 87] and [0.024 : 87].

The dotted red line in Figure 3.13 shows the heating profile for monomer on its own when no catalyst or initiator is present. This demonstrates that efficient bulk volumetric heating of the monomer using MWH can be achieved, with 160 °C being reached in 60 seconds from room temperature. However, when a catalytic amount of tin precursor (red dashed line) was present the overshoot was observed to be about 20 °C higher than when just monomer was heated. The amount of pre-catalyst added was equivalent to the level used in all the reactions reported in this study to date (< 100 ppm). This small level of catalyst was the only difference in the two heating profiles as there was no polymerisation reaction in this system because (a) at this stage of the reaction it was during the induction period and (b) no initiator species was present. Additionally, the induction period was further reduced (solid line) when the catalyst amount was doubled in relation to the monomer, i.e. the rate of

heating up was observed to be further increased as the tin concentration increases. The conclusion made from these observations was that the tin complex was being heated very efficiently by the microwave energy and that this was contributing to a significant rise in the bulk medium temperature. Furthermore, the observed increase of the bulk temperature suggests that the temperature at the tin moieties could potentially be much hotter, possibly by up to 100 °C, due to potential targeted heating. The superheated tin may have dissipated this excess heat to the bulk monomer leading to the overall temperature overshoot of approximately 20 °C. Therefore even at the low ppm amounts of catalyst there was evidence of a microwave effect *via* the specific/selective heating of the catalyst.

The effect on the bulk heating rate of various initiator (BnOH) levels was also investigated. The dielectric properties of BnOH suggest that it was highly susceptible to MWH at low temperatures.⁴⁸ The heating profiles for reaction mixtures containing various BnOH levels are shown in Figure 3.14.

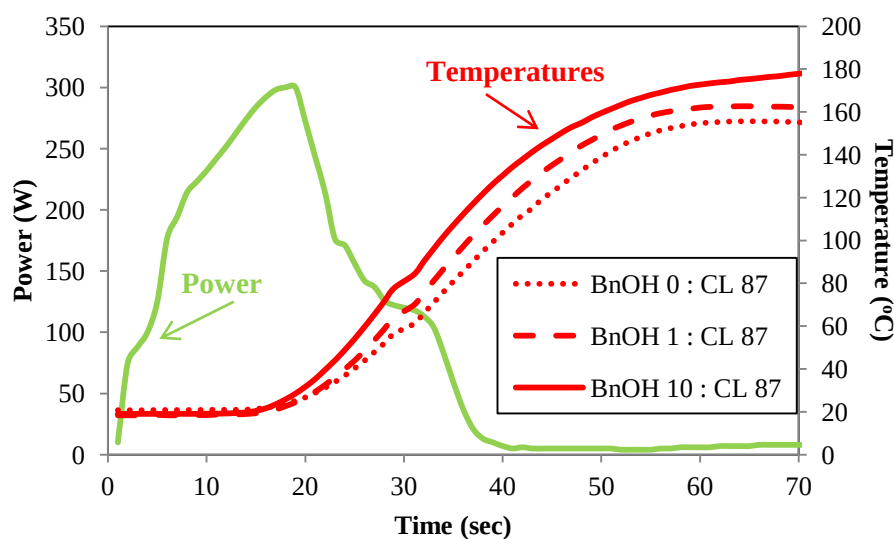


Figure 3.14 MWH heating profiles and typical power profile for BnOH: ϵ -CL solutions at pre-catalyst: monomer ratios of [0 : 87] , [1 : 87] and [10 : 87].

This data showed that increasing BnOH levels also increased the rate of heating of the bulk temperature as well as increasing the size of the overshoot. When there was only ϵ -CL being heated (dotted red line), there was no overshoot as the monomer takes 60 seconds to reach the target temperature of 150 °C. When a small amount of BnOH was introduced (red dashed line), the mixture heated faster and to a higher overall temperature. The ratio of BnOH 1 : CL 87 was the quantity used in the ROP of ϵ -CL in this thesis. However, unlike in the $\text{Sn}(\text{Oct})_2$ experiments (where a small increase in tin levels caused heating rates to increase dramatically), the effect of increasing BnOH was not as pronounced. A ten-fold increase in BnOH levels (solid red line) did result in a faster heating of the bulk, however a much smaller addition of tin caused similar heating rate enhancement. However there was evidence of the specific heating of the BnOH species at lower temperature where it

interacted with the microwave energy leading to an increase in the heating rate, which was rationalised by the high $\tan \delta$ value of the BnOH species.

These experiments have provided evidence that MWH had an effect on the induction period *via* the specific/selective heating of the pre-catalyst reagents and that these temperature overshoots cannot be reproduced with CH by simply adding the pre-catalyst reagents in this way. Consequently, this effect of targeting the tin pre-cursor and alcohol reagents using MWH to reduce the length of time needed for the induction period was studied using both MWH and CH. Thus a series of experiments were conducted at various temperatures but with the same reagent levels to establish the effect of MWH on the induction period compared with the CH equivalent, at various temperatures using the FO probe. The target DP was 87 and the duration of the induction period is given for each reaction in Table 3.1.

Table 3.1. Polymerisations conducted using MWH and CH for the ROP of CL with reagent ratio [CL]:[BnOH]:[Sn(Oct)₂] 87:1:0.012. All temperatures recorded with FO probe placed in the bulk. The induction period was calculated to be the period before any PCL growth was observed *via* NMR.

Entry	Heating Method	Temperature (°C) ^a	Induction Time (min) ^b
1	CH	130	100
2	MWH	130	65
3	CH	140	55
4	MWH	140	30
5	CH	150	40
6	MWH	150	15
7	CH	160	20
8	MWH	160	10
9	CH	170	12
10	MWH	170	8
11	CH	180	10
12	MWH	180	4

^a All temperatures recorded with FO probe placed in the bulk. ^b Calculated from formation of peak corresponding to PCL in ¹H NMR spectrum.

From Table 3.1 it is clear that the induction period in CH was reduced by approximately half using MWH. This was evidence of the efficient volumetric and instantaneous heating of the entire of the bulk reaction mixture using in MWH. As a result of the specific heating of the catalyst pre-cursors, it has been shown that the overall bulk temperature rose more quickly that could be achieved using CH methods. Therefore, it was proposed that MWH encourages a faster formation of the active catalytic species *via* the organometallic reaction of the $\text{Sn}(\text{Oct})_2$ with the BnOH units. However, this effect may just relate to a faster heat up period as a result of this selective heating. Therefore, although the use of the FO has given some evidence of specific heating, further quantitative evidence must be gained to allow the increased rates of reaction to be definitively attributed to the selective heating effect.

3.3.5.2 Initiation Period

In an attempt to further analyse the MWH effect on the reduction in reaction cycle and the delay before the main propagation reaction commences, both the induction and initiation period were studied using ^1H NMR spectroscopy. The initiation section is the next stage in the ROP reaction mechanism when the active catalyst compound, created in the induction period reacts, with the first monomer forming the initial oligomeric structures.

During the induction period, the $\text{Sn}(\text{Oct})_2$ and BnOH were involved in a ligand exchange to form the di-alkoxide species active species. Previous work,⁴⁸ used

a spectroscopic ^1H NMR study to investigate if there was a reduction in the induction period due to MWH but this study showed that this step is in dynamic equilibrium and thus the reverse step is accelerated to the same extent as the di-alkoxide formation. Rather, this data showed that the induction/initiation time reduction using MWH was due to the increased rate of addition of the first ϵ -CL unit *via* a coordination-induction mechanism to the tin di-alkoxide; which was irreversible. Thus the overall effect was enhanced because the ligand exchange was occurring at an enhanced rate, as this is the first coordination step. Thus, the overall transfer from the tin octanoate to initiated species was significantly reduced as a result of the selective heating process in MWH.

This section will report the studies on the induction/initiation period with regard to the start of polymer growth compared with the rate of initiator depletion as was the focus of the previous ^1H NMR study. Hence, the effect of MWH on the onset of ‘controlled’ polymerisation will be investigated. Furthermore, unlike the previous study, the use of FO will ensure that CH and MWH internal temperatures are identical and thus, direct comparisons can be made. To ascertain the overall rate of conversion of free benzyl alcohol to benzyl ester chain end group, a series of experiments were conducted in both CH and MWH for the ROP of ϵ -CL targeting a DP of 5 at 150 °C. The low DP would mean that the BnOH peaks were only be a fifth of the size of the monomer and polymer peaks; allowing for an improved spectroscopic analysis. Samples were taken every 20 seconds in MWH, whilst every 2 minutes when CH. This was due to the rapid volumetric heating in the MWH. The peaks

being studied were the methylene protons adjacent to the hydroxyl group on the free BnOH ($\text{C}_6\text{H}_5\text{CH}_2\text{OH}$, $\delta = 4.71$ ppm). This peak was depleted when the BnOH unit converted into the benzyl ester end group ($\text{C}_6\text{H}_5\text{CH}_2\text{OCO-}$, $\delta = 5.28$ ppm). This data is presented in Figure 3.15 (MWH) and Figure 3.16 (CH).

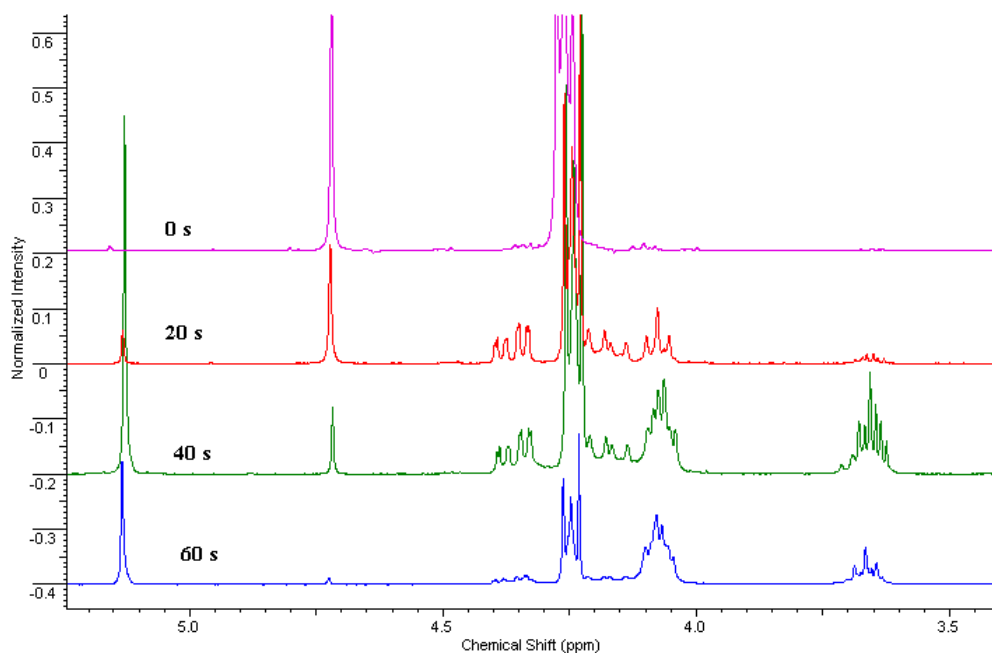


Figure 3.15 ^1H NMR of the ROP of ϵ -CL at 150°C with MWH for DP 5.

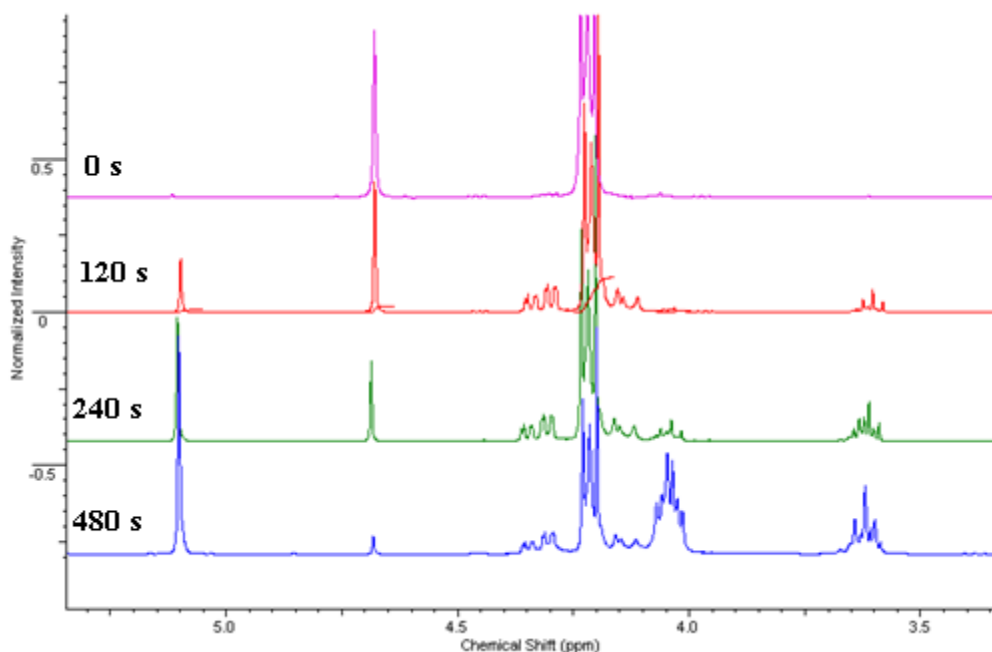


Figure 3.16 ^1H NMR of the ROP of ϵ -CL at 150°C with CH for DP 5.

It was observed that the selective volumetric heating with MWH caused the increased rate of BnOH conversion to the benzyl ester end group. Indeed, in MWH after 60 seconds (Figure 3.15) there was full conversion, compared with the 480 seconds needed with CH (Figure 3.16). Although the MWH reaction appeared to increase the rate of BnOH conversion by an order of magnitude, when comparing this rate to the actual internal FO temperatures, the two heating methods produced similar results. Both reactions heated the reagents from room temperature; the instantaneous volumetric present in MWH (as shown in section 3.3.4.1) took under a minute to reach the target temperature. Indeed, the temperature after 20 seconds was already 110°C . The BnOH conversion at this point was 28 %. Whereas after 2 minutes of CH, the BnOH conversion was 27 % and the internal temperature had finally reached 110°C after a gradual ascent.

Therefore, using the FO internal temperature, it was clear that the conversion of BnOH to the benzyl ester during the heat up stage was solely temperature dependent. There was only a thermal effect present caused by the volumetric heating of the reagents more rapidly with MWH and this caused a reduction in the induction time, i.e. the reagents get to set reaction time and hence the ligand exchange occurred more quickly. However, further investigation of the comparative rate of free BnOH and CL consumption demonstrated that, although the rate of conversion of BnOH to the benzyl ester end group was temperature dependent, the relative rate of growth of PCL was dependent on the heating method according to the ^1H NMR analysis. Indeed, analysis of this data suggested that there was a change in the mechanistic pathway adopted by the ROP reaction when using MWH due to localised heating of the catalytically active species.

In the CH reaction it was observed that essentially almost full BnOH conversion was required before the PCL chains begin growing. Indeed, for the ^1H NMR taken after 4 minutes, 60 % of the free BnOH was consumed (Figure 3.16); at this point there was only 9 % PCL conversion. Meanwhile, after 6 minutes, when there was a complete conversion to the benzyl ester, 48.7 % of the ϵ -CL monomer was found to have undergone ROP.

In comparison in the MWH experiments, after 20 seconds of reaction (Figure 3.15) the BnOH conversion was 26.8 % (which is similar to the value from the CH experiment; when the internal reaction temperatures have reached the same value), but unlike with CH, it is clear that there was a significant polymer peak present in the ^1H NMR spectrum. The peak at 4.10 ppm was the methylene

protons adjacent to the carbonyl of ϵ -CL units that had undergone ROP. Therefore there was evidence that PCL was being formed after only 20 seconds of reaction, when the target temperature of 150 °C has not been reached yet. Indeed the drop in the intensity of the monomer peak in relation to the initiator peaks further supports the view that ROP was occurring before complete true catalyst formation. The conversion of BnOH was 9.33 times faster than ϵ -CL in CH, but only 1.43 with MWH. This again suggests that the tin moiety was hotter than the measured bulk temperature and so was able to interact successfully with the monomer at a faster rate than would be predicted for the measured bulk temperature. Alternatively, it may have promoted the single alkoxide to be catalytically active, rather than the double ligand exchanged complex that is believed to be necessary to catalyse the reaction in CH experiments. The fact that the ϵ -CL was also microwave absorbing may be contributing to this effect.

The combination of “volumetrically activated” monomer and the hotter tin species may have promoted either/both; (a) the catalytic activity of the mono-alkoxide and (b) the more rapid growth of the polymer chain so that chains propagated as soon as they were formed, rather than waiting for “full initiation” to be completed before propagation begun in earnest. This would fit with the conclusions of the previous study, which concluded that the coordination- insertion reaction was the rate determining step in the CH this ROP reaction. Thus, thermally activating both the tin and monomer species which take part in the rate determining step would be expected to reduce the overall reaction time required in MWH.

However, such a change in the ROP mechanism influenced the polymer molecular structures produced at this early stage polymerisation. The reduction in the initiation period will have an effect on the control of the early stages of the reaction with MWH. As the specific heating in MWH promoted the ROP of the monomer units before all the BnOH has been converted to benzyl ester end groups, the actual number of active centres available for ROP will have been lower than the theoretical amount. Indeed after 20 seconds of the previous experiment (Figure 3.15), a fifth of overall monomer had polymerised away from only a quarter of the initiating species. These polymeric chains will therefore have been longer than the PCL chains that undergo initiation later. Therefore the less uniform initiation rates with MWH will result in the early stage of the ROP showing a reduced ‘controlled’ characteristic. This would manifest itself in a higher $\bar{D}$ and the observed M_n will be higher than the theoretical one. However, unfortunately the early initiation stage (below 15 % monomer conversion) produces PCL that was too small to be detected in the GPC, and thus quantitative analysis of microwave effect on the PCL formed during the initiation stage was unavailable. M_n was calculated by ^1H NMR for the early stages in the ROP process, however it could not provide any information about the relative degree of control that each heating method had upon the system without a comparison with GPC analysis, which was not possible at such low molecular weights.

Therefore the initiation period has been shown to be reduced with MWH when compared with CH for the ROP of ϵ -CL due to:

- (a) The dielectric volumetric heating of the reagents due to their high $\tan \delta$ values.
- (b) The increased rate of reactions observed in MWH, despite the reactions carefully undertaken at comparable bulk temperatures to CH equivalents, were theorised to have resulted from the specific heating of the tin species leading to concentrated areas of heat around the active centres approximately 20 °C above the bulk temperature.
- (c) The promotion of PCL growth before the complete conversion of free BnOH initiator to benzyl ester end groups.
- (d) The shift of equilibrium to the right when ϵ -CL is included in the pre-catalyst formation stage.

Importantly, the use of the FO probe has ensured that comparisons have been made with identical reactions and improved rates have not been caused by errors with temperature feedback.

3.3.6 Propagation Period Studies

The propagation phase of the ROP of ϵ -CL was the next stage to be studied in great depth, following on from the initiation/induction periods. The effect of the heating method on the controlled nature and the relative rates of reaction of the ROP of ϵ -CL were compared.

The propagation period of the ROP of ϵ -CL for MWH and CH reactions was analysed at various temperatures (140 °C, 150 °C, 160 °C, 170 °C and 180 °C). The plots of conversion vs molecular weight growth and $\bar{D}$ for each heating method were presented in Figure 3.17 and Figure 3.18, respectively.

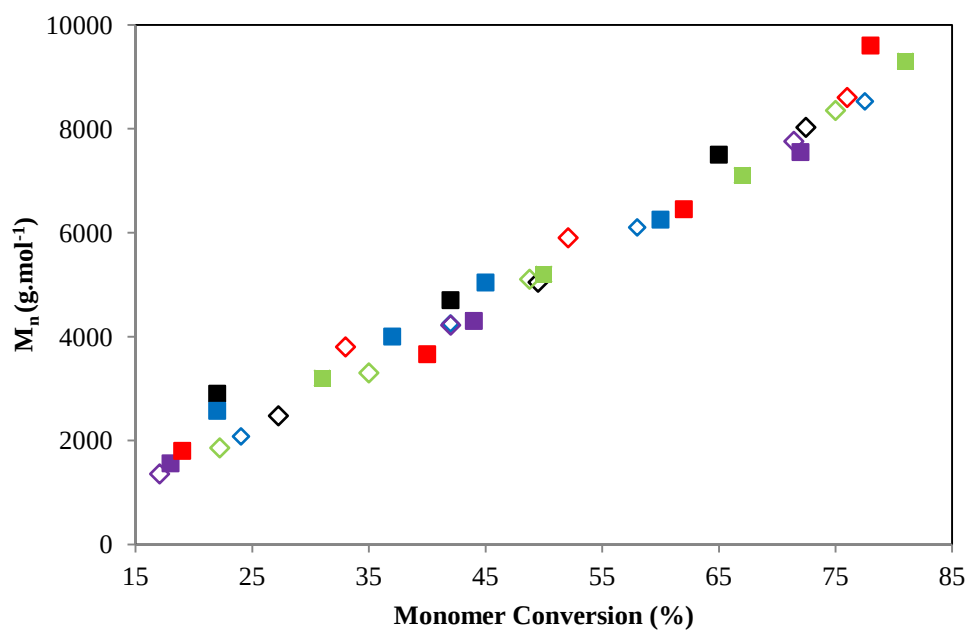


Figure 3.17: Dependence of molar mass (M_n) vs ϵ -CL conversion for MWH (■) and CH (◇) at 140 °C, 150 °C, 160 °C, 170 °C and 180 °C for the ROP of ϵ -CL.

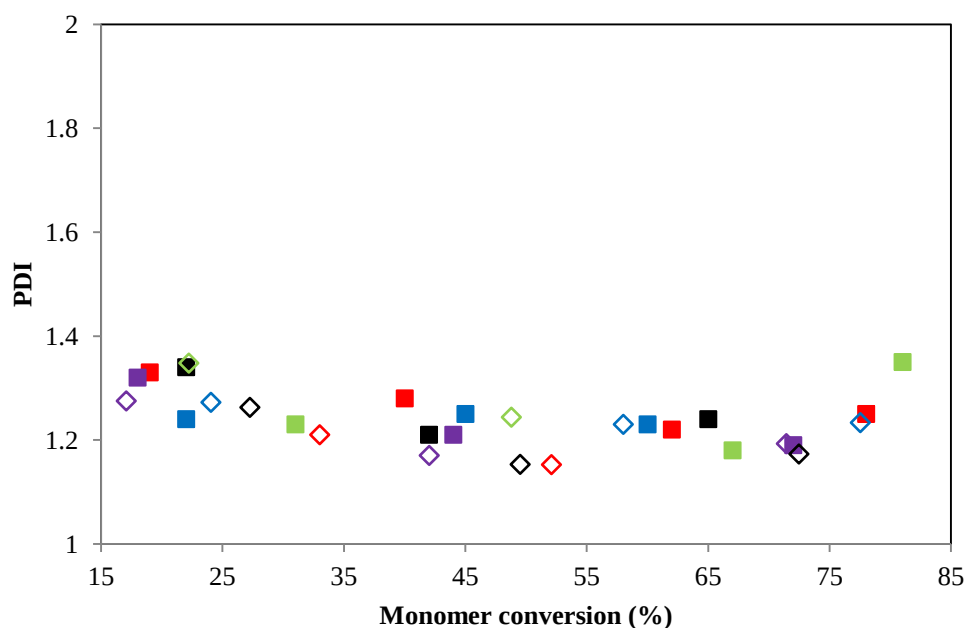


Figure 3.18: Evolution of dispersity vs monomer conversion for MWH (■) and CH (◇) at 140 °C, 150 °C, 160 °C, 170 °C and 180 °C for the ROP of ϵ -CL.

This work demonstrated the controlled nature of these reactions when heated using both MWH and CH. It was observed that M_n increased (Figure 3.17) in a linear fashion with respect to monomer conversion for MWH and CH. Additionally, the close proximity of these plots was indicative that the number of active sites was independent of the heating method adopted and very close to the initial initiator concentration. This meant that the efficiency of catalyst formation and initiation was not specifically affected by MWH during the initiation or propagation stages and an efficient chain transfer process occurred, ensuring the controlled growth of the PCL chains.

Additionally, low $\bar{D}$ values were observed (Figure 3.18) from 15 % to 85 % ϵ -CL conversion, further supporting the fact that the PCL chains were growing in a pseudo-uniform manner at all temperatures, regardless of the heating method. Indeed, all plots were noted to contain $\bar{D}$ values which lay between 1.2

and 1.4. The slight elevation at low conversion was attributed due to different rates of chain growth during the initiation stage and was discussed in the previous chapter. Furthermore, the cause of the increasing $\bar{D}$ as monomer conversion exceeds 85% was attributed to the onset of transesterification reactions that were discussed in the introductory chapter.

Therefore the control during the propagation stage for the ROP of ϵ -CL for this study was not affected by changing temperature, nor the method of heating the reaction. It is important to note that different results were obtained during the comparison of MWH and CH in Section 3.3.1 earlier in this chapter. However, the two sets of experiments are not directly comparable due to the highlighted importance of accurate temperature monitoring and efficient reagent mixing.

In the earlier study it was noted that the controlled nature of the ROP of ϵ -CL was lost at a lower monomer conversion in MWH (75 %) than with CH (85 %). However this was explained by poor experimental procedure and inaccurate external IR temperature monitoring. The use of the FO probe during the experiments in MWH in Section 3.3.4.5 indicated that a large temperature exotherm had developed after 70 % conversion. This was due to the highly viscous nature of the ROP mixture as it was primarily composed of long PCL chains. The experiments in this study were carefully conducted at the exact target temperatures and with vigorous stirring to avoid diffusion problems at high ϵ -CL conversion. This ensured that even at low monomer levels, the active sites were still able to react with the ϵ -CL units prolonging the propagation period.

A thorough kinetic study was undertaken at 140 °C, 150 °C, 160 °C, 170 °C and 180 °C targeting the propagation periods for MWH (Figure 3.19) and CH (Figure 3.20) experiments. By analysing the propagation period, and disregarding the induction/initiation stage, it is possible to calculate the rate of propagation (k_p) for each heating method from the plots taken at various temperatures.

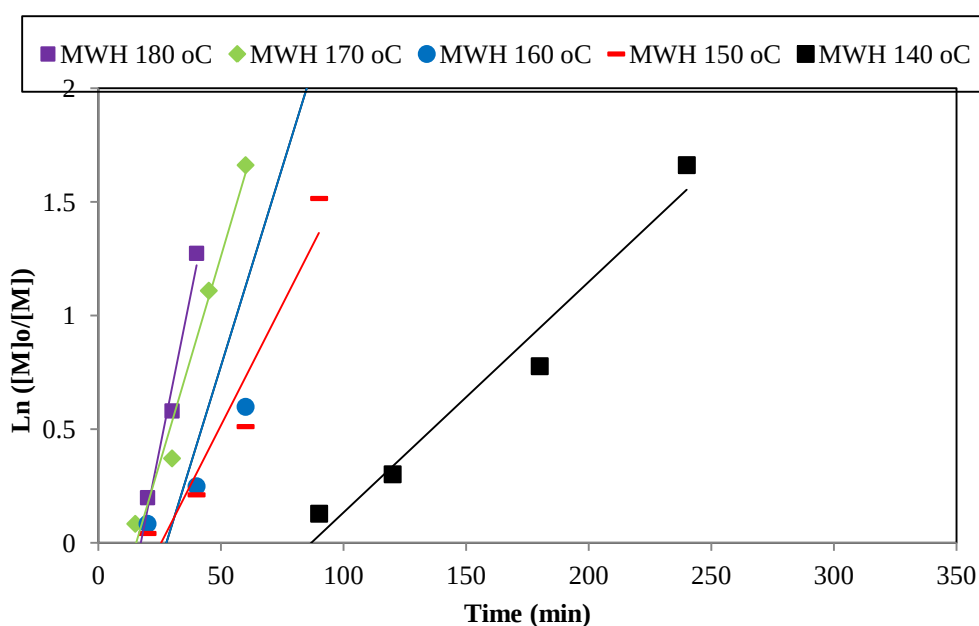


Figure 3.19: Kinetic plots of $\text{Ln} ([M]_0/[M])$ vs reaction time for the propagation period of the ROP of ϵ -CL heated by MWH at 140 °C, 150 °C, 160 °C, 170 °C and 180 °C.

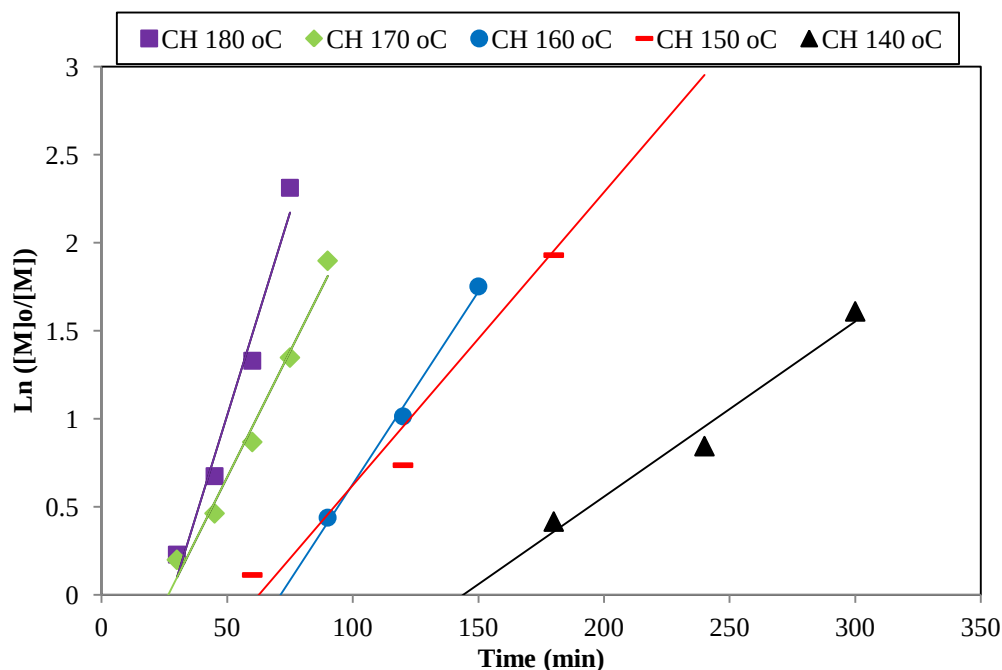


Figure 3.20: Kinetic plots of $\text{Ln} ([M]_0/[M])$ vs reaction time for the propagation period of the ROP of ϵ -CL heated by CH at 140 °C, 150 °C, 160 °C, 170 °C and 180 °C.

Analysis of the data in Figure 3.19 and Figure 3.20 lead to the conclusion that the k_p values of all the MWH reactions were approximately 1.5 times that of the CH experiments at the identical temperature (as measured by the use of the FO probe). A comparison of the various k_p values is provided in Table 3.2.

Table 3.2: Rates of propagation (k_p) calculated at various temperatures using both MWH and CH methods for the ROP of ϵ -CL.

Temperature (°C) ^a	k_p (min ⁻¹) ^b	
	MWH	CH
140	0.0101	0.0099
150	0.0212	0.0167
160	0.0349	0.0214
170	0.0365	0.0285
180	0.0537	0.0460

^a All temperatures recorded with FO probe placed in the bulk. ^b Induction and initiation periods were excluded for the calculation of k_p .

It was interesting to note that when comparing MWH and CH, the k_p variation with temperature was different to the change in initiation/induction time reductions with increasing temperature, noted in Table 3.1 in Section 3.3.5.1. It was observed that the difference in induction/initiation period data between CH and MWH was not constant with temperature in the previous section. Indeed, the induction/initiation period advantages of MWH over CH decreased with increasing temperature. This was attributed to the fact that the MWH temperature overshoot was not constant in magnitude as temperature, as explained by the dielectric properties of the reagents. At 140 and 150 °C (when the tin had the highest $\tan \delta$ value of all the reagents), MWH was able to have the greatest reduction in initiation/induction lag time over CH. Therefore, in the induction/initiation period, when there was a higher concentration of free catalyst and microwave-energy susceptible monomer, there was an elevated amount of temperature overshoot due to greater levels of selective heating induced into the system in MWH.

By comparison, the ~ 1.5 times difference between the MWH and CH k_p values remained constant despite the changing temperatures (Figures 4.4 and 4.5). This was explained by a combination of two molecular level effects. The first explanation was that the organometallic catalyst species was now typically bound to the polymer chain end during the propagation stage and thus had less freedom to interact with the incident microwave energy in the MWH polymerisations. Secondly, but linked to the first, PCL is becoming a more significant component of the reaction mixture during the propagation stage. Consequently, as the $\tan \delta$ value of PCL remained constant at above 140 °C,²⁹

the MWH effect of heating the bulk would be predicted to remain constant with respect to CH above this temperature. Therefore, increasing temperature had a similar effect for both MWH and CH.

However, the fact that the k_p value was approximately 1.5 times higher in MWH to that of the CH at the equivalent temperature suggests that even in the propagation stage, the MWH was directing energy directly into the two reacting species (the monomer and the active centre) resulting in a raised local reaction rate. This potentially infers that the tin chain end moiety local temperatures were still above that measured for the bulk.

In order to investigate this further, the plots of $\ln k_p$ versus $1/T$ for identical bulk temperature MWH and CH ROP reactions were compared (Figure 3.21), where k_p was derived from the gradient from the plots of the propagation segment of the reactions ($\ln([\epsilon\text{-CL}]_0/[\epsilon\text{-CL}])$ versus time). The induction/initiation period data was not included in these calculations because it has been shown that the system had not reached steady state during this region of the reaction profile. In this analysis, it was assumed that the total number of active chain ends was equal to the original initiator concentration.

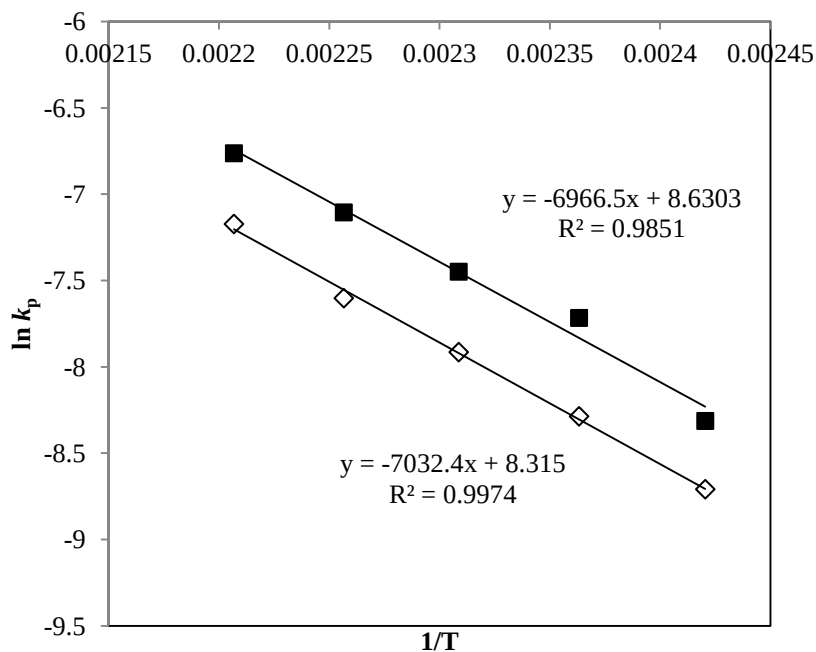


Figure 3.21: Arrhenius plots ($\ln k_p$ versus $1/T$) for the propagation period of the ROP of ϵ -CL heated by MWH (■) and CH (◇) at various temperatures (140 °C, 150 °C, 160 °C, 170 °C and 180 °C).

The plots of $\ln k_p$ versus $1/T$ were noted to have similar gradients, but that they were separated by $4.6 \times 10^{-5} \text{ } 1/T$ along the x axis, which equates to approximately 10 °C. Hence the prediction that the local increased temperature for the chain end in the MWH experiments may be in the region of 10 °C. This elevated temperature would be in line with an expected overall reaction rate increase of 1.5 times.⁵³

E_a was then calculated from the Arrhenius equation by measuring the gradient of the linear relationship as shown in Figure 3.21. There was no difference between the effect of CH and MWH on the E_a for the ROP of ϵ -CL. Indeed, the E_a calculated for MWH was 57.9 kJ mol^{-1} and 58.5 kJ mol^{-1} for CH during the propagation stage.

The diminishing MWH effect observed during the propagation stage (compared with the reduced lag time in the initiation/induction period) can be explained by the active centres losing susceptibility to MWH compared with the initiation/induction periods. This was because the tin species were located upon a much larger PCL chains and therefore has a much reduced degree of motion. Therefore, as PCL growth occurs there was much less efficiency of specifically heating the active centres compared with free tin moieties during induction and any MWH effect was reduced during the propagation stage.

However, despite the reduction of the MWH effect on the propagation stage compared with the early stages of ROP, the elevated k_p values reported at various temperatures in MWH suggests that throughout the reaction, MWH could potentially have been able to create local hot spots around the tin catalytic species, at a temperature calculated to be approximately 10 °C above the bulk temperature, which is in line with a 1.5 magnitude increase in reaction rate. Therefore there was evidence of a microwave effect during the propagation period for the ROP of ϵ -CL using MWH.

3.4 Conclusions

This chapter reports studies which, for the first time, combined the use of accurate temperature feedback methods with an in-depth assessment of the dielectric properties of reaction components to investigate and compare the ROP of ϵ -CL conducted using both CH and MWH heating methods.

The use of an FO probe inserted directly into the reaction bulk demonstrated that the “true” internal temperature in the reaction varied from that of an external IR sensor. The true internal temperature was found to be significantly higher at the start and the end of the reaction but the size of the difference between the two measurements also varied with temperature. For example; a temperature overshoot of over 20 °C was observed by the FO during the induction stage of the reaction, whilst the IR sensor did not record any excessive temperature. The elevated temperatures that were recorded by the FO were rationalised using the dielectric property measurements of the reagents. The pre-catalyst species, $\text{Sn}(\text{Oct})_2$ was found to have relatively high $\tan \delta$ values at the reaction temperatures, meaning that the “free” tin moieties had a high susceptibility to the MWH and were able to undergo specific heating. At the final stages of the reaction, the large PCL chains were observed to increase viscosity of the reaction medium, and reduce the rate of heat diffusion from the system leading to a temperature build up. It was also proposed that the microwave energy may also promote the transesterification side reactions in these viscous media because reduced mobility of the remaining monomer means that it will have difficulty locating the active species. However, the active species may still be being selectively heated by the microwave. Thus, it would be more susceptible toward taking part in the transesterification reactions than in the CH case in this high conversion region of > 85 %. These factors led to an increased true internal temperature and a premature loss of control ($\bar{D}$ values rose to 2.0 at 75 % ϵ -CL), when compared with CH (1.21 at 80 %). Despite this, the controlled characteristic nature of the ROP was present in both MWH and CH.

This combination of information was then used alongside a series of experiments to highlight why previous literature work had claimed that special MWH effect were responsible for empirically observed rate improvements and other improvements. Experiments were conducted which compared the FO and IR recorded temperatures for different reactor/vessel designs offered examples as to causes of temperature deviations that would affect rate of polymerisation calculations. Reaction design decisions, such as pre-heating reagents and reaction vessel placement, were shown to cause the recorded IR and true FO temperatures to differ (with temperatures differences of over 100 °C being observed) and lead to the comparisons between CH and MWH becoming unintentionally invalid. After elimination of these flawed temperature readings, this work examined the true effect of MWH by comparing identical reactions from MWH and CH.

It was demonstrated that, in the early stages of the reaction, during the induction and initiation periods, the reagents that were highly susceptible to MWH energy were the monomer and tin catalyst. Using the FO sensor, it was shown that small variations in the relative concentration of these caused a large temperature overshoot. This effect was attributed to microwave generated specific heating of these species at the molecular level was enhancing the volumetric heating of the bulk because these species were hotter than the set temperature. This increase in bulk temperature was also concluded to contribute to increased reactions rates on an empirical basis.

Furthermore, it has been demonstrated that the use of MWH delivered the ability to heat the reaction to the targeted temperature much more quickly than

the comparative CH system due to the selective heating of the reagents. This was noted to partly explain the reduction in the time before polymerisation is observed to occur at the start of the reaction. The increased reaction temperature, caused by the thermal overshoot, and selective heating of the several of the key components required to achieve initiation of the polymer chain was also found to reduce both the induction (when the tin and the alcohol react to form the true catalytic species) and initiation period (i.e. interaction with the first monomer) further reducing the time till polymerisation was noted to commence. The fact that the ϵ -CL monomer exhibits a $\tan \delta$ value that is similar to the Sn species was also concluded to contribute to the increase in the rate that the initiation process achieved. MWH was shown to half the induction time for a range of temperatures (130 °C, 140 °C, 150 °C, 160 °C, 170 °C and 180 °C). The onset of ROP of ϵ -CL (initiation) occurred before full production of the true catalytic species in MWH compared with CH. Indeed, 33 % PCL conversion was achieved in MWH compared with 9 % at the same point of initiator/catalyst reaction in CH. This faster onset of propagation in MWH meant that the controlled nature of ROP in MWH would be negatively affected by MWH, as some of the growth of PCL would not be even at the early stages of the reaction.

The reductions in initiation and induction periods in MWH were concluded to be due to a thermal effect. The MWH was shown to reduce lag time by rate that would be equivalent to a temperature difference of approximately 15 °C when compared to a CH experiment. In other words, a CH reaction would need a set temperature 15 °C higher than the equivalent MWH experiment to deliver the

same rate. This provided evidence that selective heating of the tin catalyst in the MWH increased the temperature around the tin, lowered the surrounding viscosity and enhanced the formation of the true catalytic species.

A detailed study of the propagation period of PCL was undertaken, with both CH and MWH observed to ensure the controlled nature of the ROP of ϵ -CL to high monomer conversions for the entire range of temperatures. Indeed, low $\bar{D}$ values (1.2 - 1.3) and linear growth of M_n were recorded up to high ϵ -CL conversion ($\sim 85\%$) independent of the heating method. Efficient mixing and accurate temperature monitoring with the FO ensured that control was not lost prematurely in the MWH at the end of the reaction when the increased reaction viscosity resulted in poor diffusion and ineffective heating, as was observed in previous studies.

A kinetic study of the propagation period found that $k_{p\text{ MWH}}$ was faster than $k_{p\text{ CH}}$, however MWH was less able to have an effect than during the induction/initiation stages. The reason for the reduction in MWH improvements at this later stage in the reaction was explained using the analysis of the dielectric properties of the components during the propagation period and by assessing the amount of microwave energy input into the system during this section of the process. An observed reduction in the dielectric properties of the system was attributed to the fact that the catalytic species was now bound to the end of a PCL chain. Thus, it was now far less able to align its dipoles to the oscillating electromagnetic field. Also, the main component of the ROP bulk mixture was now compromised of large PCL chains, which were shown to have poor dielectric properties than the monomer they were replacing

for the same reason. Furthermore, the input energy required in order to keep the reaction medium at the set temperature was also observed to drop significantly in this section of the process, i.e. typically from 300 W to 50 W. Thus the differential between the MWH and CH system would be expected to diminish as a result.

Despite the MWH being less differentiated from the CH than was observed during the early part of the reaction, it was still found that k_p was 1.5 times faster in MWH than CH even with the low power inputs achieved. This equates to a temperature elevation of approximately 15 °C. However, the use of the FO probe showed that the bulk reaction temperatures were identical in the CH and MWH reactions. Therefore it was deduced that even during the propagation period, a 15 °C increase can only be the result of localised hot spots at the tin active species as a consequence of specific heating of the tin moieties by MWH. Thus, a key element of future work will have to consider how to design the reactor such that greater levels of power can be introduced without significantly raising the bulk temperature of the reaction medium.

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4 Synthesis of Biodegradable Copolymer, PLA-co-PCL, using Microwave Heating

Chapter 4 is dedicated to an investigation into the effect of microwave heating (MWH) on the ring-opening polymerisation (ROP) synthesis of poly(D/L-lactide-co- ϵ -caprolactone) (PLA-co-PCL). At the time of commencing this study, such a systematic investigation of the synthesis and resultant properties of PLA-co-PCL block copolymers produced using MWH has not previously been reported in the literature.

The goal is to improve and optimise the manufacture of such ROP block copolymers of PLA-co-PCL, which are known to be difficult to produce whilst retaining a low dispersity ($\bar{D}$) and target theoretical molecular weight due to the influence of side reactions at higher conversion levels. Therefore, as in Chapter 3, a detailed knowledge of the dielectric properties of the reagents involved was used to rationalise any experimentally procured observations on the differences in the copolymerisation of ϵ -caprolactone (ϵ -CL) and D/L-lactide (DLLA) when conducted using MWH and conventional oil bath heating (CH).

4.1 Introduction

ROP is an important method for producing controlled polymers of DLLA and ϵ -CL. The aliphatic polyesters made from these monomers, poly(ϵ -caprolactone) (PCL) and poly(lactic acid) (PLA) are manufactured and utilised in great quantities for a wide range of medical applications.¹⁻¹¹

PCL is a semi crystalline polymer that is biodegradable and has high biocompatibility and its thermal properties are defined by its glass transition temperature (T_g) and melting temperature (T_m) which have been reported to be -60 °C and 60 °C respectively.¹² PLA is produced from a bio-renewable resource. The lactide monomer units used to form PLA affects the final polymer's crystallinity. PLA made from L-Lactide is semi-crystalline. PLA produced from DLLA is fully amorphous with a $T_g = 45-55$ °C, which is problematic as it can be too rigid at body temperature.¹³ Its advantages as a biomedical polymer are its biocompatibility, fast biodegradability and good mechanical properties.¹⁴

DLLA and ϵ -CL monomers undergo the same ROP mechanism when reacted with stannous octanoate ($\text{Sn}(\text{Oct})_2$) catalyst and an initiator containing a hydroxyl group, such as benzyl alcohol (BnOH).^{15, 16} Other catalysts have been studied, such as aluminium,^{17, 18} however $\text{Sn}(\text{Oct})_2$ is approved by the Federal Drugs Administration¹⁹ and as such experiences a great deal of interest.²⁰ The exact mechanism for ROP is still under debate however, the coordinated-insertion approach is the most commonly accepted.²¹ The length of each block chain in the final copolymeric structure is controllable and the

properties of the copolymer are affected by the size and separation of the individual block segments. The thermal properties of copolymers depend on the co-monomer distribution.²²

4.1.1 PLA-co-PCL Copolymers

A key advantage of producing PLA-co-PCL is that the copolymer will contain useful properties that each homopolymer possesses, whilst overcoming any shortfalls they may have. For example PCL has very high permeability; however its degradation life time can be too long and non-uniform for many biomedical applications.²³ Whereas, PLA has a much shorter life time, but its T_g is approximately 45 °C, thus it has issues with its mechanical properties when handled around body temperature. PLA-co-PCL has been proved to acquire the high permeability of PCL and improved rate of degradation of PLA whilst maintaining high flexibility and mechanical strength mandatory for many biomedical applications.^{24, 25} Some examples of potential applications for this copolymer could be nerve guides, permeable skin, implants, sutures, substitute blood vessels, artificial scaffolds and implantable long term drug delivery methods.^{3, 26, 27}

ROP is considered a controlled polymerisation, which means linear growth of molecular weight with conversion and the possibility for the formation of block copolymers by sequential addition of a second monomer aliquot or if the two monomers contain significantly different reactivity rates.²⁸ This is because the

active centres remain constantly protected, and when more monomer is added, the catalytic centre will reactivate leading to further growth of the polymer chains. A common aspect of controlled polymerisation is the need for a rapid equilibrium forming between the exchange of active centres and dormant species. If this is the case all polymer chains will grow at comparable rates, which provide good control over the reaction. This requires a constant concentration of active sites. The rate of initiation must also be significantly greater than the rate of polymerisation.²⁹

The control over ROP using the $\text{Sn}(\text{Oct})_2$ coordination-insertion method is affected by the amount of transesterification reactions.³⁰ These can occur both intramolecular (*via* backbiting) and intermolecular reactions where the ester groups are exchanged.³¹ These unwanted side reactions reduce the control over molecular weight and increase the Đ. Bimolecular transesterification reactions have been reported to have a higher rate of reaction than propagation leading to transesterification reactions even from the start of the polymerisation.¹⁷ Different factors affect this side reaction with varying impacts. Elevated temperatures have been shown to be the most important cause of esterification, followed by the ratio of monomer to catalyst. Increased reaction time also worsens the amount of control as degradation reactions will start occurring.¹⁷

In recent years, many studies have been conducted into the formation of random and block PCL-co-PLA using $\text{Sn}(\text{Oct})_2$. Moravek *et al.* compared conventional one-pot copolymerisation with sequential addition using a relatively high catalyst concentration.³² Reaction time was reduced in the sequential method, however both final products showed high levels of

transesterification and random copolymers. Hao *et al.* used surface analysis techniques, such as X-ray Photoelectron Spectroscopy and Atomic Force Spectroscopy, to study the effect the monomer weight ratio has on the surface properties of random copolymer formed in a one-pot method.³³ They found that the monomer ratio determined the average block length which had a large influence on the surface microstructures of the copolymer. Nalampang *et al.* investigated the effect of synthesis conditions on the final product by using sequential monomer addition.³⁴ In their study, the ROP of ϵ -CL was stopped at 70 % conversion to minimalise transesterification reactions before adding L-lactide (LLA). They found that the two-step method produced longer lengths of lactidyl and caproyl units, with less observed transesterification and more ‘blocky’ chain structure than the one-pot method. Hiljanen-Vainio *et al.* synthesised PCL-co-PLA via one-pot bulk experiments, producing a copolymer containing minor ϵ -CL content.³⁵ ^{13}C NMR illustrated that the copolymers contained ‘blocky’ regions with about 5 % random structure. Transesterification reactions were shown to be influenced by temperature. Indeed, when the reaction temperature was increased from 120 °C to 160 °C the average caproyl length decreased from 3.1 to 1.7.³⁵

4.1.2 ROP of DLLA in Microwave

The first use of MWH for the ROP of DLLA using a $\text{Sn}(\text{Oct})_2$ catalyst was reported by Lui *et al.* in 2001.³⁶ It was observed that the reaction time required to produce $\sim 50,000 \text{ g mol}^{-1}$ PLA was reduced from 24 hours in CH to under 1

hour in MWH, with $\bar{D}$ values under 1.7 indicating that a relatively controlled ROP was possible in MWH.

The impact of the power intensity on the ROP of DLLA was investigated by Zhang *et al.*,³⁷ by varying the forward power from 170 W to 510 W. Even at the lowest level of forward power, a high polymer conversion of over 75 % was achieved after just 15 minutes and further reaction afforded high M_w product of 40,000 g mol⁻¹. Increasing the power reduced reaction time, but it was noticed that the M_w values decreased. When over 300 W was irradiated, a M_w maximum was reached after 10 minutes, after which point the MWH energy caused significant degradation of the final polymer. After 15 minutes of 510 W energy, the PLA had degraded down to a fifth of its earlier molecular weight. Most work published since the Zhang paper, including the research in this thesis, has used power below 300 W for the MWH ROP of DLLA to avoid significant product degradation.

The accuracy of temperature monitoring has been shown to have a significant impact upon the accuracy of observed rates of reaction for the ROP of DLLA in MWH. As was reported in the preceding chapter of this Thesis, recent advances in FO temperature monitoring technology have suggested that previously reported enhanced rates were caused by ineffective external IR sensors. A paper by Nikolic *et al.*³⁸ presented examples of supposedly increased rates occurring at lower temperatures in MWH compared with CH. Only using a IR sensor, it was claimed that the ROP of DLLA using a Sn(Oct)₂ catalyst was reduced from 30 hours at 120 °C in CH to 30 minutes at 100 °C in the MWH. The IR sensor recorded a large temperature overshoot at the start of

the reaction to 140 °C when the maximum level of power was irradiation the reaction. This temperature overshoot was explained by the exothermic nature of the polymerisation reaction.

In contrast to the Nikolic paper quoting IR reading, a subsequent work by Ramier *et al.*³⁹ was the first to use an FO temperature probe to investigate the presence, or absence, of non-thermal microwave effect on the ROP of DLLA. Unlike the Nikolic paper work which was done in bulk, Ramier conducted the reactions in toluene. They found improved rates were consistent with the Arrhenius equation; any observed improvement was the result of purely thermal effects in the MWH, such as fast and volumetric heating of the reaction mixture. The use of toluene also suppressed the temperature overshoot that was observed by Nikolic. This was due to the fact that the reaction protocol by Nikolic was to heat the DLLA from room temperature (when it is a solid) to reaction temperature through its melting point. The solid nature would have meant that not all the DLLA would have been heated at the same time. As was observed in the previous chapter, a non-uniform temperature gradient would have occurred in the reaction, with the IR sensor recording the solid, and colder, outer part of the DLLA mixture. The true internal temperature would have been much hotter.

Therefore recent work, including the studies conducted in this chapter, utilised the FO probe to ensure any observed enhancements in MWH were not caused by reaction methodology errors or ineffective temperature monitoring, thus accurate comparisons between heating methods were possible.

4.2 Experimental

4.2.1 Materials

ϵ -Caprolactone (99%) was purchased from Acros Organics and used without further purification. D/L-lactide (98 %+) was purchased from Alfa Aesar and was dried under reduced pressure for 24 hours prior to use. Anhydrous benzyl alcohol (99 %) and tin 2-ethylhexanoate (99 %) were purchased from Sigma Aldrich.

4.2.2 One-Pot, One Step Reaction

For the homopolymerisation of PLA, DLLA (7.9 g, 54.8 mmol) was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μ L, 0.63 mmol) and Sn(Oct)₂ catalyst (5.1 mg, 0.0126 mmol). For the one-pot copolymerisation reactions, DLLA (3.95 g, 27.4 mmol) and ϵ -CL (3.125 g, 27.4 mmol) were placed into the test tube. A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ¹H NMR and GPC. When the reaction had finished, it was quenched with liquid N₂ and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition of the polymerisation solution into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of

the final polymer was analysed with GPC and the thermal properties monitored by DSC.

4.2.3 One-Pot Two Step Copolymerisation Reaction

The first monomer species was placed into a 50 mL glass test tube with benzyl alcohol initiator (65 μ L, 0.63 mmol) and Sn(Oct)₂ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ¹H NMR and GPC. When the reaction had been calculated to have reached the target conversion, the second monomer was added directly to the reaction vessel and left to polymerise to high conversion. The second monomer was heated to reaction temperature prior to addition. When the reaction had finished, it was quenched with liquid N₂ and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition of the polymer solution into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed with GPC and the thermal properties monitored by DSC.

4.2.4 Two-Pot Two Step Copolymerisation Reaction

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4.2.5 Monomer Conversion

The extracted samples were analysed by ^1H NMR to determine the conversion and M_n values and degree of polymerisation (DP). Figure 4.1 presents a typical ^1H NMR spectrum.

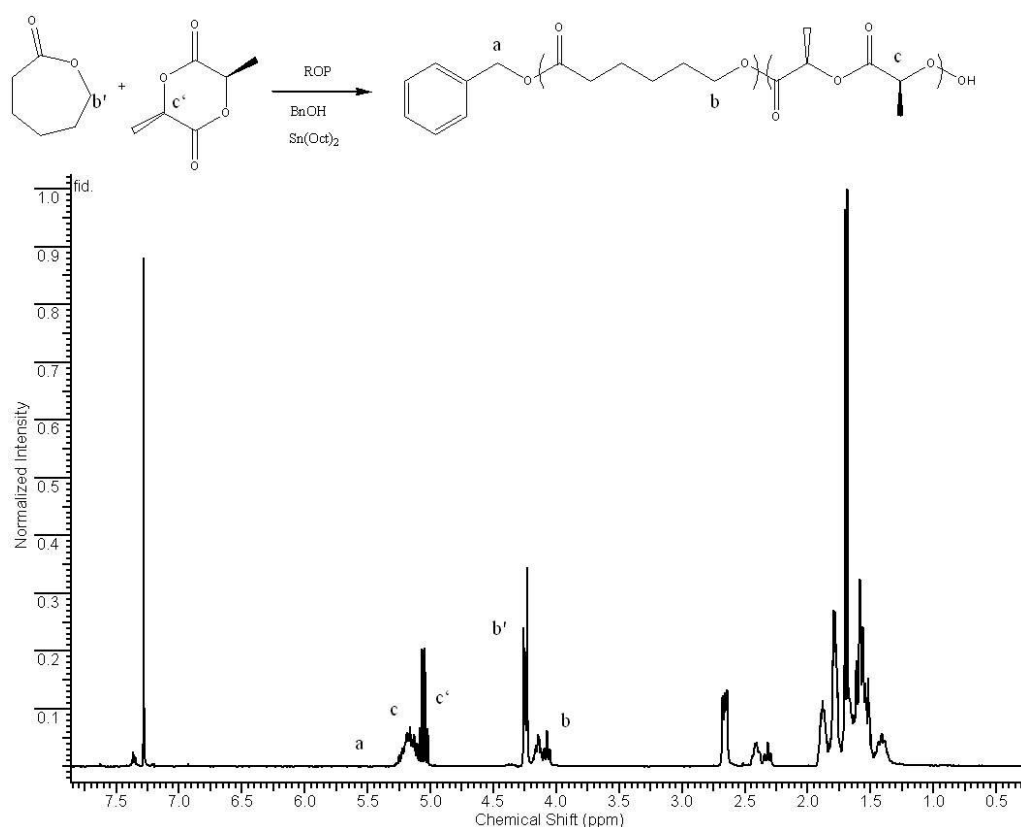


Figure 4.1 ^1H NMR spectrum of PCL-co-PLA measured in CDCl_3 .

DLLA monomer conversion was calculated by comparing the integrated values of the quartet of the DLLA methyne ($\delta = 5.04$ ppm) and the multiplet signal of the PLA methyne ($\delta = 5.16$ ppm). ϵ -CL monomer conversion was calculated by comparing the integral of the proton resonance of the methylene adjacent to the oxygen on the carbonyl group of the monomer ($\delta = 4.24$ ppm) and polymer ($\delta = 4.07$ ppm) using the following equation:

$$\text{conversion (\%)} = \frac{\text{integral value of } b}{\text{integral value of } b + b'} \times 100$$

The M_n was calculated by multiplying the DLLA molecular weight (144.11 Da) and ϵ -CL molecular weight (114.14 Da) by the DP.

4.2.6 Dielectric Property Measurement

The method used for calculating the dielectric properties of DLLA and PLA was the cavity perturbation technique. A small amount of sample (~50 mg) was introduced into a cavity and the changes to the properties of the cavity were measured. The dielectric property of the sample was measured initially at room temperature before being moved automatically into the furnace, where the sample was heated conventionally at the required temperature for 10 minutes. The sample then returned to the cavity for measurement. This process was repeated for all the required temperatures within the target range of 20 °C – 180 °C. The equipment allowed for calculating the dielectric properties at 2.45 GHz.

4.3 Results and Discussion

The purpose of this work programme was to develop and optimise the synthesis of biodegradable copolymers based on the ROP of ϵ -CL and DLLA

using MWH. It is known that both ϵ -CL and DLLA undergo the same coordination-insertion mechanism in order to successfully achieve ROP and it was theorised that MWH could affect the k^{app} values of the monomers, and thus produce blocks with tuneable material, degradation and rheological properties.

4.3.1 Comparison of ϵ -CL, DLLA, Sn(Oct)₂ and BnOH Dielectric Studies

As discussed in Section 3.3.1, the $\tan \delta$ values of ϵ -CL and BnOH were highest at room temperature and gradually decreased until 180 °C, which was the point at which the temperature sweep was terminated (see Figure 4.2).

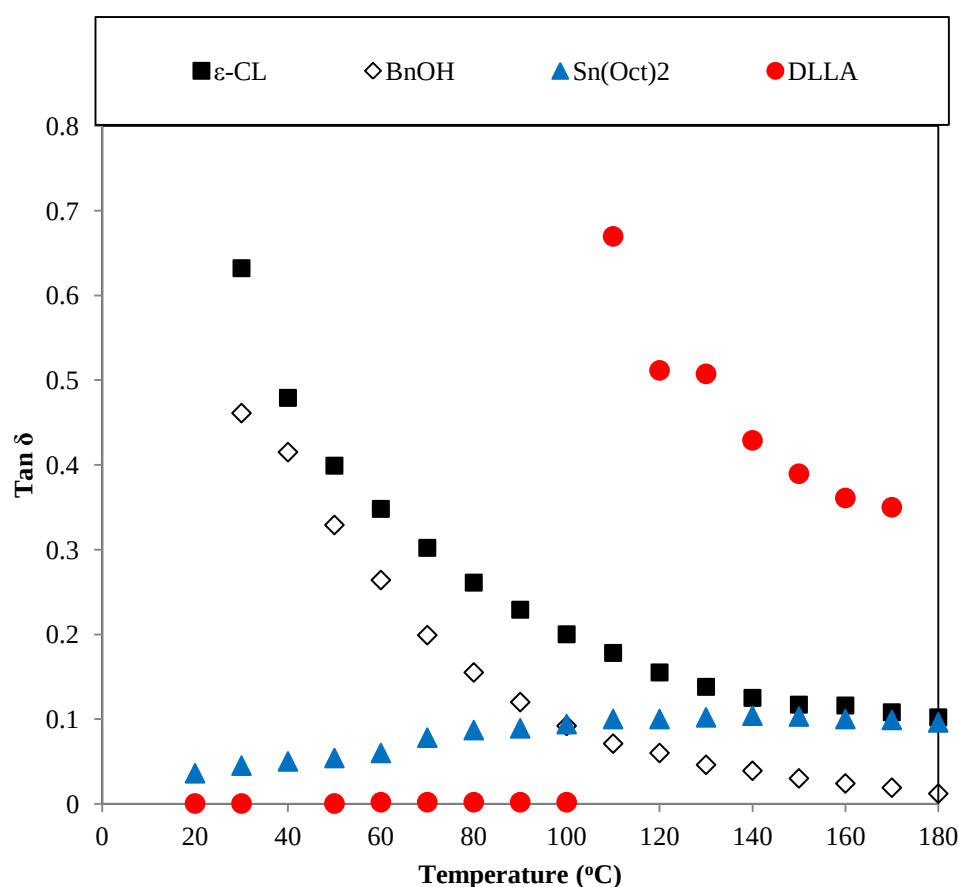


Figure 4.2: Dielectric properties ($\tan \delta$) of ϵ -CL (■) BnOH (◇) Sn(Oct)₂ (▲) and DLLA (●) against temperature (°C). Determined using cavity perturbation technique with a furnace as an external heating source with temperature range = 20 – 180 °C. Sample volume 0.3 mL; 0.2 mg.

The reduction in the $\tan \delta$ values of ϵ -CL and BnOH has been related to the reduction in the density of the material leading to reduced intermolecular friction and thus a reduction in the ability of the material to heat the mixture. Meanwhile, DLLA was observed to produce a significant $\tan \delta$ above 110 °C, coinciding with the melting point of DLLA (116 – 119 °C). Thus, whilst in solid form, the dipoles ability to align with the applied field was restricted due to the materials physical form. Upon melting they were free to respond to the applied energy such that the reagent exhibited its highest $\tan \delta$ just after its melting point. After which, it too shows a gradual decline related to density

reduction as temperature is increased. Therefore, by comparison of the relative $\tan \delta$ values of ϵ -CL (approximately 0.12) and DLLA (approximately 0.38) at the proposed ROP reaction temperatures of 150 °C, it was proposed that the DLLA units could experience selective dielectric heating and thus lead to a increased propensity to create block copolymers directly from a homogeneous mix of the two monomers without the need for sequential addition of monomers. However it should be noted that the dielectric property analysis was carried out on pure DLLA. The DLLA in the bulk ROP mixture will not be in its solid form as the temperature approaches 100 °C as the DLLA dissolves into the liquid ϵ -CL. This means than even below its melting point, DLLA will have increased dielectric properties when dissolved in ϵ -CL.

The study in this chapter will utilise this knowledge and understanding of the temperature influence on the dielectric properties of the various reagents for the ROP reaction to synthesise PCL-co-PLA. The experimental observations will be explained using information gained from the dielectric study and for the first time the exact MWH effect can be probed for the copolymerisation reactions.

4.3.2 Homopolymerisation of PLA

Prior to attempting to produce PCL-co-PLA copolymer, the homopolymerisation of PLA using CH and MWH was investigated in detail with a view to establishing which heat method provided better control over the

polymerisation. Comparative reactions were undertaken using a monomer: initiator: catalyst ratio of $[\text{DLLA}]_{87} : [\text{BnOH}]_1 : [\text{Sn}(\text{Oct})_2]_{0.02}$. Thus, the target degree of polymerisation (DP) was set to be 87 and $M_{n\text{Theo}}$ of $12,500 \text{ g mol}^{-1}$. The temperature was set to 150°C and ^1H NMR was used to follow the rate of monomer consumption. The plots of molecular weights growth and $\bar{D}$ distribution against DLLA conversion in the synthesis of PLA *via* ROP using CH and MWH are provided in Figure 4.3 and Figure 4.4.

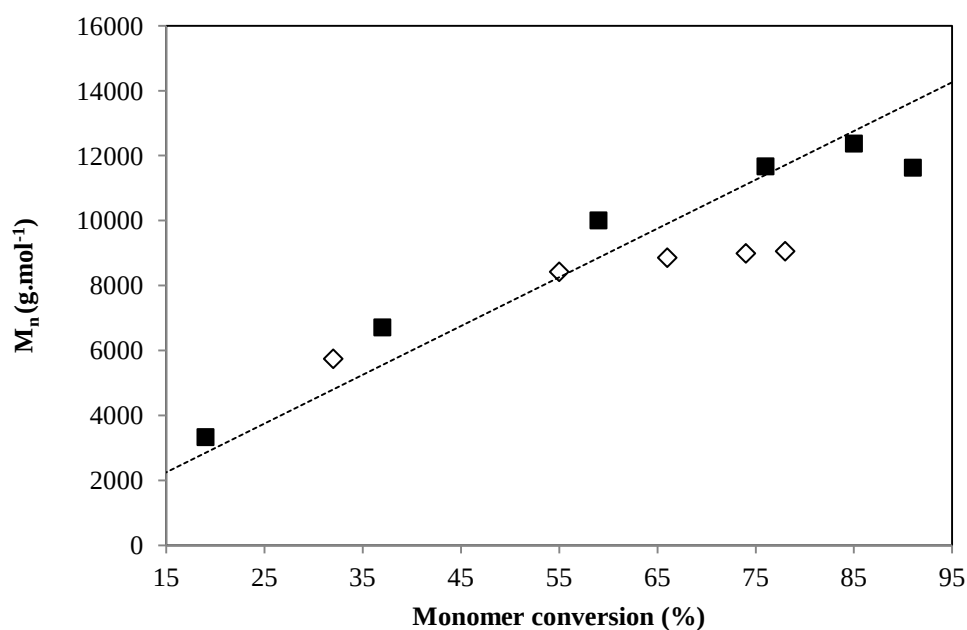


Figure 4.3 Dependence of molar mass (M_n) on DLLA conversion (the line represents the theoretical variation of M_n with conversion) for MWH (■) and CH (◇) at 150°C for the ROP of DLLA.

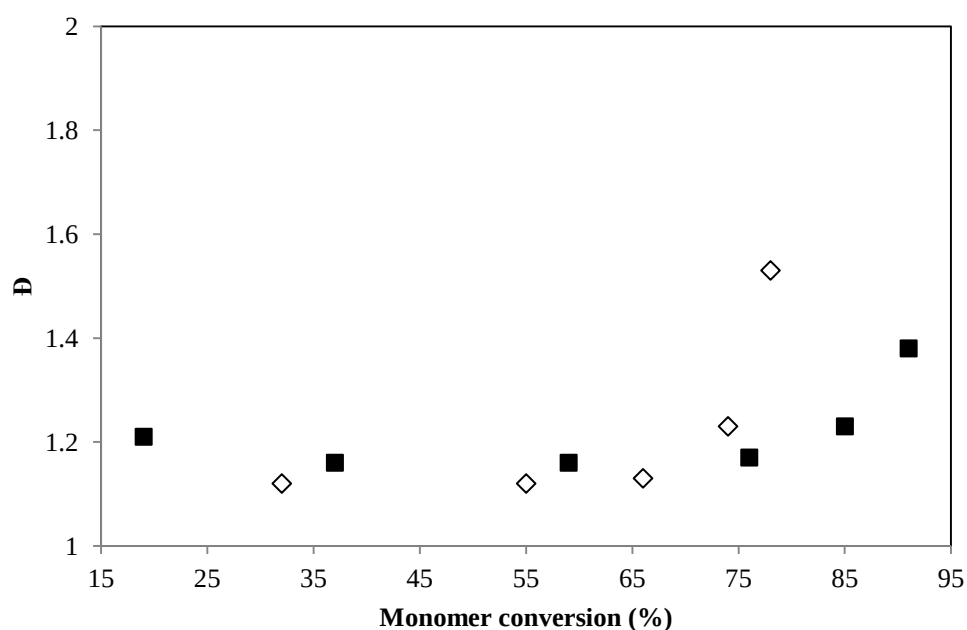


Figure 4.4 Evolution of dispersity on DLLA conversion for MWH (■) and CH (◇) at 150 °C for the ROP of DLLA.

As was noted in the ROP of ϵ -CL in the previous chapter, the controlled nature of the ROP of DLLA when heated using both MWH and CH over a particular conversion range window was evident by comparing molecular weight growth (Figure 4.3) and $\bar{D}$ (Figure 4.4) with conversion. The data in Figure 4.3 shows controlled linear growth of M_n against conversion for both CH (◇) and MWH (■) for the ROP of DLLA. The M_n values closely follow the $M_{n, \text{Theo}}$ target as conversion increased over a particular conversion window (15 % - 80 %) for both techniques. The $\bar{D}$ for both heating methods (◇ CH) (■ MWH) were also found to drop to less than 1.2 within this well controlled region of the reaction (Figure 4.4).

As in the PCL case in the previous chapter, the reactions deviated from the controlled characteristic at high monomer conversions, as it was observed that the $\bar{D}$ value increased and the linear growth of M_n deviated. From an

assessment of Figure 4.3 and Figure 4.4, it is clear that the loss of control occurred at differing levels of DLLA conversion for the two heating methods. For CH, the growth of M_n levelled off and $\bar{D}$ increased at approximately 60 % monomer conversion, which is widely accepted in current literature for control of ROP of DLLA to diminish.¹⁵ However, the onset of undesired loss of control was delayed to 85% monomer conversion using MWH. The $\bar{D}$ value at 85% was still only 1.23, increasing to 1.49 at 93% conversion.

The loss of control at the later stages of ROP was due to the active catalytic centres located at the end of the polymer chains reacting with ester linkages in the polymer backbone. The active sites become increasingly unable to react with the remaining DLLA units and unwanted side reactions dominate due to the increased viscosity and lower available monomer concentrations. The active centre reacts with other ester linkages, either on its own polymer backbone (intramolecular transesterification) leading to cyclisation, or attacking the back bone of a separate chain (intermolecular transesterification) causing inter chain scissoring.

However, using MWH the increase in the size of the well controlled reaction window was attributed to the selective heating of the active centres and the DLLA monomer. It is proposed that they exhibit a greater level of diffusion throughout the system and so are able to react due to an increased temperature or lower local viscosity. This culminates in propagation reactions dominating over side reactions until higher conversion levels are obtained.

The dielectric heating properties of the DLLA may explain why the propagation mechanism was encouraged, rather than transesterification, at low monomer levels. In MWH, at high conversion, the majority of the bulk reaction mixture was constructed of long PLA chains. These large macromolecules were very viscous and relatively immobile. Therefore, as seen in PCL reactions in the previous chapter, the PLA chains were less susceptible to microwave energy than the DLLA monomers. At high monomer conversion, the remaining monomer would have been the most susceptible to microwave energy. This will have resulted in the monomer being at higher temperature than the surrounding bulk mixture and thus more likely to react, causing the k_p to be greater than k_{trans} .

These results show that both CH and MWH produced controlled ROP, but the major difference was that the control over the reaction was maintained for a longer reaction window and to higher monomer conversion using MWH. This has applications for efficiency; if the reaction was stopped early to ensure low $\bar{D}$, the ROP using MWH would be more cost effective as half as much unreacted monomer would be discarded during the purification process.

4.3.3 PLA-co-PCL Copolymerisation Studies

The work discussed up to this point has shown that MWH affected both the ROP rates in the synthesis of PCL and PLA. Consequently, the copolymerisation of the two monomers, ϵ -CL and DLLA, was then

investigated. To the best of our knowledge, up to this date, there has been no previous detailed investigation into the effect of MWH upon the ROP copolymerisation of PLA and PCL to form PLA-co-PCL copolymers.

From the reviews of the rigorously measured dielectric properties for both the monomers and polymers that have been reported earlier in this study (see Section 4.3.1), it was theorised that MWH had the potential to directly produce controlled block copolymers, *via* exploiting the difference in monomer response to the microwave energy. This could lead to a more efficient copolymerisation process, as there would be no requirement for isolation of the first block prior to the sequential addition of the second monomer.

4.3.3.1 One-Pot, One Step Copolymerisation Studies

The conventional one-pot synthesis of PLA-co-PCL, i.e. both monomers were present in the reaction vessel at the onset of the reaction, was undertaken using MWH and was compared and contrasted with the equivalent CH reaction, to analyse the effect of CH and MWH on rate of reaction and final product composition (Table.4.1). The reagent ratio used in these polymerisations was $[\text{DLLA}]_{43.5} : [\epsilon\text{-CL}]_{43.5} : [\text{BnOH}]_1 : [\text{Sn}(\text{Oct})_2]_{0.02}$ and ^1H NMR was used to follow monomer conversion.

Table.4.1: One-pot, one step bulk synthesis of PLA-co-PCL at 150 °C.

Entry	Heating method	Monomer Ratio ϵ -CL : DLLA	Conv (%) ^a ϵ -CL/ DLLA	M_n theo (g mol ⁻¹) ^c	M_n obs (g mol ⁻¹) ^b	$\bar{D}$ ^b	Tg (°C) ^d	Reaction time (min)
1	MWH	43.5 : 43.5	83 / 98	12,500	11,560	2.25	-9.4	180
2	CH	43.5 : 43.5	92 / 97	12,500	11,570	1.86	-4.4	360
3	MWH	21.8 : 65.2	85 / 98	12,500	11,870	2.47	17.0	180
4	MWH	65.2 : 21.8	85 / 96	12,500	13,000	2.08	-44.3	180

^a Determined using ¹H NMR. ^b Determined using GPC-RI (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^c Theoretical M_n calculated from product of monomer conversion and monomer molecular weight. ^d Determined using DSC (sample size = 0.5 - 3 mg; heating rate = 10 °C min⁻¹).

4.3.3.2 Effect of Heating Method on the One-Pot, One Step Synthesis of PLA-co-PCL

Entries 1 and 2 in Table.4.1 are the data from MWH and CH reactions for the synthesis of PLA-co-PCL with an equal initial monomer ratio. The kinetic plots for the monomer conversion in these reactions are presented in Figure 4.5 (MWH) and Figure 4.6 (CH).

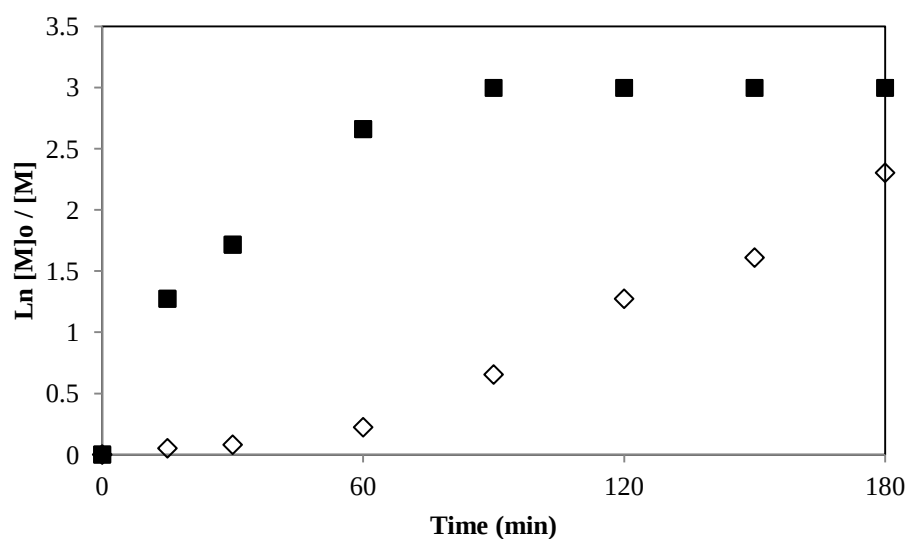


Figure 4.5: Kinetic plots of $\ln ([M]_0/[M])$ vs reaction time for DLLA (■) and ϵ -CL (◇) for the synthesis of PLA-co-PCL using MWH at 150 °C with monomer ratio [DLLA] : [ε-CL] = [43.5]: [43.5].

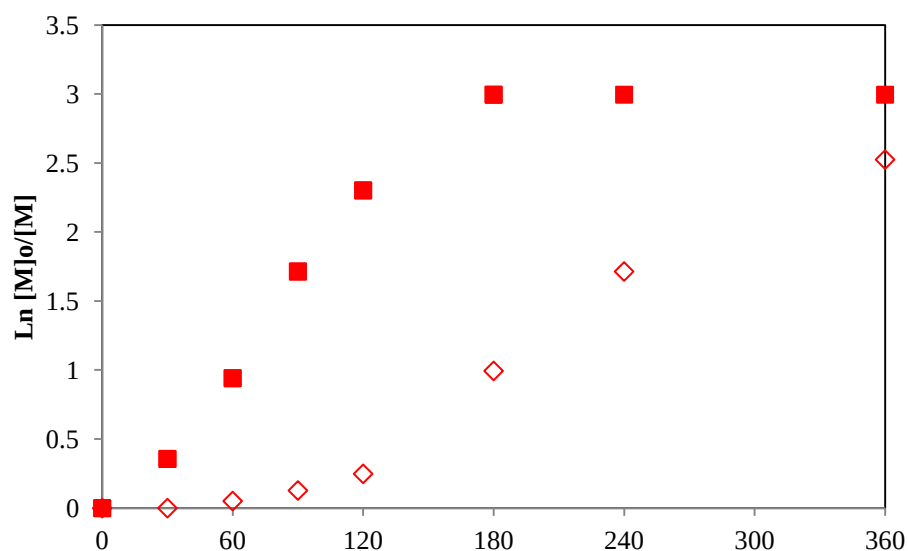


Figure 4.6: Kinetic plots of $\ln ([M]_0/[M])$ vs reaction time for DLLA (■) and ϵ -CL (◇) for the synthesis of PLA-co-PCL using CH at 150 °C with monomer ratio [DLLA] : [ε-CL] = [43.5]: [43.5].

From a comparison of Figure 4.5 and Figure 4.6, it can be deduced that there is an overall improved reaction cycle time reduction achieved with MWH. The time taken to achieve full conversion was much less than that of the equivalent

CH polymerisation, with 180 and 360 minutes needed to reach full monomer conversion respectively. This is consistent with the reduction in reaction times observed using MWH for the homopolymerisations of both PCL (in the previous chapter) and with the PLA reactions earlier in this chapter.

Additionally, this data demonstrated that the rate of propagation (k_p) was an order of magnitude faster for PLA compared to PCL in both MWH ($k_{p \text{ PLA}} = 0.0477 \text{ min}^{-1}$, $k_{p \text{ PCL}} = 0.0101 \text{ min}^{-1}$) and CH ($k_{p \text{ PLA}} = 0.0165 \text{ min}^{-1}$, $k_{p \text{ PCL}} = 0.0063 \text{ min}^{-1}$) experiments, see Figure 4.5 and Figure 4.6 respectively. Thus, these experiments have shown that, when using both heating methods, the higher reactivity of DLLA caused preferential ROP of this monomer over ϵ -CL, which is consistent with current literature.

Furthermore, it was interesting to note that the ratio of $k_{p \text{ PLA}} / k_{p \text{ PCL}}$ was twice as large in MWH compared to CH. Thus it was concluded that MWH was affecting the relative monomer reactivity, thus encouraging the ROP of DLLA over and above that of ϵ -CL. It was also noted that DLLA was reacted in MWH to a higher conversion before the ROP of PCL occurred, than in the CH equivalent reaction. This suggested that the resultant polymer from this one step reaction may indeed have blocky character. Unfortunately, matrix assisted laser desorption-ionisation time of flight (MALDI-TOF) analysis was unable to be carried out on the samples due to the broad $\bar{M}$ and large M_w of the samples. Thus a greater understanding of the copolymeric structure was not possible using MALDI.

The dielectric properties of the DLLA and ϵ -CL monomer units, presented in Figure 4.2, may offer a potential explanation of this observation. At the high temperature applied (150 °C), the $\tan \delta$ of DLLA was observed to be higher (~ 0.5) than ϵ -CL (~ 0.1). Therefore under MWH the DLLA moieties will be more susceptible to the microwave energy and thus potentially exhibit a greater localised temperature with regard to the bulk. Thus, this may lead to faster rate of polymerisation for the DLLA with MWH, therefore allowing it to dominate until high PLA conversion. This effect will be exasperated by the relative suppressed rate of the “less susceptible” ϵ -CL.

Another difference noted in the two reactions was the lack of initiation/induction period observed in the MWH reaction, whilst in the CH there was a delay before the ROP can be achieved. In Figure 4.6, it can be assumed that there was an induction period of approximately 10 minutes in CH. There is no such lag in the MWH reaction.

GPC analysis can provide information about the molecular weight of the copolymer products. The molecular weight information gained from the GPC analysis (Figure 4.7) for the MWH reaction is provided alongside the ϵ -CL and DLLA, conversion as determined by ^1H NMR, in Table 4.2.

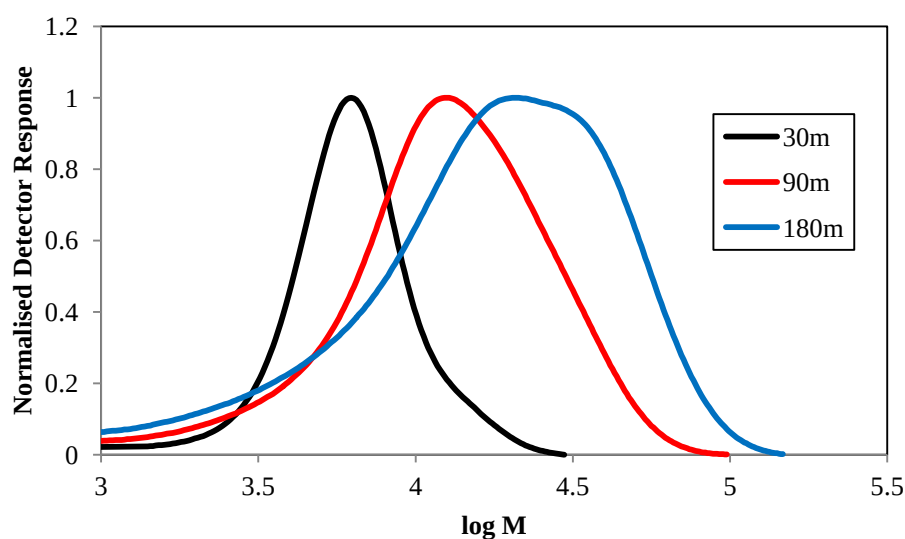


Figure 4.7 GPC trace overlay of samples taken during the MWH one-pot, one step reaction of PLA-co-PCL (Entry 1, Table.4.1).

Table 4.2 Following the evolution of monomer conversion and molecular weight against reaction time for DLLA and ϵ -CL for the synthesis of PLA-co-PCL using MWH in the one-pot, one step method at 150 °C with monomer ratio [DLLA] : [ϵ -CL] = [43.5] : [43.5].

Time (min)	Monomer Conversion (%) ^a		Molecular weight (g mol ⁻¹)		
	DLLA	ϵ -CL	M _n Theo ^c	M _n Obs ^b	$\bar{D}$ ^b
15	72	5	5,400	4,800	1.20
30	82	7.7	5,900	5,880	1.22
60	93	20	7,600	7,700	1.37
90	95	48	9,400	10,100	1.56
120	95	72	10,700	10,500	2.25
150	95	80	11,000	10,800	2.47
180	95	90	11,800	10,800	2.61

^a Determined using ¹H NMR. ^b Determined using GPC-RI (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^c Theoretical M_n calculated from product of monomer conversion and monomer molecular weight.

The sample analysed after 15 minutes in Table 4.2 clearly showed that a high level of DLLA conversion was achieved before significant PCL incorporation had been achieved. The data in Figure 4.5 and Table 4.2 demonstrated that there was little PCL growth, until more than 70 % of the DLLA had been

consumed in the MWH reaction. After 30 minutes in the MWH case, 77 % of the DLLA had been converted into PLA, whereas only 7 % of the ϵ -CL had been polymerised. The observed M_n at this point was $5,880 \text{ g mol}^{-1}$, which was very close to $M_{n \text{ theo}}$ of $5,940 \text{ g mol}^{-1}$ and a low $\bar{D}$ of 1.23 was recorded. The GPC traces (Figure 4.7) of subsequent samples showed a narrow distribution for the PLA after 30 minutes, which broadened and shifted to higher molecular weight as more ϵ -CL underwent ROP (90 minutes).

The broadening of the $\bar{D}$ and increasing M_n values provided evidence that the reacted ϵ -CL units were being added to the PLA chain, thus it was concluded that the formation of separate homopolymer PCL chains was being suppressed. In the final trace, taken after 180 minutes, there was evidence of a shoulder appearing at high molecular weight. This was attributed to the onset of by-product transesterification reactions. This was also accompanied by an increase of low molecular weight species, generated by the inter-chain scission mechanisms. Thus, the presence of a bi-modal peak suggested that MWH was encouraging transesterification reactions at high monomer conversion. The impact of MWH at low monomer levels will be discussed later in this chapter.

Consequently, the fact that one monomer seemed to have reacted to high conversion before the other monomer became involved in the process suggested the possible formation of a block copolymer. Therefore, DSC analysis was conducted in order to confirm this. If a block copolymer had been produced, then two T_g 's would be observed, where each value would be representative of the T_g of each homo-polymer. However, the DSC results indicated a random statistical copolymer being produced, due to the fact that

only one T_g was observed which exhibited a composite value between those of the two individual homo-polymers. Subsequent calculations conducted using the Fox Equation (Equation 4.1) provided further evidence for the formation of a statistical copolymer.

$$\frac{1}{T_g} = \frac{W_1}{T_{g1}} + \frac{W_2}{T_{g2}}$$

Equation 4.1: The Fox Equation determines the T_g for statistical copolymers. W_1 and W_2 are the weight fraction of components 1 and 2. The theoretical T_g values that were used for the Fox Equation calculations were PCL = - 60 °C and PLA = 45 °C.

The DSC trace of the final products had one T_g (-9.4 °C in MWH and -4.4 °C in CH), and these empirical results were found to be very close to the theoretical values calculated from the Fox equation (Equation 4.1). For example, with a weight fraction of 0.5 for each polymer (i.e. the 50:50 monomer feed ratio used) the predicted T_g temperature calculated using the Fox Equation was - 7.5 °C. Hence the fact that these two values are similar was indicative of the synthesis of a highly transesterified, random copolymer. Therefore, it was concluded that, when the polymerisation were taken to almost complete conversion, that transesterification reactions were causing ϵ -CL units to be dispersed throughout the PLA chain in a random manner, resulting in the formation of an amorphous statistical copolymer.

The GPC trace evolution of the CH equivalent reaction, Entry 2 in Table.4.1 is provided in Figure 4.8.

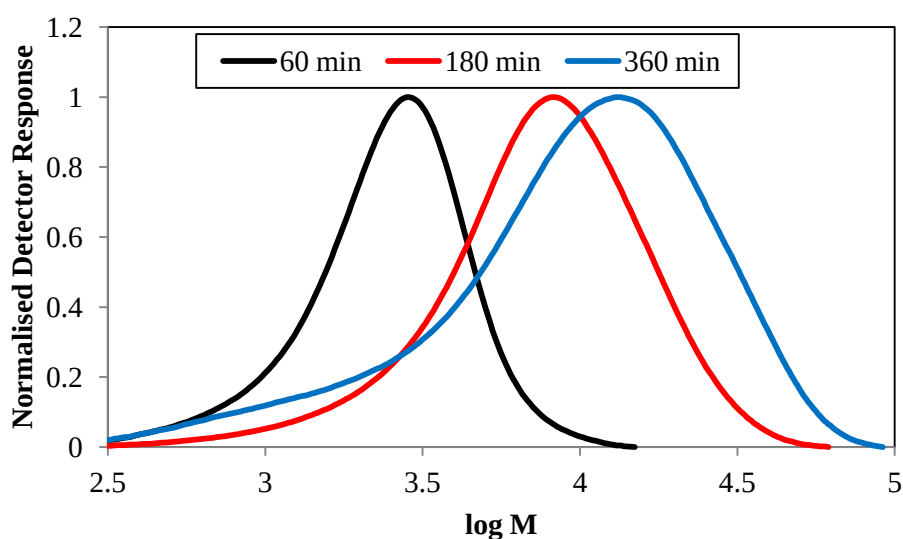


Figure 4.8 GPC trace of final PLA-co-PCL sample taken during the CH one-pot, one step reaction (Entry 2, Table.4.1).

The CH reaction also showed high level of control at similar levels of conversion (PLA 75 % and PCL 9 %) after 120 minutes with M_n close to the theoretical value and $\bar{D}$ at 1.22. Additionally, the uni-modal nature of the GPC trace (Figure 4.8) at 360 minutes shows that, like the MWH reaction, the PCL units are adding to the PLA chain, not forming homo-PCL.

It was also observed that the final product of the CH reaction showed less evidence of transesterification reactions, as the final peak (360 minutes) in Figure 4.8 was much more symmetrical (i.e. more uni-modal) than the final product of the MWH reaction (Figure 4.7, 180 minutes). Thus it was concluded that CH was unable to promote inter-chain reactions as prominently as had been observed with MWH. This can be explained by the lack of selective heating of the active centres in CH, thus the tin will be less able to interact at high conversions because it will not be experiencing as high a localised temperatures and thus potentially low viscosity that was possible in MWH.

4.3.3.3 Effect of Monomer Feed Ratio on the One-Pot, One Step Synthesis of PLA-co-PCL using MWH

Further reactions were conducted using MWH to form PLA-co-PCL copolymers with varying monomer feed ratios. For a reaction conducted using the feed ratio $[DLLA]_{65.2} : [\varepsilon\text{-CL}]_{21.8}$, the molar masses and thermal properties are displayed as Entry 3, Table.4.1 and the kinetic plot of the reaction is provided in Figure 4.9.

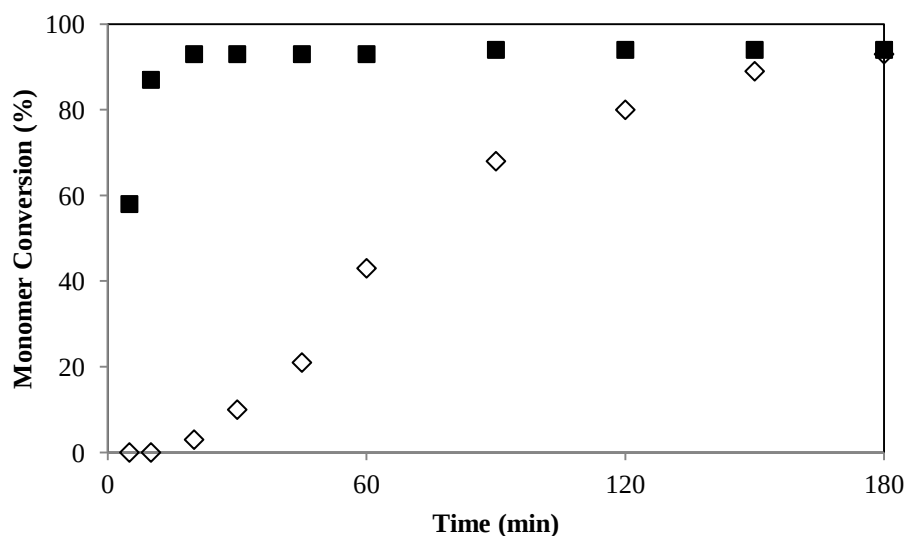


Figure 4.9: Kinetic plots of monomer conversion vs reaction time for DLLA (■) and $\varepsilon\text{-CL}$ (◇) for the synthesis of PLA-co-PCL using MWH at 150 °C with monomer ratio $[DLLA] : [\varepsilon\text{-CL}] = [65.2] : [21.8]$.

Altering the monomer feed ratio was found to have affected the relative k_p for each homopolymer. Analysis of Figure 4.9 indicated that when the monomer ratio was $[DLLA] : [\varepsilon\text{-CL}] = [68.2] : [21.8]$, the $k_{p\text{ PLA}}$ increased to 0.2329 min^{-1} whilst the $k_{p\text{ PCL}}$ reduced to 0.0160 min^{-1} . Meanwhile, Figure 4.10 plots the DLLA and $\varepsilon\text{-CL}$ conversion against time for the experiment listed as

Entry 4, Table.4.1, which had a monomer ratio of [DLLA]_{21.8} : [ε-CL]_{65.2}.

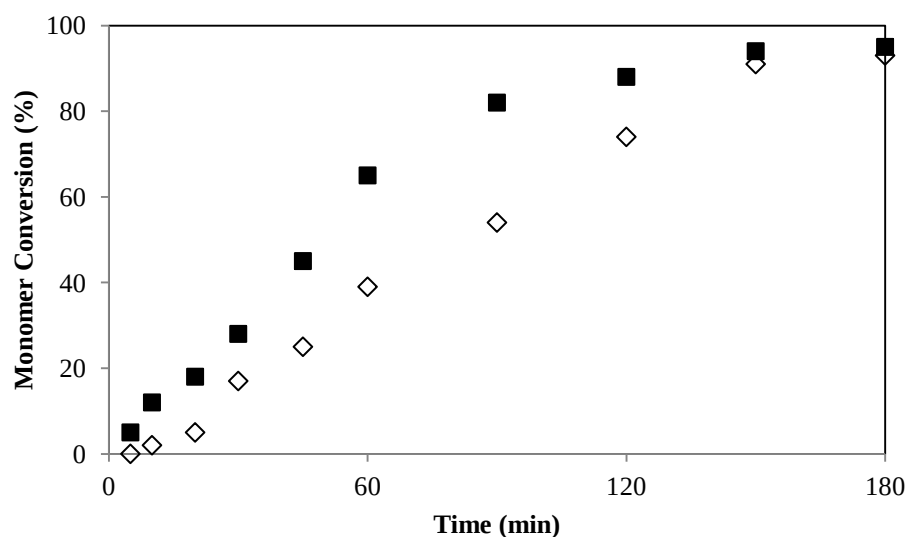


Figure 4.10: Kinetic plots of monomer conversion vs reaction time for DLLA (■) and ε-CL (◇) for the synthesis of PLA-co-PCL using MWH at 150 °C with monomer ratio [DLLA] : [ε-CL] = [21.8] : [65.2].

It is evident that, when the monomer reagent ratio was reversed as in Entry 4, i.e. molar ratio [DLLA] : [ε-CL] = [21.8] : [65.2], the $k_{p\text{ PLA}}$ and $k_{p\text{ PCL}}$ calculated from Figure 4.10 were found to be very similar (0.0190 min^{-1} and 0.0157 min^{-1} respectively). This variation of k_p relative to monomer feed was concluded to be due to the relative abundance of monomers around the active centre.

Again a similar trend/change in monomer reactivity related to the monomer feed ratio was observed in the equivalent CH reactions. However, the $k_{p\text{ PLA}} / k_{p\text{ PCL}}$ ratio was larger in MWH compared with CH, for example when the monomer ratio was [DLLA] : [ε-CL] = [65.2] : [21.8], the $k_{p\text{ PLA}} / k_{p\text{ PCL}}$ ratio in MWH was double the CH value. This suggested that the effect of encouraging the ROP of PLA is more prominent with MWH. An observation

that was also related to the presence of selective heating in the MWH experiments and highlighted the influence of the higher susceptibility of DLLA units to MWH, as indicated from its $\tan \delta$ values.

DSC was used to establish the T_g values for the final copolymeric products from the reactions heating using MWH with a view to establishing the final structure of the PLA-co-PCL formed. The plot of T_g against the monomer feed ratio is provided Figure 4.11, along with the theoretical values as calculated from the Fox Equation (Equation 4.1).

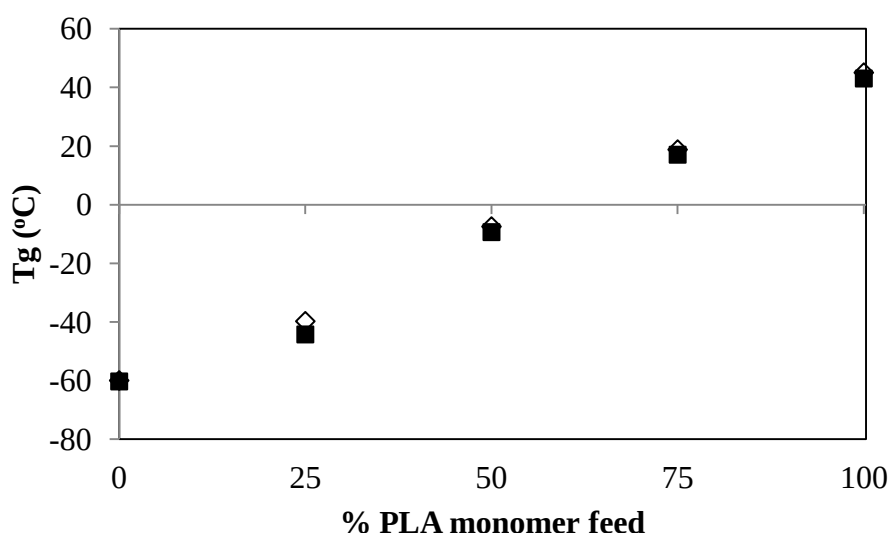


Figure 4.11 Plot of T_g against % of DLLA in the monomer feed for PLA-co-PCL using MWH (■): (Sample size = 0.5 – 3 mg; heating rate = 10 °C min⁻¹). Theoretical values (◇), as calculated by Fox equation, by using for the T_g of the homopolymers the following literature values: PLA = 45 °C ; PCL = - 60 °C.

The DSC spectra for all reactions exhibited only one T_g , which was indicative that a statistical copolymer had been produced. Furthermore, it is clear from Figure 4.11 that the experimental T_g values are similar to their respective theoretical T_g values, as calculated using the Fox Equation, thus proving the

formation of highly transesterified statistical PLA-co-PCL copolymer. Therefore all reactions produced statistical copolymers with $M_{n \text{ Theo}}$ values similar to $M_{n \text{ obs}}$ experimentally.

4.3.3.4 One-Pot, One Step Copolymerisation Conclusions

Therefore, MWH has been successfully shown to produce statistical PLA-co-PCL copolymers *via* a one-pot, one step method. Whilst ^1H NMR analysis showed that DLLA units were polymerised faster in the early stages of the polymerisations, both GPC and DSC data indicated that ϵ -CL units were incorporated into the PLA chains, forming a statistical copolymer. Furthermore, it was concluded that the polymerisation mechanism changed toward inclusion of/domination by the transesterification reactions as the monomer conversion in the system increases, which resulted in a random copolymer being isolated. It was also shown that the copolymers formed using MWH had similar composition to the CH equivalents. However, MWH has been shown to reduce the time of reaction with faster rates of reaction being achieved *via* the reduction/elimination of the induction period and the increased k^{app} as shown in the previous chapter.

Therefore MWH has been shown have the following effects on the one-pot, one step copolymerisation reactions of PLA-co-PCL:

- a) The increase the overall k_p for all monomer ratio reactions in MWH compared to CH.
- b) The superior heating mechanism, due to selective heating in MWH, led to faster rates and thus shortened/eliminated induction times with respect in CH.
- c) The DLLA units reacted preferentially in MWH than CH, as explained by their high dielectric values.
- d) There was greater evidence for the transesterification within the MWH for the full range of reagent ratio reactions. This suggested that the selective heating at high conversion promoted this mechanism to a greater extent than in the CH reactions.

4.3.4 Regrowth Studies

As the one-pot, one step method (i.e. all reagents present at start of reaction) only produced statistical copolymers, a sequential monomer addition method was investigated in order to attempt to synthesise block copolymers. It was hypothesised that using one homopolymer as a macro-initiator for a second polymer would result in block copolymer formation using MWH. However, it was also postulated from the data above that the transesterification process may be promoted in MWH which would mean that statistical copolymers may be isolated.

4.3.4.1 One-Pot, Two Step Copolymerisation Studies

In the one-pot, two step method used in this section of the study, only one monomer was present at the start of the reaction with the initiator and catalyst. The initial monomer underwent ROP leading to the formation of the respective homopolymer. When the ROP had achieved the target conversion of ~70 % (calculated *via* ^1H NMR), the first step was considered to have completed, and the second monomer was added without any isolation or purification of the initial homo-polymer. After addition of the secondary monomer, the overall monomer conversion was allowed to proceed until full conversion. The data from these reactions is contained in Table 4.3.

Table 4.3 One-pot, two step synthesis of PLA-co-PCL at 150 °C.

Entry	Heating method	Initial monomer conv (%) ^a in macro-initiator	Final Conv (%) ^a PCL/PLA	Initial Block				Final Copolymer				Reaction time (min)	DSC scan of final product ^d		
				M _n theo ^c (g mol ⁻¹)	M _n obs ^b (g mol ⁻¹)	M _w obs ^b (g mol ⁻¹)	Đ ^b	M _n theo ^c (g mol ⁻¹)	M _n obs ^b (g mol ⁻¹)	M _w obs ^b (g mol ⁻¹)	Đ ^b		T _g (°C) (PCL)	T _g (°C) (PLA)	T _m (°C) (PCL)
1	MWH	DLLA 71	91 / 98	8,920	10,470	11,860	1.13	21,280	14,000	20,300	1.88	540	-39	-7	No T _m
2	CH	DLLA 70	83 / 95	8,660	8,700	9,900	1.14	20,130	8,000	11,300	1.60	720	-58	43	53

^a Determined using ¹H NMR. ^b Determined using GPC-RI (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^c Theoretical M_n calculated from product of monomer conversion and monomer molecular weight. ^d Determined using DSC (sample size = 0.5 - 3 mg; heating rate = 10 °C min⁻¹).

4.3.4.2 One-Pot, Two Step - PLA First Studies

The one-pot, two step sequential monomer addition method with the formation of a macro-initiator of PLA was examined. In this case, the DLLA was reacted to $\sim 70\%$ conversion before the addition of ϵ -CL monomer. The NMR, GPC and DSC analysis of the final product from the CH reaction is provided as Entries 2 in Table 4.3. The CH reaction's GPC traces of the PLA macro-initiator and final product are given in Figure 4.12.

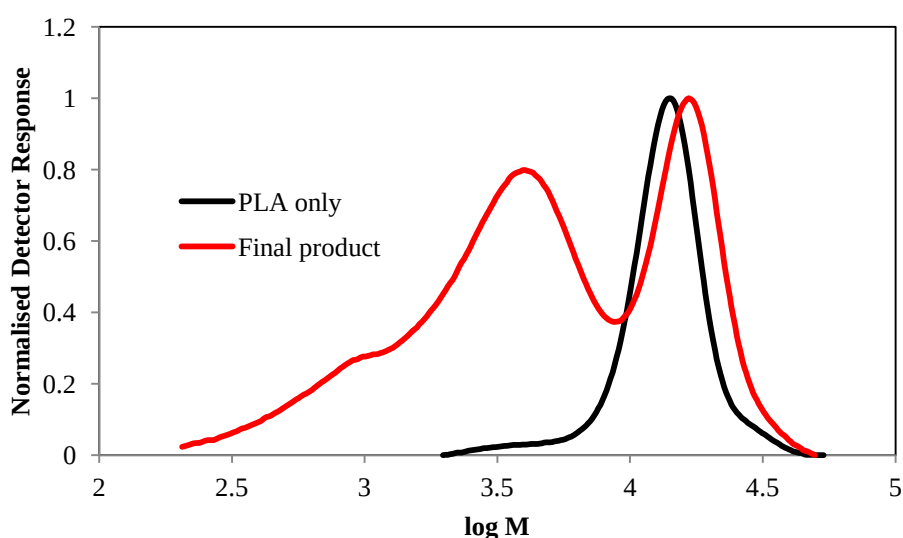


Figure 4.12 GPC trace overlay of samples taken before and after ϵ -CL addition during the CH one-pot, two step attempted synthesis of PLA-co-PCL (Entry 4, Table 4.3).

The addition of the second monomer was timed to occur before the onset of any significant transesterification of the first block, which from the earlier experiments was shown to be near to 60% DLLA conversion using CH. Indeed the GPC of the first block shows good controlled characteristic with $\bar{D}$ of 1.14

(Figure 4.12). The PLA macro-initiator had a M_n of 8,660 g mol⁻¹, which was very similar to the $M_{n\text{ Theo}}$ (8,700 g mol⁻¹).

However, the GPC traces show that during the CH one-pot, two step reaction (Figure 4.12), PCL was formed as separate homopolymer chains rather than achieving growth away from the PLA macro-initiator. This was indicated by the appearance of a new, broad peak at lower molecular weight than the initial PLA macro-initiator peak. Also, the initial PLA peak did not exhibit a significant shift to higher molecular weight or broaden its distribution after addition of ϵ -CL, suggesting no significant growth of PCL away from the PLA macro-initiator. However, the increase in M_w from 9,900 g mol⁻¹ to 11,300 g mol⁻¹ may have been the result of the unreacted DLLA units reacting with the macro-initiator after the addition of ϵ -CL. The DSC data would provide an indication whether the slight regrowth was homo or copolymerisation.

DSC data supported the conclusion that two separate homopolymers were formed. The two T_g 's were observed at -58 °C and 40 °C which are very close to those typically expected for the pure PCL and PLA values. There was no presence of a T_g relating to an intermediate copolymer structure in this case. Finally, a large T_m peak at 53 °C was located and was attributed to being indicative of large crystallised areas of homo-PCL. Thus, it was concluded that, in the CH reaction, after the remaining DLLA units were added to the macro-initiator, the active sites underwent chain transfer and there was a clear growth of PCL, i.e. $k^{app}_{PCL + CL}$ mechanism dominated, as the majority of DLLA units had already undergone ROP. Any remaining DLLA units added to the homo-

PLA. Hence, the presence of the homo-PCL peak in the GPC. There was no evidence of transesterification of the initial PLA block with CH as the shape and size of the PLA peak barely alters before and after PCL formation (Figure 4.12).

Entry 1 in Table 4.3 details the data from the MWH equivalent reaction of the one-pot, two step process with PLA as the initial block. The GPC traces of samples taken before and after ϵ -CL addition are presented in Figure 4.13.

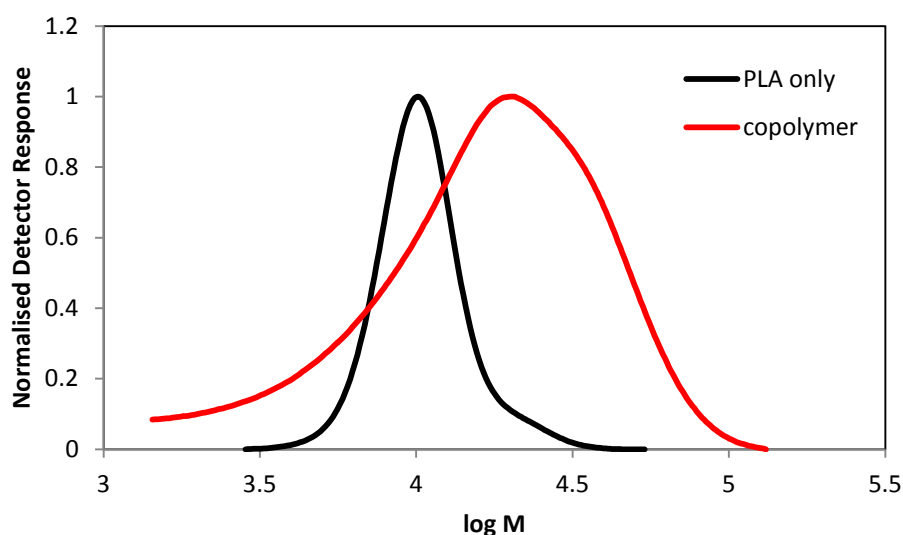


Figure 4.13 GPC trace overlay of samples taken before and after ϵ -CL addition to PLA macro-initiator during the MWH one-pot, two step synthesis of PLA-co-PCL (Entries 3, Table 4.3).

The initial PLA block showed good controlled character, with a low $\bar{D}$ of 1.13 and good control over molecular weights. Figure 4.13 shows the GPC traces of the MWH reaction after ϵ -CL addition. The main difference seen between Figure 4.12 and Figure 4.13 is the evidence of extensive regrowth onto the PLA macro-initiator using MWH. The addition of PCL to the homopolymer from the first step caused the peak of the PLA macro-initiator to shift to much

higher molecular weight with a clear broadening of the molecular weight distribution to 1.88 from 1.13. The homo-PLA M_w value was 11,860 g mol⁻¹, which almost doubled after the addition of PCL to 20,300 g mol⁻¹. The increase was concluded to be the result of ϵ -CL units adding to the PLA chains, as well as any remaining DLLA moieties, leading to the formation of PLA-co-PCL.

Also observed in the GPC trace of the final copolymer structure is a shoulder appearing at high molecular weight. The multi-modal peak with a broadened distribution led to the conclusion that MWH promoted the transesterification at very high ϵ -CL and DLLA conversion (> 80 % for both monomers) and which may contribute to the mixing of the copolymers.

Figure 4.14 contains the comparison of the DSC thermograms of the one-pot, one step and one-pot, two step sequential addition polymers using MWH. The one-pot, one step reaction was discussed as Entry 1, Table.4.1 in Section 4.3.3.1.

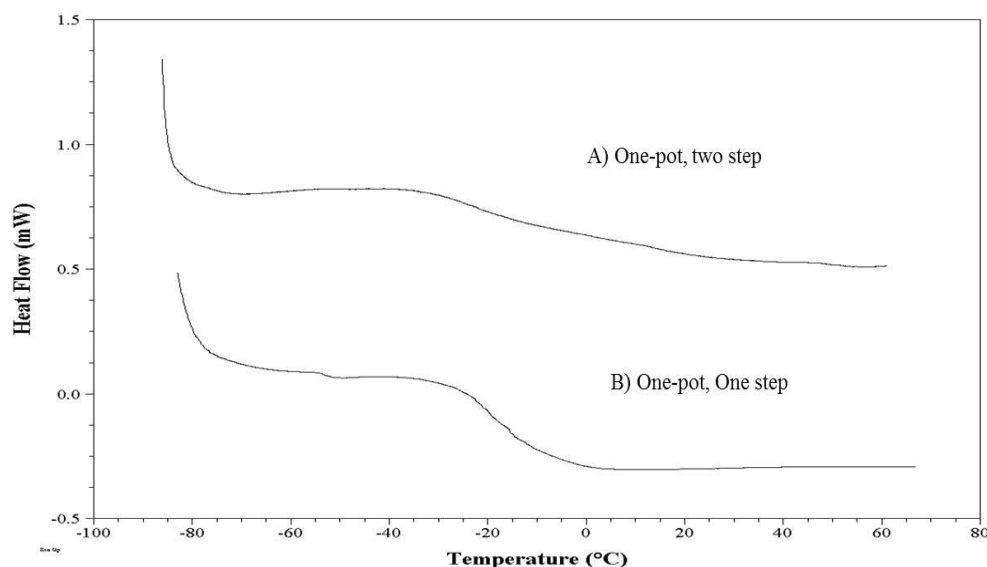


Figure 4.14 DSC thermograms of PLA-co-PCL copolymers produced with MWH via the one-pot, two step process with PLA macro-initiator (A) and PLA-co-PCL copolymers produced via the one-pot, one step process (B). Determined using DSC (sample size = 0.5 - 3 mg; heating rate = 10 °C min⁻¹).

The DSC analysis provides evidence of PCL addition to the initial PLA chains using MWH, to form an impure block copolymer in the one-pot, two step method (Trace A, Figure 4.14). If there had been no addition to the pre-existing PLA chains it would be expected a T_g of 45 °C, i.e. PLA homopolymer would be observed. However, the addition of the ϵ -CL has lowered the copolymer T_g to -11.44 °C. Using the Fox Equation this T_g value represents a copolymer formed of 60 % PCL units and 40 % PLA.

Another T_g was observed at -39.50 °C. This temperature is closer to the region expected for pure PCL. Therefore, this glass transition temperature was believed to represent a segment containing almost all PCL within the block copolymer. The relative amount of PCL and PLA in this copolymer was

calculated to be in region of 80 % and 20 % respectively (Fox Equation). Therefore, a combination of MWH encouragement for transesterification and the fact that there was still DLLA monomer present when the second monomer (ϵ -CL) is added has resulted in some PCL units inserted into the PLA backbone and vice versa. Thus, this final product mixture consisted of two statistical copolymers of differing PCL and PLA ratios. Evidence that this structure has been isolated also came from the fact that no T_m was observed for this product. This means that there is no PCL segment which was large enough to crystallise. The trace from the one-pot, one step reaction (Trace B, Figure 4.14) has included for comparison. This reaction produced a single statistical copolymer, with the PLA and PCL units randomly dispersed in the copolymer backbone, hence one 'sharp' T_g was observed, as opposed to the gradual and numerous T_g observed for the formation of impure block copolymer in the one-pot, two step method.

Therefore, analysis of the ^1H NMR, GPC and DSC data, has shown that MWH was able to synthesise two separate statically copolymers with varying PCL to PLA ratios from a PLA macro-initiator. Therefore, this method has clearly inspired significant growth away from the PLA macro-initiator. However, this has not been an exclusive mechanism responsible for polymer generation in two step procedure. Rather, chain transfer to generate a more PCL rich polymer segment and/or transesterification of PCL segments into the pre-existing PLA backbone has occurred. The ability of MWH to selectively heat the active centres to a higher localised temperature may explain some of the different mechanistic routes observed compared with the CH equivalent reaction above.

The overall polymer physical and mechanical properties of such a copolymer mixture have proved to create quite a bit of interest in the application groups within the University of Nottingham. Thus, being able to reproducibly generate such a mixture may have some significant application benefits.

Therefore, it is clear that the MWH reactions conducted using the two differing monomer addition methodologies produced different product polymers from one another. Also, the reactions using MWH have generated different materials from the CH reactions which adopted the same addition strategy.

4.3.4.3 Two-Pot, Two Step Studies

In a further attempt to synthesise block copolymers of PLA-co-PCL, a two-pot, two step approach was undertaken. This strategy was attempted because one of the potential reasons why the one-pot, two step process did not succeed in producing block copolymers could have been the presence of the initial monomer in the second step of the process, affecting the monomer : polymer equilibrium leading to enhanced transesterification reactions that inserted the secondary monomer into the macro-initiator structure.

Therefore, to avoid the onset of transesterification in the two-pot, two step approach, the ROP of the first homopolymer was stopped before 75% conversion. This homopolymer was then isolated from any remaining monomer, before the second monomer was added. After the addition of the

second monomer, all the reactions were continued until the second monomer had undergone high conversion. The results of the two-pot, two step polymerisation for PLA as the macro-initiator when heated using MWH and CH are presented in Table 4.4.

Table 4.4 Two-pot, two step synthesis of PLA-co-PCL at 150 °C.

Entry	Heating method	Initial monomer conv (%) ^a in macro-initiator	Final Conv (%) ^a PCL/PLA	Initial Block				Final Copolymer				Reaction time (min)	DSC scan of final product ^d		
				M _n theo ^c (g mol ⁻¹)	M _n obs ^b (g mol ⁻¹)	M _w obs ^b (g mol ⁻¹)	Đ ^b	M _n theo ^c (g mol ⁻¹)	M _n obs ^b (g mol ⁻¹)	M _w obs ^b (g mol ⁻¹)	Đ ^b		T _g (°C) (PCL)	T _g (°C) (PLA)	T _m (°C) (PCL)
1	MWH	DLLA 66	78 / 66	8,140	11,000	14,600	1.17	17,560	18,040	34,100	1.89	150	-28	42	No T _m
2	CH	DLLA 72	75 / 72	9,020	9,300	10,400	1.11	18,440	10,200	13,300	2.16	1140	-60	45	52

^a Determined using ¹H NMR. ^b Determined using GPC-RI (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^c Theoretical M_n calculated from product of monomer conversion and monomer molecular weight. ^d Determined using DSC (sample size = 0.5 - 3 mg; heating rate = 10 °C min⁻¹).

4.3.4.4 Two-Pot, Two Step – PLA First Studies

Entry 1 in Table 4.4 presents the data from reaction in MWH when DLLA was polymerised to < 70 % conversion, to afford a PLA homopolymer as a first block that has yet to experience significant transesterification. After purification to remove the unreacted monomer, ϵ -CL was added (Figure 4.15).

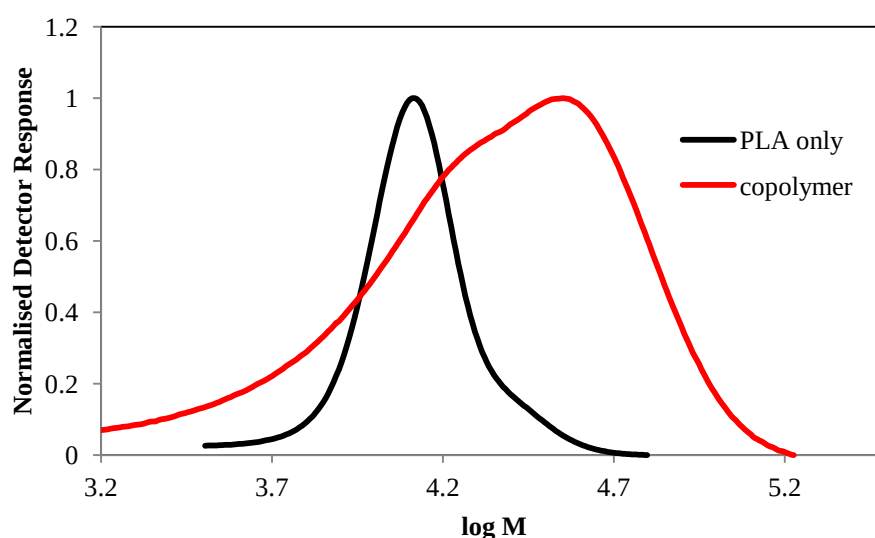


Figure 4.15 GPC trace overlay of samples taken before and after ϵ -CL addition during the MWH two-pot, two step reaction of PLA-co-PCL (Entry 3, Table 4.3).

The initial PLA block had a M_n of $11,000 \text{ g mol}^{-1}$ and a $\bar{D}$ value of 1.17 (Figure 4.15). Again, it has been shown that MWH was capable of producing PLA with highly controlled characteristics. The GPC data of the final product shows that the initial PLA block had grown to $18,040 \text{ g mol}^{-1}$, which was evidence that the ϵ -CL was adding to the PLA block with the MWH. The $k_{\text{PLA+CL}}$ was high enough to ensure that PLA-co-PCL was being formed. The multi-modal shape of the GPC trace of the final product is indicative that more than one mechanism was present producing different structures. The shift to higher

molecular weight for the PLA peak was evidence of copolymer formation, however the broadening of the peak to $\Delta 1.89$ suggests transesterification reactions occurring thus it may not be a block copolymer. The GPC data was analysed alongside the DSC trace (Figure 4.16) of the final polymer to ascertain the nature of the molecular structure present in the final copolymers.

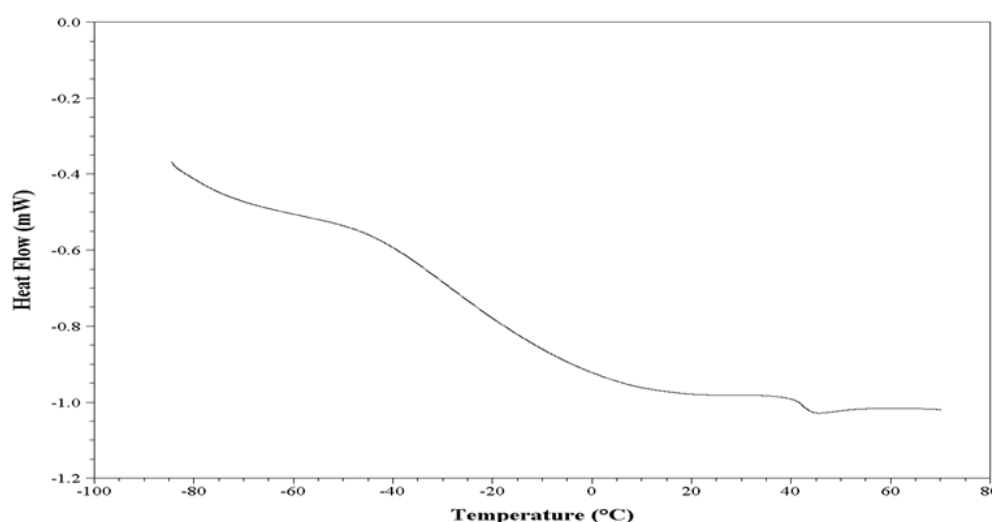


Figure 4.16 DSC thermograms of PLA-co-PCL copolymers produced via the two-pot, two step process with PLA macro-initiator using MWH. Determined using DSC (sample size = 0.5 - 3 mg; heating rate = $10\text{ }^{\circ}\text{C min}^{-1}$).

From closer inspection of the DSC data it was noted that the PCL units are not forming separate homopolymers as there was no T_g at $-60\text{ }^{\circ}\text{C}$ nor a T_m relating to homo-PCL (Figure 4.16). Instead there is a broad T_g at approximately $-30\text{ }^{\circ}\text{C}$, indicative of PLA-co-PCL regions with significant PCL contribution. The MWH appears to have encouraged the PLA and PCL segments to be interspersed together, as evident from the broad peak in the GPC and the composite T_g value. There is also a T_g observed at approximately $40\text{ }^{\circ}\text{C}$, which has been attributed to a quantity of PLA macro-initiator that had undergone some reaction with the ϵ -CL monomer. The PLA macro-initiator's increase to

higher M_w in the GPC trace coupled with the T_g in the DSC appearing at lower temperature than homo-PLA supports the view that MWH encouraged ϵ -CL to react with the PLA macro-initiator. Thus it was concluded that MWH was encouraging regrowth of the initial homopolymer *via* selective heating of active species to produce polymer chains which have cross-propagation of PCL units with runs of PLA, rather than promoting a chain transfer mechanism. The latter of which would have led to PCL homopolymers only. Thus, it would appear that the transesterification process was further promoted by the MWH method if the Sn chain end is located upon a PLA based macromer, as was indicated by the composite T_g values and broad traces in the GPC.

Entry 2, Table 4.4 presents the data from the CH reaction, with the GPC trace of the initial homopolymer and subsequent final product given in Figure 4.17.

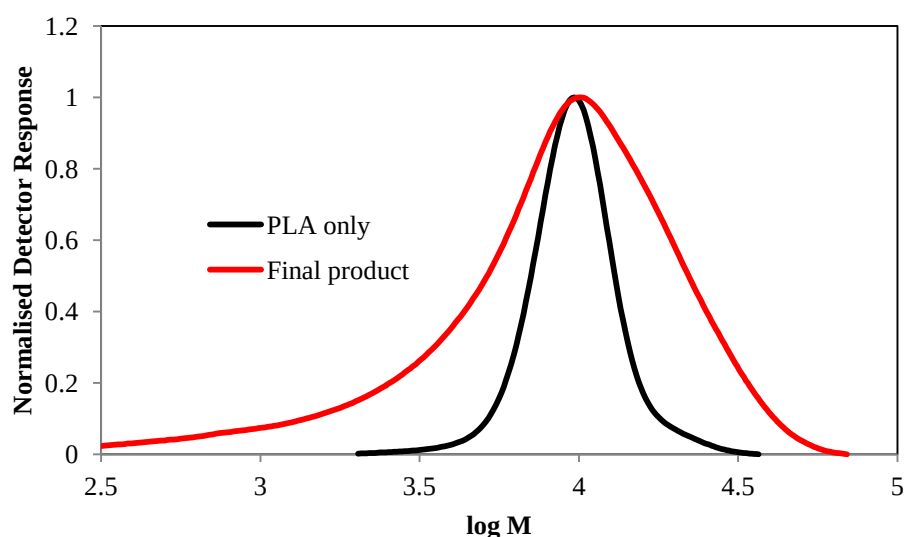


Figure 4.17 GPC trace overlay of samples taken before and after ϵ -CL addition during the CH two-pot, two step reaction of PLA-co-PCL (Entry 3, Table 4.3).

The GPC and DSC data clearly demonstrated that different reaction mechanisms had dominated the CH reaction compared to the MWH equivalent, and thus a different product was formed. Indeed, from the GPC trace, there was no regrowth away from the PLA block. The M_n does not increase significantly ($9,300 \text{ g mol}^{-1}$ to $10,200 \text{ g mol}^{-1}$) after full PCL conversion had been achieved. However, a large increase in $\bar{M}_w$ was observed suggesting relatively poor control and highly transesterified PCL and PLA homopolymers. Two T_g (-60 and 45°C) and a clear T_m (52°C) in the DSC analysis supports the GPC conclusion that two homopolymers were formed with no evidence of regrowth of the PLA macro-initiator in CH. There is also no evidence for transesterification between PLA and PCL segments that is thought to result in the isolation of the products from the MWH experiment. This would fit with the conclusions made throughout this thesis, that MWH significantly promotes transesterification at high conversion especially if the chain end is attached to a PLA macromer. The fact that the reaction took 1140 minutes (19 hours) to reach full PCL conversion using CH, compared with 150 minutes with MWH is further evidence of a specific heating of the ϵ -CL units leading to an enhanced rate of reaction rate, whether this be propagation or transesterification. The active centres were much more likely to react, either monomer or an adjacent chain, because they are being selectively heated in MWH.

4.4 Conclusions

The work presented in this chapter analysed and compared attempts to synthesis PLA-co-PCL using both CH and MWH. Detailed analysis of the dielectric properties of the various reaction reagents required to do this found that, at the elevated reaction temperatures used (140 – 160 °C), the DLLA monomer and the tin active species will be the most susceptible to microwave heating.

The ROP of DLLA was proved to have controlled character in MWH. It was interesting to note that the controlled growth window was extended in MWH to a conversion level significantly beyond that exhibited by CH. The control of both $\bar{D}$ and M_n growth was observed to continue to 85 % DLLA conversion in MWH compared to 65 % in CH. For the first time, dielectric properties of the DLLA and the other ROP reagents were able to rationalise this observation. The $\tan \delta$ value for DLLA was much higher (0.4) than the other reaction components, especially the PLA chains, thus the DLLA units were heated more efficiently than the bulk. Therefore, the remaining monomer would be much more likely to react with the active species, which was not as prominent in CH method, as CH was unable to selectively heat the monomer or Sn active species. The hotter DLLA units will have been able to diffuse through the viscous mixture to locate and react with the active sites more efficiently, thus extending the control window. However, once into the region in which transesterification was present, the MWH methods appeared to promote these by-product reaction

to a greater extent than CH, again due to enhanced reactivity at the active centre.

Copolymerisation studies were undertaken to compare the ability to produce PLA-co-PCL material using both heating methods alongside analysis of the structure and properties of the final products. In the case of MWH this is the first report of investigations into such copolymerisations utilising a one-pot, one step approach. ^1H NMR, GPC and DSC analysis proved that a statistical copolymer was produced *via* both heating methods. There was only one T_g observed in the DSC trace, which the Fox Equation confirmed as being the theoretical temperature of a statistical copolymer for the feed ratios used. The effect of the heating method on the rates of reaction was analysed. Although DLLA reacted preferentially for each heating method, the $k_p \text{ PLA} / k_p \text{ PCL}$ ratio was found to be larger in MWH. In other words, the MWH encouraged the reactivity of DLLA with respect to ϵ -CL. The dielectric properties of the monomers were used to rationalise this observation. Indeed, DLLA was found to have a higher $\tan \delta$ value than ϵ -CL at the reaction temperature, thus may have been experiencing selective heating, thus increasing $k_p \text{ PLA}$ over $k_p \text{ PCL}$. Additionally, the GPC data showed that the MWH method appeared to promote transesterification in these reactions, as a higher molecular weight entity was observed in the trace and the $\bar{M}$ was broadened.

A sequential monomer addition approach was attempted (one-pot, two step) to synthesis PLA-co-PCL from a PLA homopolymer macro-initiator that had been converted to ~70 % monomer conversion, before the addition of the second monomer which was then used without purification.

When a PLA homopolymer was polymerised initially, MWH produced a mixture of two statistical PCL-co-PLA copolymers with differing copolymer ratios. This was attributed to transesterification processes being promoted by the MWH due to the presence of selective heating of the monomers and the active sites located in the initial PLA macro-initiator. GPC and DSC analysis proved that some PCL units were added into the PLA (MWH enhanced transesterification). Additionally, a shoulder at high M_w in the GPC and the lack of PCL T_m indicated that a transesterification mechanism had been present. These results were not reproduced in the CH equivalent reactions, where separate PLA and PCL homopolymers were formed and little /no evidence of transesterification was present.

Finally, a two-pot two step approach was investigated, with the initial homopolymer purified to remove any unreacted monomer that may have resulted in enhanced transesterification later in the reaction profile. For the PLA first block method, MWH encouraged the ϵ -CL to add to the PLA block which again resulted in two statistical copolymers with varying comonomer contents. This again was attributed to selective heating of the monomers and the active sites, resulting in the promotion of transesterification reaction in the MWH case, which was especially evident when a PLA macro-initiator was present. The CH case by comparison, produced two homopolymers and exhibited little/no evidence of transesterification.

Thus the overall conclusions upon the effect of heating method on the copolymerisation mechanism are the following: MWH, especially in the presence of either DLLA or a PLA macro-initiator appear to promote

transesterification process which resulted in a mixed statistical copolymer material which may prove to have interesting application opportunities if it can be made repeatedly and controllably (i.e the molecular weight and copolymer ratio can be targeted at the outset of the reaction). With the CH method, the PLA initiated copolymerisation strategies led to a chain transfer dominated system which produced largely homopolymers.

The final conclusions from this work is that it should be possible to specifically target specific reactions within a multi-component reaction mixture by careful choice of the reagents based upon their dielectric properties and physical form at the reaction temperature used. In this way, a target product may be produced due to the key reagent exhibiting a greater response to the MWH, as in the case of the copolymerisation, transesterification or PLA homopolymerisation reactions discussed above.

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5 Synthesis of Branched Poly(ϵ -Caprolactone) using Microwave Heating

The aim of the work presented in this chapter was to study the synthesis of soluble branched polymers with microwave heating (MWH). The main objectives were to use MWH to improve rates of reaction and enhance the degree of branching of the final product, compared with conventional oil bath heating (CH).

The study focussed on the ring-opening multi-branching polymerisation (ROMBP) of ϵ -caprolactone (ϵ -CL) with a di-lactone ((4,4-Bioxepanyl-7,7'-dione ; BOD) branching agent in a CEM-Discover microwave reactor. The dielectric properties of the various reagents used in the reaction were studied, with BOD dielectric values indicating a high susceptibility to microwave energy, thus efficient heating.

The synthesis of branched poly(ϵ -caprolactone) (*b*-PCL) was confirmed with GPC-RI, GPC-MALLS and DSC analysis. The composition of the polymerisation solution was analysed during the ROMBP using ^1H NMR and GC-MS, allowing for calculation of reagent consumption and relative rates of reaction. Finally, D/L-lactide (DLLA) was used as a co-monomer in the successful synthesis of *b*-PCL-*co*-PLA using BOD as the branching agent.

5.1 Introduction

Polymers are known to exist in a wide range of forms and structures. The polymer architecture controls many of the mechanical and rheological properties of the polymer.¹⁻¹² A wide range of complex, non-linear, polymers has been studied, with some examples of these provided in Figure 5.1. The architectures that have been most commonly studied are linear, star, graft, hyperbranched and dendrimeric polymers. The synthesis and applications of hyperbranched polymers will be the focus of this chapter.

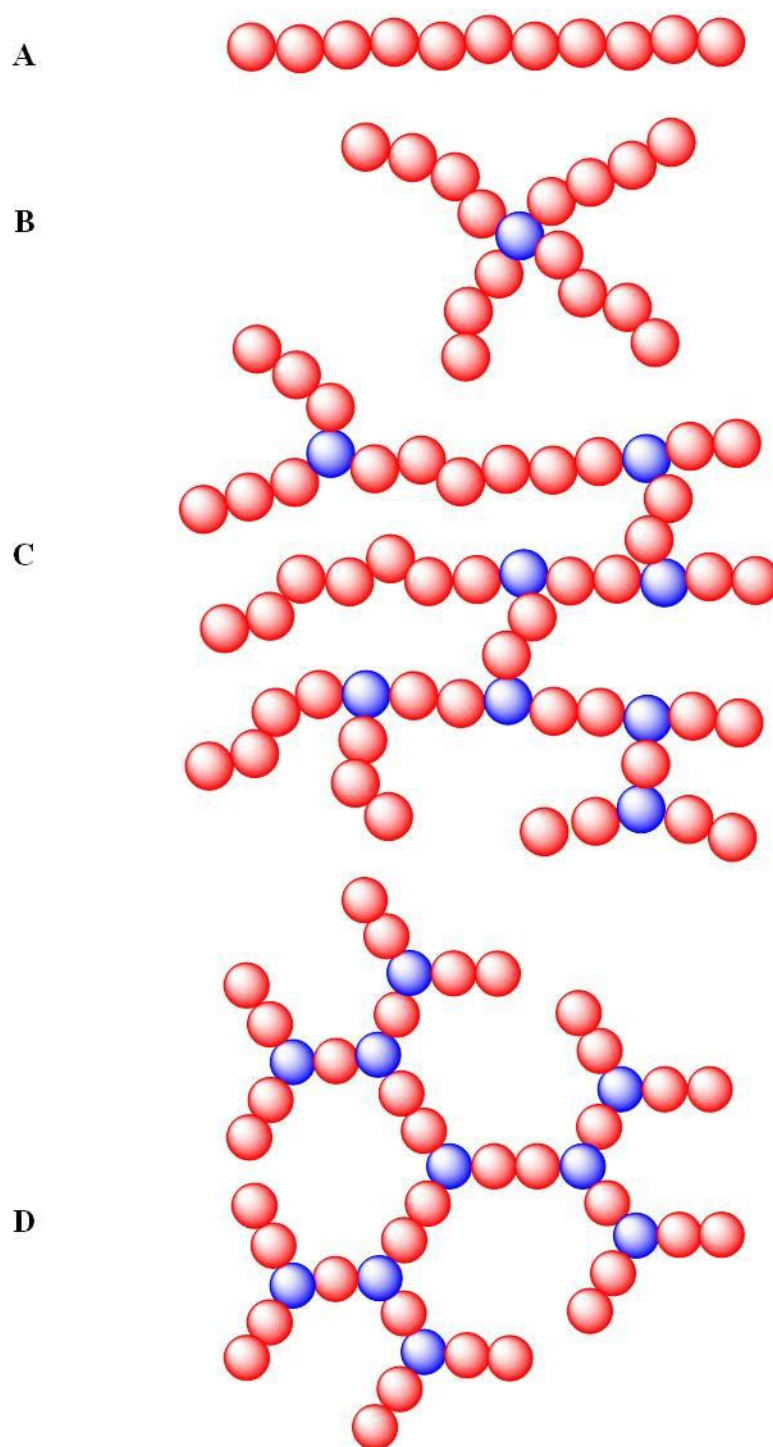


Figure 5.1: Examples of various polymer architectures. A = linear; B = star; C = hyperbranched; D = dendrimer.

Dendrimers are a class of perfectly ordered branched polymers whose advantages over linear polymers are that, along with lower viscosity, they also

contain ‘micro-environments’ in the core and a shell containing a very high concentration of functional groups.^{4, 6, 13-15} Despite their interesting properties and wide ranging applications, the major drawback to the use and scale up of dendrimeric polymers is the multi step and time consuming synthesis with demanding purification processes that is necessary for their production.¹⁵

Hyperbranched branched polymers are a cheap and quick alternative to dendrimers.^{6, 15-19} There has been a large amount of interest from industry in hyperbranched polymers due to their one-pot synthesis on a reaction timescale of a few hours, rather than weeks. However, compared with dendrimers, hyperbranched polymers have a much more random composition with less control and a lower degree of branching. Despite this, hyperbranched polymers have many potential applications for drug delivery, resins, coatings and dispersants, among others.^{6, 20, 21}

5.1.1 Synthesis of Hyperbranched Polymers

The main synthetic routes to hyperbranched polymers are step-growth polycondensation, polyaddition step-growth polymers, self-condensing vinyl polymerisations (SCVP) or ring-opening multi-branching polymerisations (ROMBP). A wide range of branched polymers has been produced from these methods, including polyamides, polyesters, polycarbonates and polyurethanes.^{15,22} Step-growth and multi-branching ring-opening polymerisation methods have been used to create branched polyesters,

including hyperbranched poly(ϵ -caprolactone) (*hb*-PCL), which is the target of the work presented in this chapter.

The step-growth polycondensation approach is a one-pot method that follows Flory's early work into hyperbranched polymers²³ using a AB_x or $AB_x + B_y$ (where $x \geq 2$ and $y \geq 3$) monomer system. Figure 5.2 is a schematic representation of an AB_2 method utilised by Frechet *et al.*¹⁵

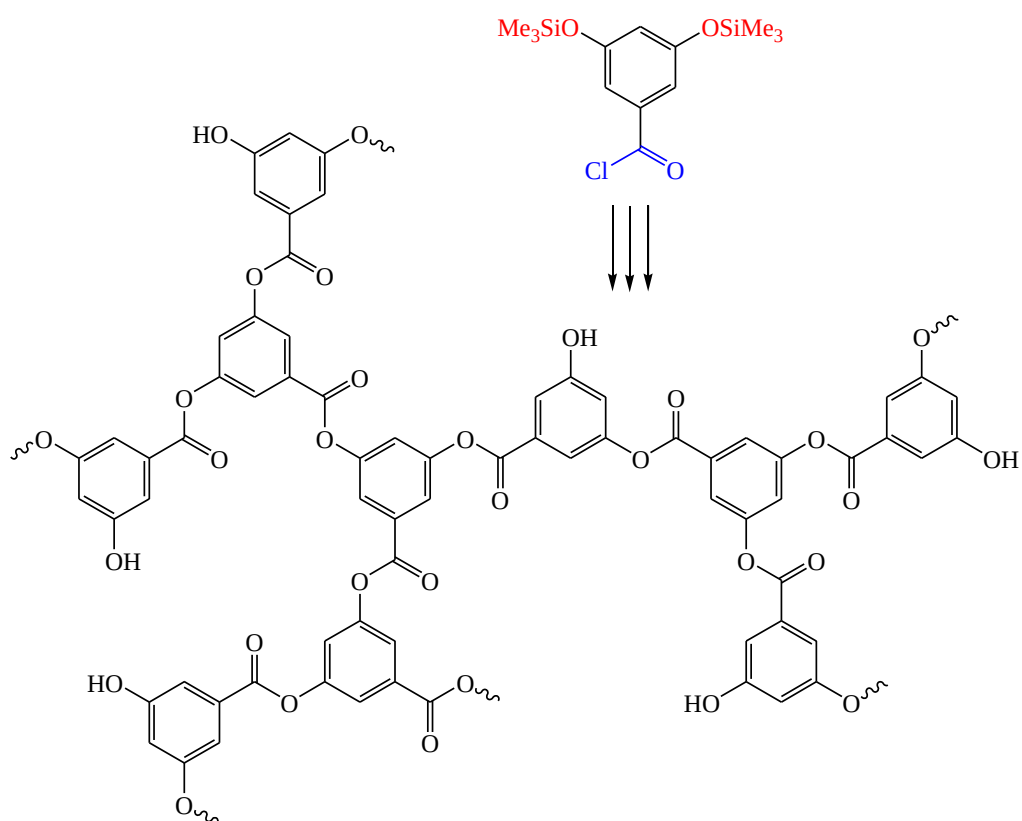


Figure 5.2; AB_2 monomer approach¹⁵ to synthesise a hyperbranched polyester using 5-bis(trimethylsiloxy)benzoyl chloride.

Step-growth polycondensation has been used to synthesise a wide range of hyperbranched polymers with varying functionalities. A requirement for this process to be successful is that the monomers have similar reactivity and no intramolecular cyclisation reactions occur. A major issue with systems that

contain greater than two functional groups is that undesired side reactions can occur in three dimensions, resulting in an insoluble gel. Gelation is an uncontrolled process that involves excessive inter-macromolecular bonds that result in a very high molecular weight (M_w) structure which is insoluble and crashes out of the system. It is formed when a branched structure bonds to another branched structure forming a large network.

Step-growth polycondensation is the most widely used method to synthesise hyperbranched polymers, but chain-growth processes have become recently well understood and increasingly employed. Self condensing vinyl polymerisation (SCVP) is a type of chain-growth reaction that is often formed by an AB^* monomer, Figure 5.3. 'A' represents the vinyl group and 'B*' is the initiating moiety, which can be a radical, cation or a carbanion.¹⁵

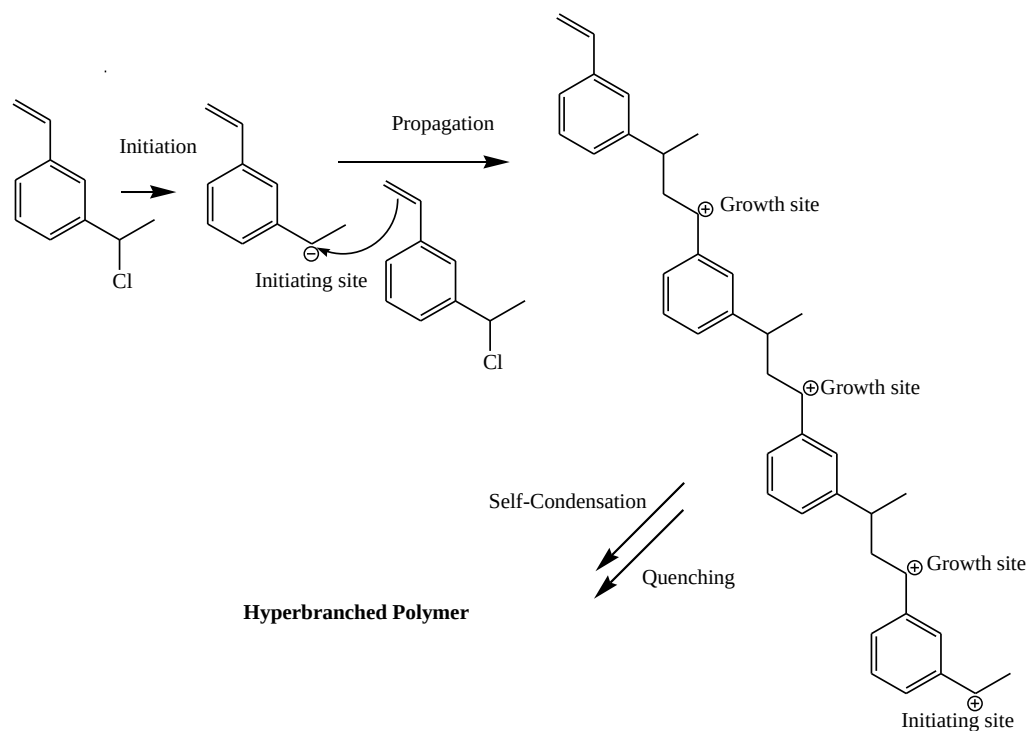


Figure 5.3: Mechanism of SCVP via an AB* monomer for the synthesis of hyperbranched polystyrene.¹⁵

The process was first developed by Frechet *et al.* who used 3-(1-chloroethyl)-ethenylbenzene as the monomer (Figure 5.3).²⁴ It contained a polymerisable vinyl moiety and a chlorobenzene initiator, which was able to initiate other monomers in the system. This process afforded hyperbranched polymers with higher yields ($\sim 80\%$) and large M_w of $240,000 \text{ g mol}^{-1}$ in 8 hours.²⁴

Ring-opening multibranching polymerisation (ROMBP) is another type of chain-growth method used to produce hyperbranched polymers. The process has been used with AB_2 and AB^* monomers, Figure 5.4.²²

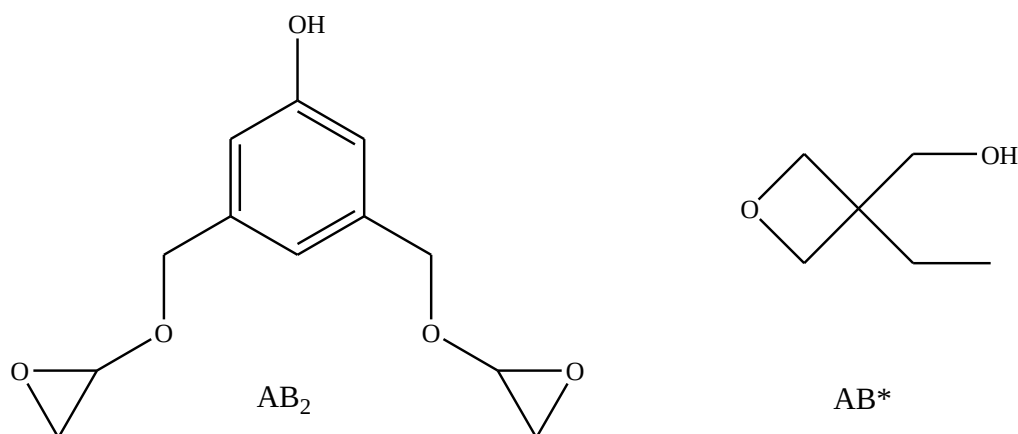


Figure 5.4: Examples of AB₂ and AB* monomers for ROMBP.²²

Frechet and Chang used an AB₂ di-epoxy phenol species (Figure 5.4) to create a hyperbranched polymer of M_w of 206,000 g mol⁻¹.²⁵ The phenol was deprotonated, forming the phenolate, which reacted with one of the epoxy rings from another molecule, forming a dimer. A proton transfer mechanism from the secondary alkoxide ensured that another phenolate was formed, which reacted with another molecule creating a hyperbranched poly(hydroxyether).

Another method of synthesising hyperbranched polymers using ROMPB is using an AB* type monomer. This is similar to the AB* SCVP, but a cyclic monomer replaced the vinyl group, and a hydroxyl is the initiator. This process was first used by Penczek *et al.* via the cationic ROP of 3-ethyl-3-(hydroxymethyl)oxetane (Figure 5.4).²⁶ The initial ROP process occurred when the oxygen in the oxetane ring was protonated and the ring was cleaved via a nucleophilic attack from another monomer. Branching occurred later through a chain-transfer mechanism, when the protonated oxygen in the oxetane ring reacted with a pendant hydroxyl unit in the polymer chain.

A relatively new route to hyperbranching uses controlled transfer reactions of latent multifunctional monomers with radical chain-growth polymerisation, Figure 5.5.^{18, 27-32}

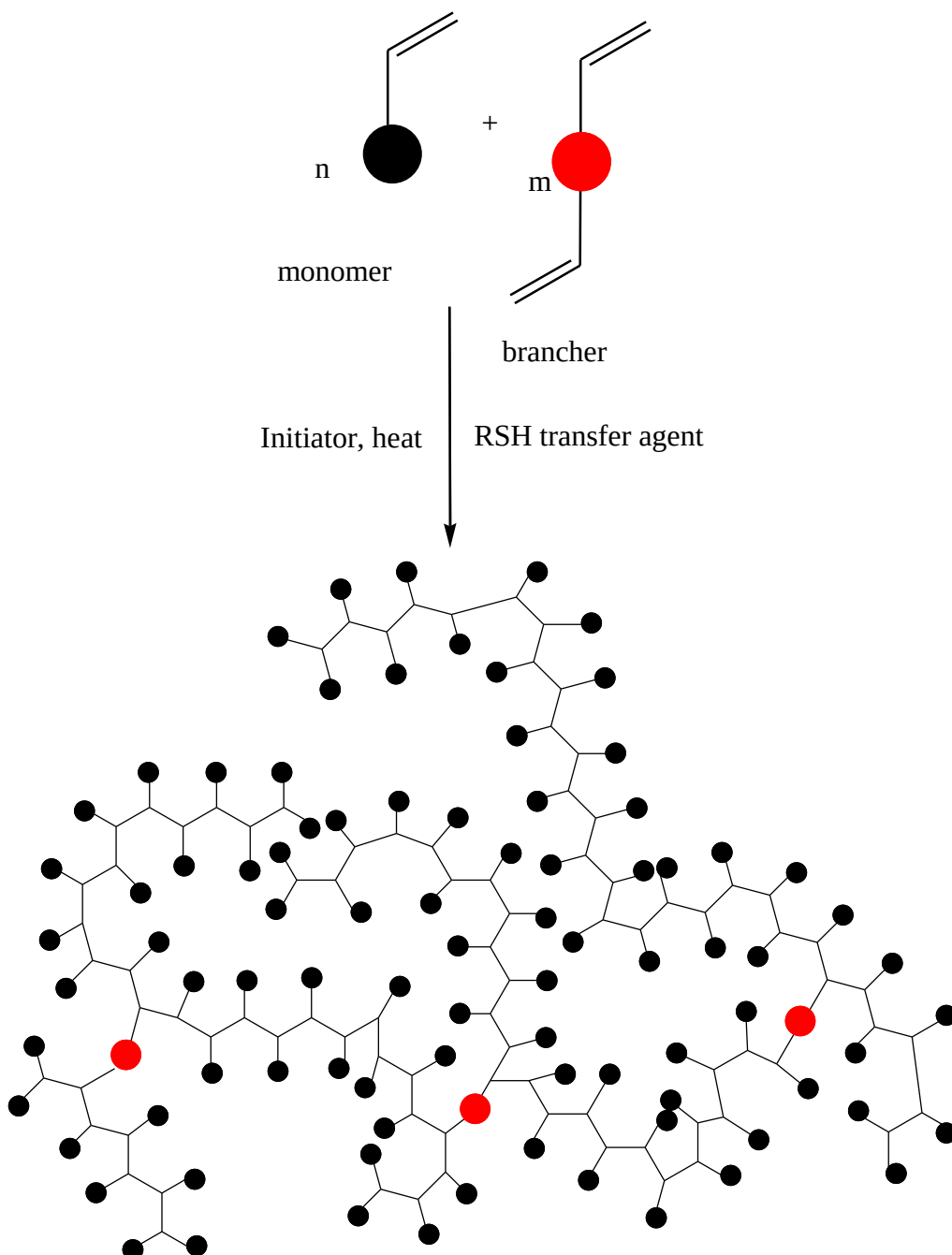


Figure 5.5: Synthesis of hyperbranched polymers through Free Radical Polymerisation with branched difunctional monomers and significant amounts of chain transfer agents.²²

Bifunctional monomers, e.g. bismethacrylates, have been used with vinyl monomers to create hyperbranched polymers in an $A + A_2$ style mechanism (Figure 5.5), in combination with large amounts of chain transfer agents to avoid gelation; this process is known as the ‘Strathclyde Method’.³⁰ ‘A’ represents the mono-functional monomer and ‘ A_2 ’ is the di-functional monomer composed of two joined ‘A’ units.

5.1.2 Hyperbranched PCL

Both polycondensation and ROMBP processes have been used to create *hb*-PCL. Hedrick *et al.*^{33, 34} used a combination of AB_2 polycondensation and ROMBP around a 2,2-bis(hydroxymethyl)propanoic acid (bis-MPA) central branching point (Figure 5.6 and Figure 5.7).

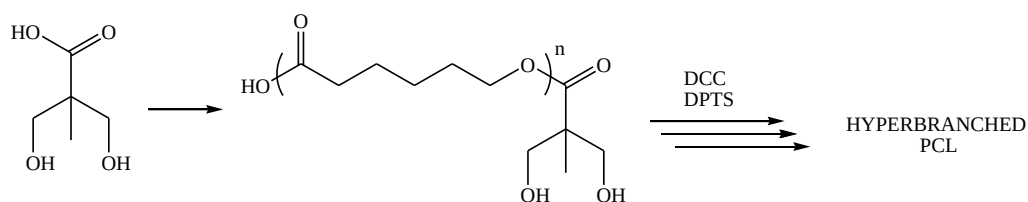


Figure 5.6: Synthesis of *hb*-PCL using AB_2 1-armed macromonomer.³³

Figure 5.6 shows the method the authors used, with a linear PCL chain and a bis-MPA end group as the macromolecular AB_2 branching agent.³³ A condensation process was used to produce the *hb*-PCL using DCC and DPTs in an esterification process. High yields (80 %), large M_w (25,000 – 20,100 g mol⁻¹) and wide $\bar{D}$ (1.89 – 2.72) were recorded.³³

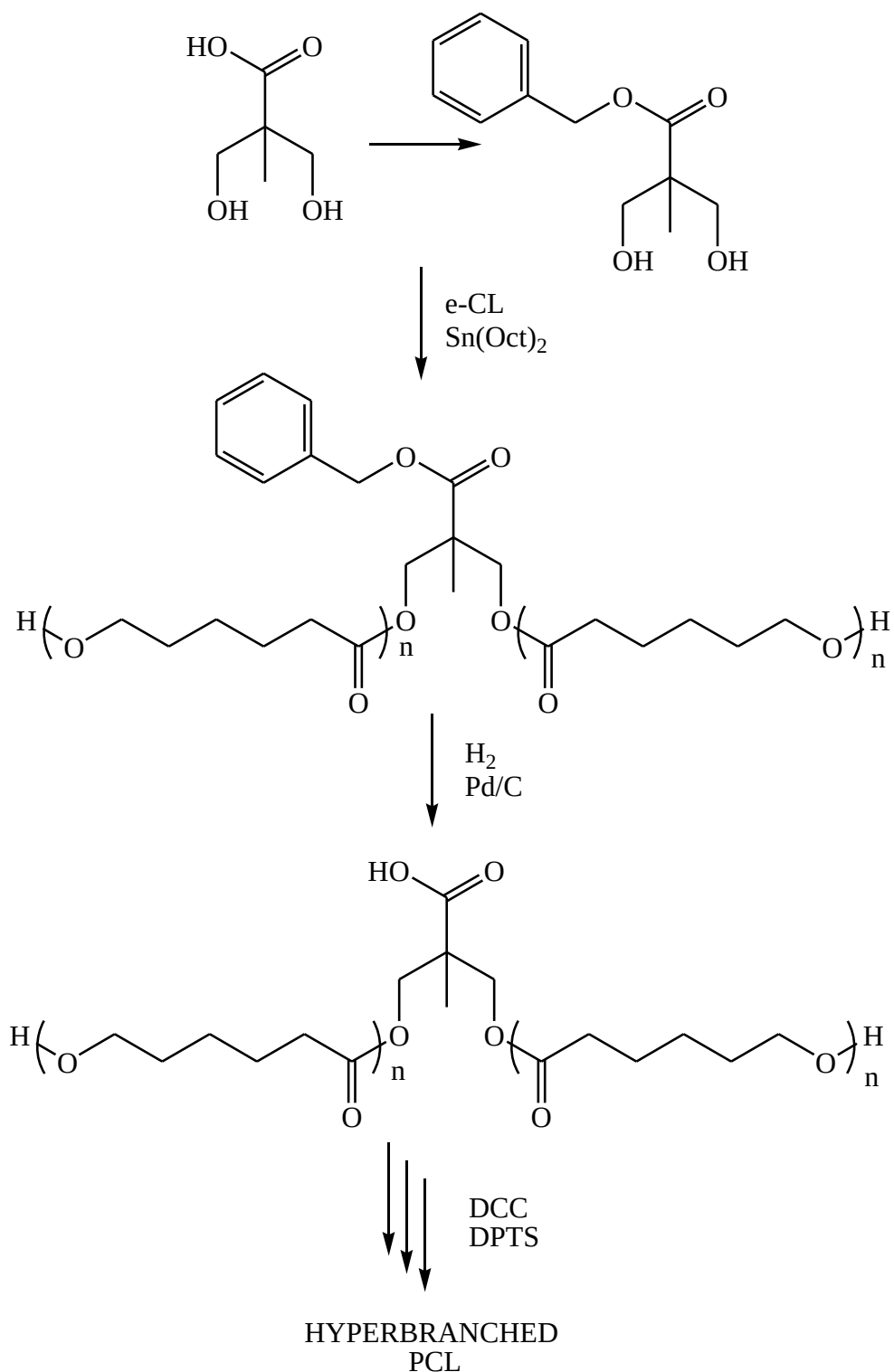


Figure 5.7: Synthesis of *hb*-PCL using AB₂ 2-armed macromonomer.³⁴

Figure 5.7 provides an alternative method of producing *hb*-PCL, but with an initial two-armed PCL AB₂ macroinitiator.³⁴ The carboxylic acid on the

bis-MPA was protected with a benzyl ester, whilst the two hydroxyl groups hosted the growth of linear PCL. The benzyl ester was then removed by catalytic hydrogenation affording a novel AB₂ macromonomer capable of self-polymerisation producing *hb*-PCL at high yields of up to 90 %, 60,000 to 140,000 g mol⁻¹ M_w with Đ values between 1.31 and 2.18.³⁴ ROMBP was used by Frechet *et al.* to synthesis *hb*-PCL using 4-(2-hydroxyethyl)- ϵ -caprolactone as the monomer (Figure 5.8).³⁵

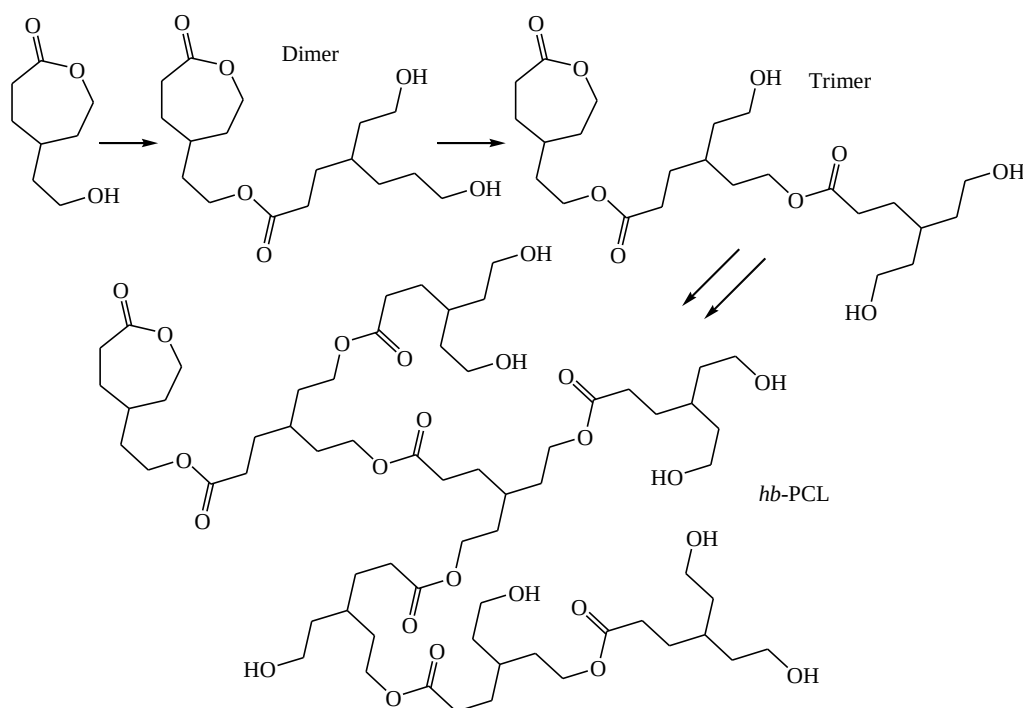


Figure 5.8: *hb*-PCL formed using an AB monomer with ROMBP.³⁵

The monomer is composed of a ϵ -CL unit that could undergo ROP and a primary alcohol that is known to initiate ROP with the Sn(Oct)₂ catalyst at 110 °C. The ‘true’ branching agent is formed when two monomers react together, forming an AB₂ type dimer (Figure 5.8). It is composed of one ϵ -CL

ring (A) and two primary alcohol groups (B_2). Large *hb*-PCL was produced in a one-pot system with 65,000 – 85,000 g mol⁻¹ M_w and $\bar{D}$ values up to 3.2.

Hedrick *et al.* combined the Frechet concept of a modified ϵ -CL monomer with Hedrick's earlier work with bis-MPA derivatives to create *hb*-PCL via a self-condensing ROMBP.³⁶

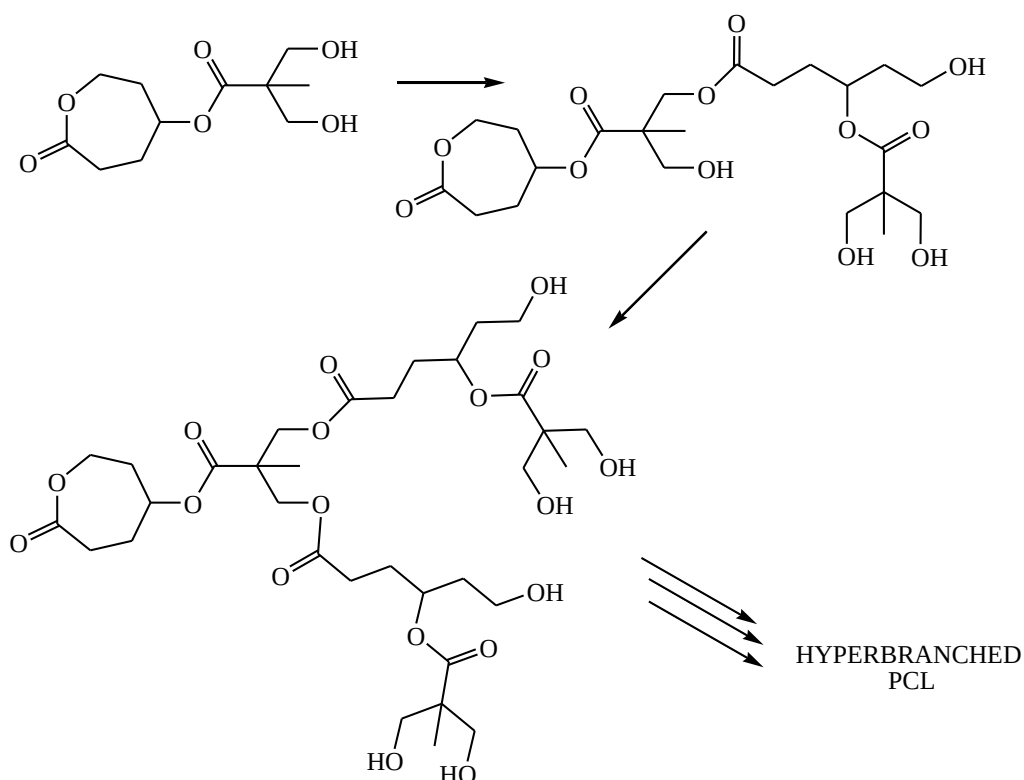


Figure 5.9: ROMBP with bis(MPA) substituted ϵ -CL monomer to create *hb*-PCL.³⁶

The AB_2 type monomer was a ϵ -CL ring (A) bonded to a bis(hydroxymethyl) moiety (B_2) derived from bis-MPA. The self-polymerisation ROMBP was conducted with and without ϵ -CL as the comonomer at 110 °C with $Sn(Oct)_2$ as the catalyst. A step-growth process dominated early in the reaction, with dimers and trimers preferentially formed. Linear ROP was noted to occur later,

producing *hb*-PCL with wide $\bar{D}$ values between 2.30 to 2.81 and M_w of between 3,000 and 8,000 g mol⁻¹.

Recently, work has been carried out synthesising *b*-PCL using the ‘A + A₂’ method, similar to the process for methacrylates and bismethacrylates described in the previous section, also known as the ‘Strathclyde Methodology’. The use of ϵ -CL as A, and the di-functional ϵ -CL moiety, (4,4-Bioxepanyl-7,7'-dione ; BOD; Figure 5.10) as A₂ was another method that was recently been shown to create branched PCL.

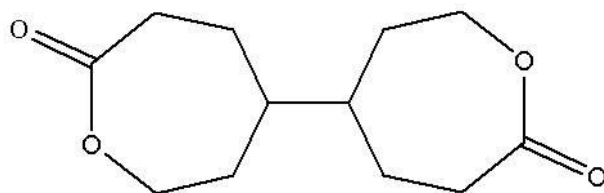


Figure 5.10: Molecular Structure of di- ϵ -CL monomeric species (4,4-Bioxepanyl-7,7'-dione; BOD).

Unlike the ‘Strathclyde Method’, the use of BOD does not require chain-transfer agents. However, the two processes are similar with the prerequisite that gelation can be avoided if there is no more than one branching point (BOD) per primary chain. The mechanism for BOD incorporation is shown in Figure 5.11.

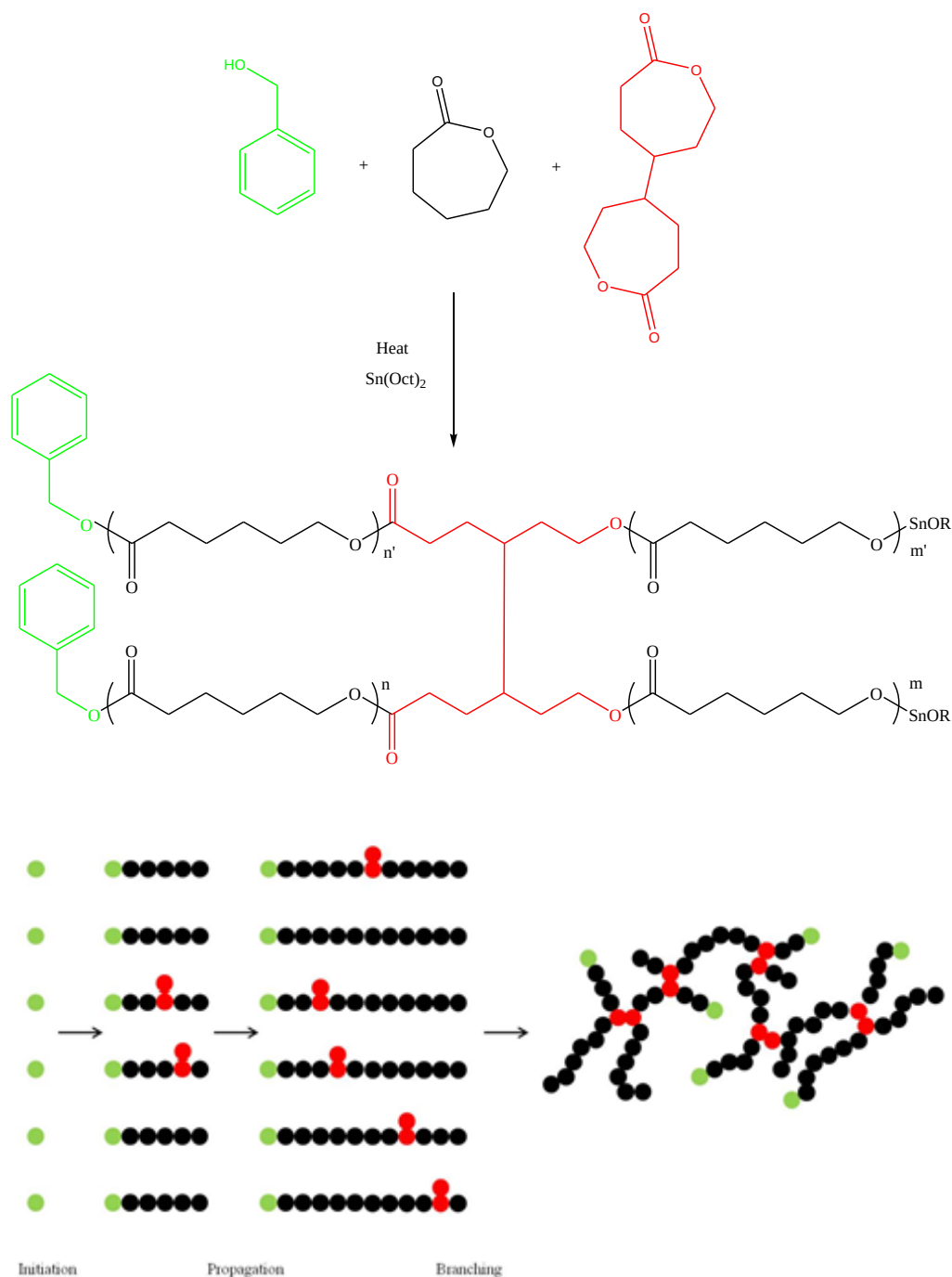


Figure 5.11: Schematic formation of *b*-PCL using ROMBP with ϵ -CL monomer and di-functional ϵ -CL (BOD) as branching agent.

Due to the similar reactivity of BOD and ϵ -CL, the BOD units are incorporated into the growing PCL linear chains (Figure 5.11). It has been shown that the latent branching only occurs late in the reaction,³⁷ i.e. when most of the ϵ -CL

has been depleted (> 90 %) and the pendent BOD rings react forming a branched macromolecule, which is consistent with the Strathclyde Method experiments using methacrylates and bis(methacrylates)s.²⁸

Previous works by Qiao *et al.*³⁸⁻⁴² and Thurecht *et al.*⁴³ have only used BOD with ϵ -CL to create core cross-linked star (CCS) polymers. These structures were synthesised with a core containing PCL and BOD cross-linked scaffold, with various functionalised outer shells: CCS polymer with methacrylates *via* RAFT⁴³ and *via* ATRP^{38, 42}, and fluorescent saccharide CCS polymers *via* ‘click’ chemistry^{40, 41}. These microparticles all contained a highly dense and cross-linked core of PCL and BOD.

However, recent work by the Irvine Research Group³⁷ has been the first to study the use of BOD and ϵ -CL to synthesise branched structures, instead of cross-linked cores. It was found that the formation *b*-PCL was possible using the A + A₂ (ϵ -CL + BOD) system; as long as the Strathclyde Methodology was maintained (i.e. less than one branching point per primary chain). Soluble *b*-PCL was synthesised using a Sn(Oct)₂ pre-catalyst with high yield (99 %) and large M_w of over 140,000 g mol⁻¹ with a Đ of 6.0 in a 60 minute reaction.

The work contained in this chapter will continue the research by Nguyen³⁷ and will study the effect of MWH on the synthesis of *b*-PCL using the Strathclyde Method with mono and di-functional ϵ -CL moieties. The dielectric properties of the various reaction components will be a potential route to establishing if the heating method will alter the rates of reaction and the structure of the final branched product.

5.1.3 Branching using Microwave Heating

Recent literature has described the synthesis of branched polyesters using MWH. Zhang *et al.* used MWH to create star-shaped PCL-*co*-poly(L-lactide) using a 6-armed initiator, dipentaerythritol.⁵⁰ The process was achieved at high monomer conversion (> 80 %) producing 20,000 – 60,000 g mol⁻¹ crystalline copolymers. Nguyen³⁷ used MWH to create 3 and 4-armed star PCL from trimethylolpropane and pentaerythritol as initiators, respectively. Zhang and Nguyen came to similar conclusions regarding the effect of MWH: they both observed faster rates of reaction in MWH, but the structure and properties of their respective final products were not significantly affected by the heating method.

The work presented in this thesis examines in great detail the exact effect of MWH on the various stages on the synthesis of *b*-PCL, with observations rationalised using a thorough understanding of the dielectric properties of the reagents and polymeric structures.

5.1.4 Branched PCL-*co*-PLA

The introduction to Chapter 4 in this thesis provided many examples and applications for PCL-*co*-PLA as resorbable polymers for biomedical applications.^{44, 45} The biocompatibility and biodegradability of PCL-*co*-PLA, along with their tuneable mechanical properties, have created a large amount of

research and interest, both academic and industrial into the PCL-*co*-PLA linear copolymer.^{46, 47} Another method of adapting the PCL-*co*-PLA copolymer has been the introduction of branching and crosslinking in order to alter the product's properties, including its strength, elasticity, degradation rate and ability to swell.^{7, 8, 48-50}

One method of synthesising cross-linked PCL-*co*-PLA is by using a multi-armed initiator, before cross-linking the arms. Helminen *et al.*⁴⁸ used this method to create cross-linked PCL-*co*-PLA with elastic properties. They grew PCL-*co*-PLA off a four-armed initiator, pentaerythriol. Methacrylic anhydride was added to the end of the copolymeric arms, which were cross-linked to form the elastic branched copolymers of between 20,000 and 50,000 g mol⁻¹.⁴⁸ Amsden *et al.*⁷ synthesised photo-cross-linked acrylate functionalised star PCL-*co*-PLA elastomers *via* the same method as Helminen, but they studied the rate of copolymer degradation through *in vivo* studies in rats. They found that the branching density affected the degradation mechanism. In low M_w polymers with high branching density, the product degraded by surface erosion. However, copolymers with a low branching density underwent bulk erosion.⁷ Muroya *et al.* studied the effect of varying the DLLA and ϵ -CL ratio on the cross-linked PCL-*co*-PLA using pentaerythriol as the initiator.⁴⁹ They found that branched PCL-*co*-PLA with 80/20 ϵ -CL/DLLA monomer ratio produced the highest level of linear degradation as the crystallinity was disrupted by the branching.

The previous work has primarily been focused on the synthesis and applications of star-shaped cross-linked PCL-*co*-PLA. The work presented in

this chapter presents for the first time the attempt to synthesise branched PCL-co-PLA using a di-lactone based moiety, BOD using MWH.

5.2 Experimental

5.2.1 Materials

ϵ -Caprolactone (99 %) was purchased from Acros Organics and used without further purification. D/L-Lactide (98 %+) was purchased from Alfa Aesar and was dried under reduced pressure for 24 hours prior to use. Anhydrous benzyl alcohol (99 %) and tin 2-ethyl hexanoate (99 %) were purchased from Sigma Aldrich. 4,4'-Bis(cyclohexanone) was purchased from Tokyo Chemical Company.

5.2.2 4,4-Bioxepanyl-7,7'-dione (BOD) synthesis

Urea hydrogen peroxide (20g, 0.21 mol) was dissolved in formic acid (100mL) in a 250 mL round-bottomed flask at room temperature for 90 minutes whilst stirring. 4,4'-Bis(cyclohexanone) (10g, 0.05 mol) was added to the solution slowly over 20 minutes due to the exothermic nature of the addition. After stirring for 240 minutes, the solution was washed with water (200ml) and extracted with chloroform (4 x 200 mL). The collected portion was dried overnight with sodium sulfate. After filtration to remove the sodium sulphate,

the solvent was removed by rotary evaporation and the crude product was purified by dissolving in warm ethyl acetate before filtering to remove the impurities dissolved in the filtrate, to give a white powder (7.0 g, 60 % yield). ^1H NMR (300 MHz, CDCl_3), δ (ppm): 4.34 (R, R) 4.17 (S, S) (t, 2H, $-\text{CH}_2-\text{OOC}-$), 2.73 (R, R) 2.60 (S, R) (t, 2H, $-\text{CH}_2\text{COO}-$), 1.93 – 1.83 (m, 2H, $-\text{CH}_2\text{CH}_2\text{OOC}-$), 1.70 – 1.60 (m, 2H, $-\text{CH}_2\text{CH}_2\text{COO}-$), 1.49, (q, 1H, $-\text{CHCH}_2-$).

5.2.3 *b*-PCL synthesis

For the target DP 87 reactions, ϵ -CL (6.25 g, 54.8 mmol) was placed into a 50 mL glass test tube with BOD crosslinking agent (0.143 g, 0.630 mmol), benzyl alcohol initiator (65 μL , 0.63 mmol) and $\text{Sn}(\text{Oct})_2$ catalyst (5.1 mg, 0.0126 mmol). A rubber septum was used to seal the reaction vessel, which was either submerged into an oil bath set to the required temperature, or placed into the CEM-Discover cavity. Samples of 20 – 30 mg were taken at regular intervals for monitoring *via* ^1H -NMR and GPC. When the reaction had finished, it was quenched with liquid N_2 and dissolved in ~ 50 mL of dichloromethane. Purification was achieved by drop wise addition of the polymer solution into ~ 500 mL cold methanol. The precipitate was filtered and dried *in vacuo* for 24 hours. The molecular weight and dispersity of the final polymer was analysed with GPC and the thermal properties monitored by DSC.

5.2.4 Dielectric Property Measurement

The method used for calculating the dielectric properties of BOD was the cavity perturbation technique. A small amount of sample (~50 mg) was introduced into a cavity and the changes to the properties of the cavity were measured. The dielectric property of the sample was measured initially at room temperature before being moved automatically into the furnace, where the sample was heated conventionally at the required temperature for 10 minutes. The sample was then returned to the cavity for measurement. This process was repeated for all the required temperatures within the target range of 20 °C – 180 °C at 2.45 GHz.

5.3 Results and Discussion

This chapter examines the influence that MWH has upon the synthesis of *b*-PCL when using a di- ϵ -CL monomeric species (4,4-Bioxepanyl-7,7'-dione; BOD; Figure 5.12) as the branching agent.

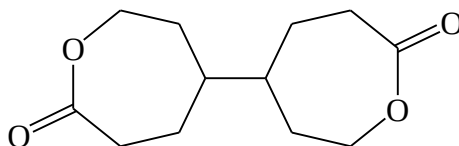


Figure 5.12: Molecular Structure of di- ϵ -CL monomeric species (4,4-Bioxepanyl-7,7'-dione; BOD).

Consequently, the dielectric properties of BOD were analysed and compared with the other reagents required for the ROMBP of ϵ -CL. The initial section of

this study investigated the effect of MWH upon the onset and rate of BOD addition and contrasted the results against those obtained from the CH equivalent reactions. This was because it had been proposed from the work presented in Chapters 3 and 4 that MWH may promote transesterification reactions in the $\text{Sn}(\text{Oct})_2$ catalysed system. Thus, it was also proposed that MWH may also promote an additional level of branching obtained when a di-functional monomer is included. ^1H NMR and GC-MS analysis was then utilised to examine the effect of temperature on the reactivity of BOD compared with the other reaction reagents. Finally DLLA was introduced at varying levels in an attempt to synthesise *b*-PCL-*co*-PLA using BOD for the first time.

5.3.1 BOD Dielectric Properties

The dielectric properties of the branching agent/di-functional monomer, BOD, were analysed to determine if it would be susceptible to MWH. More importantly, the dielectric properties of BOD were then compared with the other reagents used in the synthesis of *b*-PCL to propose the level of influence it may have over the heating of the system as a whole and establish any indications of selective heating. The dielectric properties of ϵ -CL, DLLA,, BnOH and $\text{Sn}(\text{Oct})_2$ had been previously examined and presented in Section 4.3.1. However in order to review these alongside BOD in this part of the study, the variation in the $\tan \delta$ value of all the components with temperature is presented in Figure 5.13.

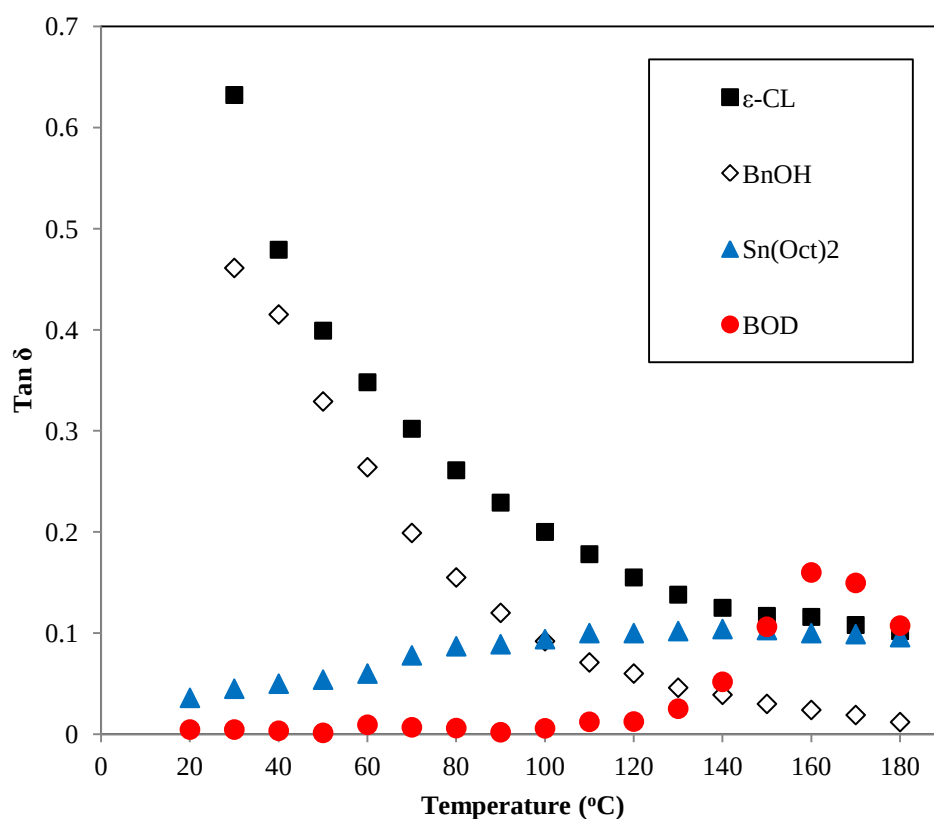


Figure 5.13 Dielectric properties ($\tan \delta$) of ϵ -C (■) BnOH (◇) Sn(Oct)₂ (▲) and BOD (●) against temperature (°C). Determined using cavity perturbation technique with a furnace as an external heating source with temperature range = 20 – 180 °C. Sample volume 0.3 mL; 0.2 mg.

As discussed in Section 3.3.1, the $\tan \delta$ values of ϵ -CL and BnOH were highest at room temperature, but decreased as temperature increases. At high temperatures, where the ROP of PCL is conducted (~ 150 °C), the ϵ -CL and Sn(Oct)₂ had the highest $\tan \delta$ value and thus would be predicted to contribute a significant amount to the heating of the reaction mixture *via* selective volumetric heating.

The BOD dielectrics presented in Figure 5.13 suggest that BOD would be susceptible to MWH at the high temperatures reached during the ROP process. At low temperatures the BOD $\tan \delta$ value is negligible, thus will not be heated

dielectrically. This is due to the physical nature of the BOD species. It has a melting point at 120 - 125 °C, therefore below this temperature the dipoles are restricted in their ability to orientate to the oscillating electromagnetic field and there is a lack of friction between the molecules because it is in solid physical form. Consequently, above 125 °C when it is in its liquid physical form, it exhibits elevated $\tan \delta$ values. At 160 °C, BOD had a $\tan \delta$ value of 0.16, higher than the ϵ -CL and $\text{Sn}(\text{Oct})_2$ (0.11 and 0.10 respectively). Therefore, the BOD units were predicted to experience selective MWH heating when at the elevated reaction temperatures used in the ROMBP process (approximately 150 °C). However, it should be noted that the BOD in the bulk ROPMB mixture would not have been in its solid form as the temperature exceeds 100 °C as the BOD dissolves into the liquid ϵ -CL. It is possible that the dissolved BOD may have higher $\tan \delta$ value than solid BOD at temperatures between 100 – 140 °C, however it is still postulated that the ϵ -CL dielectric properties would still be the dominant factor in the bulk heating. Unfortunately it is not possible to identify individual component's dielectric property values in a mixture.

5.3.2 *b*-PCL Studies: Target Degree of Polymerisation = 87

Having gained in-depth measurements of the dielectric properties of BOD, MWH was utilised in an attempt to create *b*-PCL. This is the first time MWH has been used to create *b*-PCL via the use of such a di- ϵ -CL branching agent. As in all cases in the study, the MWH reactions were then compared and contrasted with the CH equivalents. The target DP was 87,

which was chosen in order to be consistent with the previous chapters in this thesis, where linear polymers were formed. The results of BOD addition at various stages of ϵ -CL conversion are presented in Table 5.1.

Table 5.1: ^1H NMR and GPC data from *b*-PCL Studies: Target Degree of Polymerisation = 87

Entry	Heating method	ϵ -CL conv (%) ^a at BOD addition	Final PCL conv (%) ^a	$M_{n \text{ theo}}$ (g mol ⁻¹) ^c	$M_{n \text{ obs}}$ (g mol ⁻¹) ^b	$M_{w \text{ obs}}$ (g mol ⁻¹) ^b	$\bar{D}$ ^b	Reaction time (min)
1	MWH	0	98	9,700	6,780	35,100	5.18	360
2	CH	0	98	9,700	7,030	34,100	4.85	420
3	MWH	70	98	9,700	10,410	56,050	5.38	380
4	CH	68	98	9,700	8,400	29,900	3.55	360
5	MWH	100	98	9,700	10,400	19,900	1.71	300
6	CH	100	98	9,700	11,700	18,600	1.58	420

^a Determined using ^1H NMR. ^b Determined using GPC-RI ($500 < M_n < 2,000,000 \text{ g mol}^{-1}$, calibrated with PS standards). ^c Theoretical M_n based on linear equivalent at identical monomer conversion.

The reagent ratio was $[\epsilon\text{-CL}]_{87} : [\text{BnOH}]_1 : [\text{SnOct}_2]_{0.02} : [\text{BOD}]_{0.6}$. The ratio of 0.6 BOD units per polymer chain was chosen to avoid gelation. This key criterion for avoiding gelation had been defined from earlier work conducted in the group at the University of Nottingham.³⁷

5.3.2.1 BOD Addition at 0 % ϵ -CL Conversion

In this reaction strategy, all reagents (monomer, branching agent, catalyst and initiator) were present in the reaction medium at the start of the reaction. Figure 5.14 and Figure 5.15 provide a comparison of the kinetic plots for conversion

of ϵ -CL and BOD when 0.6 molar equivalents of BOD as a co-monomer were included at the start of the reaction heated with MWH. The plot of L_n ($[M_0]/[M]$) against reaction time is provided in Figure 5.14 and Figure 5.15 presents the growth of M_n plotted against conversion of ϵ -CL monomer.

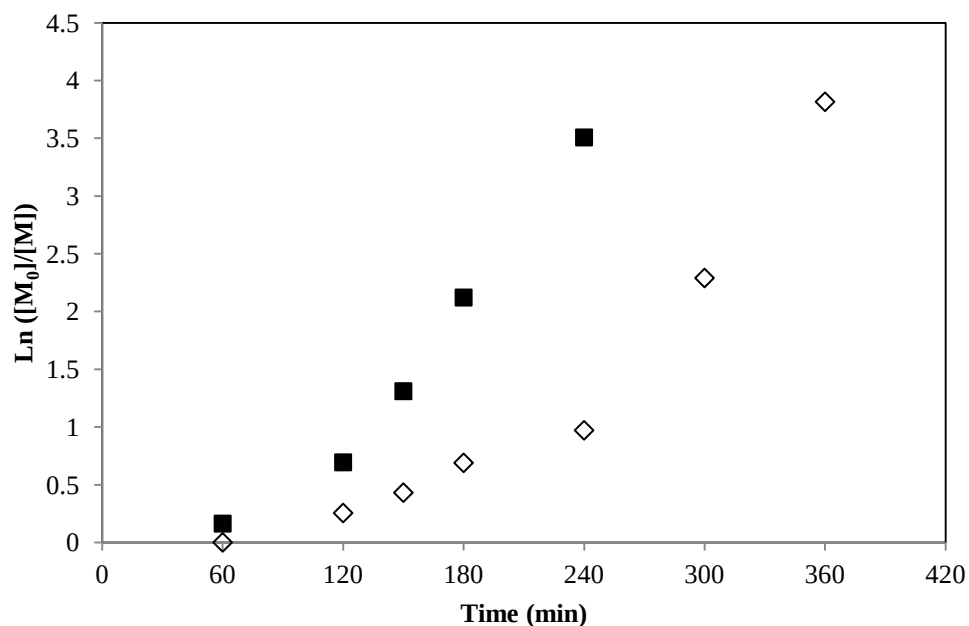


Figure 5.14 Kinetic plots of $L_n ([M_0]/[M])$ versus reaction time for ϵ -CL (■) and BOD (◇) for the synthesis of *b*-PCL with MWH at 160 °C.

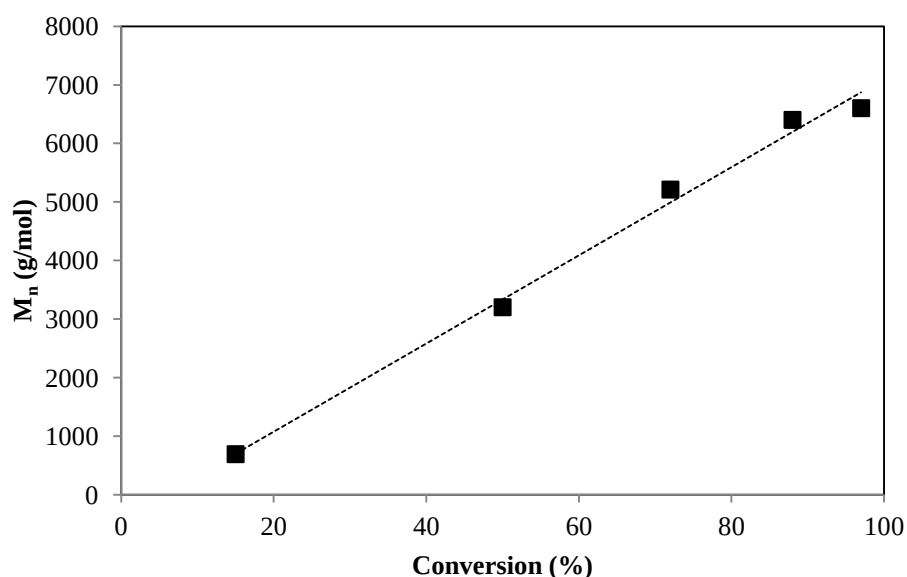


Figure 5.15: Dependence of molar mass (M_n) on monomer conversion (the dashed line represents the theoretical variation of M_n with conversion) for the synthesis of *b*-PCL with MWH at 160 °C.

The linear nature of both the plots of L_n ($[M_0]/[M]$) against reaction time (Figure 5.14) and the linear growth of M_n against conversion (Figure 5.15) indicate that the presence of BOD does not disrupt the controlled nature of the ROP during the early stages of the reaction (i.e. up to 90 % ϵ -CL conversion). However the rate of propagation (k_p) for ϵ -CL was much depressed with the addition of BOD when compared to PCL on its own. The k_p in this reaction was 0.0191 min^{-1} which was less than half the k_p observed for the equivalent homo-PCL reaction (0.0402 min^{-1} in Section 3.3.3). It was noted that BOD appears to have an increased induction/initiation lag period compared with ϵ -CL. The variation of molecular weight and $\bar{D}$ throughout the reaction is listed in Table 5.2.

Table 5.2: Following the evolution of monomer conversion and molecular weight against reaction time for ϵ -CL and BOD for the synthesis of *b*-PCL using MWH at 160 °C with monomer ratio [ϵ -CL] : [BOD] = [87]: [0.6]

Time (min)	Monomer Conversion (%) ^a		Molecular Weight Analysis (g mol ⁻¹)			
	ϵ -CL	BOD	M_n Theo	M_n Obs ^b	M_w Obs ^b	$\bar{D}$ ^b
60	15	0	1,500	690	1,020	1.48
120	50	22	5,000	3,200	4,400	1.38
150	72	35	7,100	5,210	8,300	1.85
180	88	50	8,700	6,400	13,400	2.11
240	97	62	9,600	6,600	21,500	3.25
300	98	90	9,700	6,240	28,000	4.49
360	98	98	9,700	6,780	35,100	5.18

^a Determined using ¹H NMR. ^b Determined using GPC-RI (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^a Theoretical M_n based on linear equivalent at identical monomer conversion.

After 2 hours of reaction (Table 5.2) it was observed that half of the monomer had undergone ROP. The ¹H NMR analysis indicated that 22 % of the BOD has been consumed at this point. Additionally, the $\bar{D}$ of 1.38 indicated a controlled growth of PCL. Therefore, whilst BOD was being incorporated into the polymer, the material was still essentially linear in its architecture, with little evidence for branching.

Therefore, when BOD units react with the active centres, the ring-opened BOD will now be situated on the end of the growing chain. This will result in enhanced steric hindrance that the extra pendent ring brings, potentially slowing the rate of further PCL propagation. However, whilst the reduced k^{app} led to a longer reaction time, it provided further empirical evidence that the BOD units were being incorporated into the growing PCL chains throughout the reaction. However, there was evidence from the GPC trace that a small

degree of branching occurred at 50 % ϵ -CL conversion (Figure 5.16) because the PCL peak was noted to be slightly asymmetric.

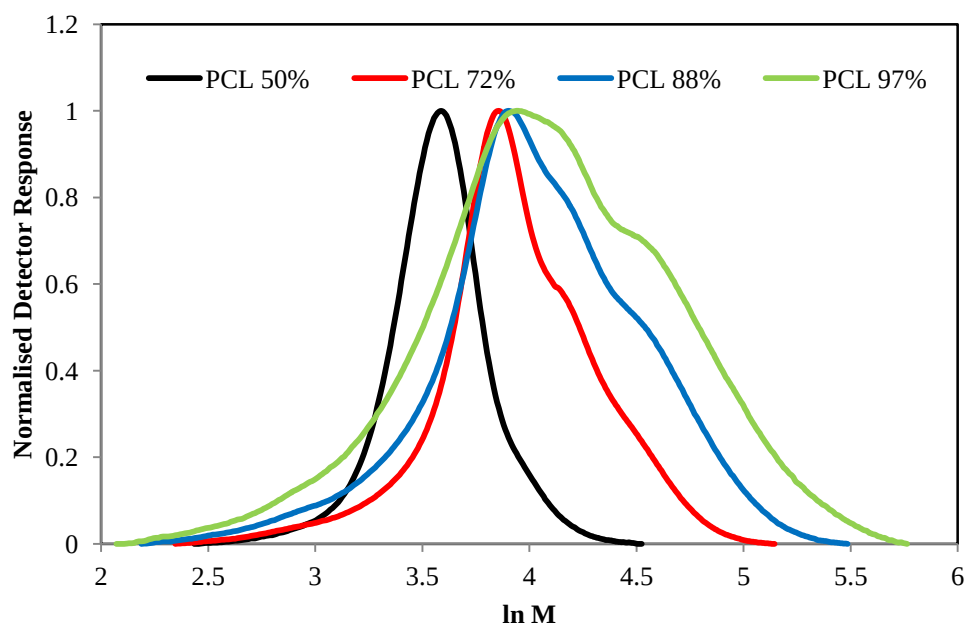


Figure 5.16 GPC trace overlay of samples taken during the ROP reaction forming *b*-PCL using MWH at 160 °C with the ϵ -CL conversion at each sample listed.

Meanwhile, the formation of *b*-PCL was clearly evident at 72 % ϵ -CL conversion, when approximately 35 % of BOD has been consumed (estimated from ^1H NMR analysis). This is indicated by a significant shoulder evident at high molecular weight in the GPC trace and the fact that the $\bar{D}$ has increased to above 1.85. The M_w after 72 % ϵ -CL conversion was much larger than the 50 % sample ($8,300 \text{ g mol}^{-1}$ compared with $4,400 \text{ g mol}^{-1}$) despite the M_n only increasing from 3,200 to $5,210 \text{ g mol}^{-1}$. This increase in M_w was also noted to be much greater than that of the linear PCL equivalent, indicative of branching rather than simply transesterification reactions.

When transesterification reactions dominate at high monomer conversion, the narrow peak in the GPC tends to broaden in a more symmetric fashion. As intermolecular reactions occur, larger chains are formed at the same rate as smaller chains, as the active centre reacts with the backbone of a second, separate chain. Therefore the net outcome of these trans-esterification processes is the generation of both larger and smaller chain lengths. It is clear from the very different GPC profiles of the polymer products from reactions which have incorporated BOD that a very different mechanism leads to a broadening of $\bar{D}$ in these cases. This supports the conclusion that this is due, at least in part, to the occurrence of branching within the structure in the presence of BOD. In these cases, this was due to an active centre on a PCL chain reacting with a pendent BOD ring located on a separate polymer chain and growth away from this pendant BOD ring *via* the tin centred coordination:insertion mechanism. Thus, there is little/no formation of low molecular weight chains; rather the broadening is focussed upon the growth of three-dimensional branched structure of high M_w . Consequently, multi-modal shoulders at high M_w were present without any evidence of low molecular weight chains being formed. The M_w was 21,500 g mol⁻¹, which was considerably larger than M_n , 6,600 g mol⁻¹ with BOD conversion was almost 90 % and a $\bar{D}$ value of 3.25. The reaction was continued for another hour until full BOD conversion was achieved. The M_w was observed to have increased to 35,100 g mol⁻¹, however M_n decreased to 6,780 g mol⁻¹. It can be deduced that branching reactions are now occurring alongside transesterification. Therefore smaller chains were formed, indicated by the drop in M_n .

GPC-MALLS analysis was used to gain further evidence of the formation of *b*-PCL using MWH. GPC-MALLS data provides a more accurate description of non-linear polymers than GPC-RI, a comparison of the results on the final products from the two detectors is provided in Table 5.3.

Table 5.3: Comparison of GPC-RI and GPC-MALLS data of the *b*-PCL formed in MWH with BOD addition at 0 % ϵ -CL conversion (Entry 1, Table 5.1).

	$M_{n\text{THEO}}$ (g mol ⁻¹)	M_n (g mol ⁻¹)	M_w (g mol ⁻¹)	$\bar{D}$	R_g (nm)	R_g/M_w slope
GPC-RI ^a	9,700	6,780	35,100	5.18	n/a	n/a
GPC-MALLS	9,700	8,300	36,700	4.95	13.9	0.30

^a Determined using GPC-RI ($500 < M_n < 2,000,000$ g mol⁻¹, calibrated with PS standards).

The GPC-MALLS data supports the conclusions drawn from the GPC-RI detector. The large M_w value of 36,700 g mol⁻¹ is significantly larger than the theoretical value for a linear equivalent (9,700 g mol⁻¹) at the same monomer conversion. Indeed, a large $\bar{D}$ value of 4.95 confirms a non-linear branched architecture. As expected, the M_w value was larger in GPC-MALLS than the GPC-RI equivalent, whilst the $\bar{D}$ was smaller. This was because the GPC-MALLS typically has increased sensitivity towards higher molecular weight region of the chromatogram.

The GPC-MALLS analysis was also able to provide a value for the radius of gyration (R_g) for each polymer fraction. The true size and shape of the polymer was calculated as it passed through the detector and the data showing the variation of R_g against elution volume is provided in Figure 5.17.

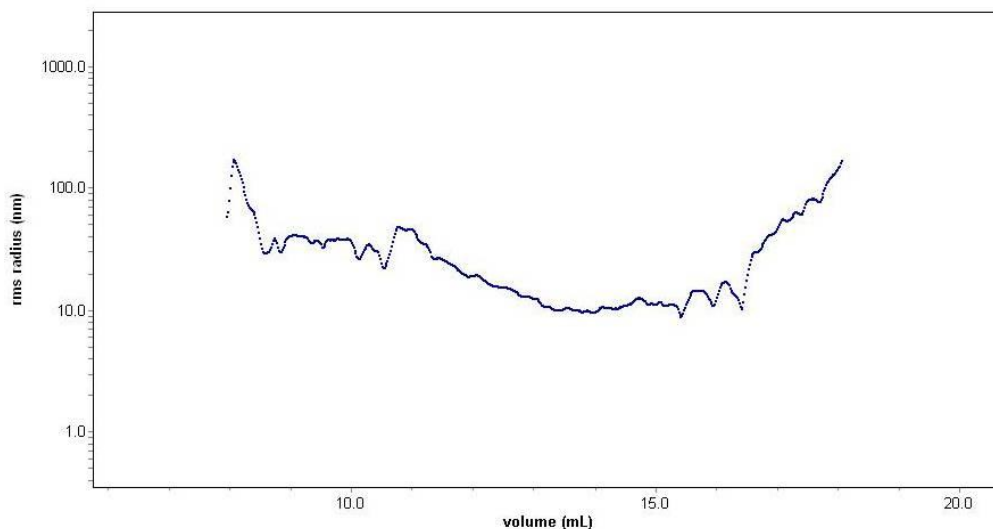


Figure 5.17: The radius of gyration (R_g) against elution volume as calculated by GPC-MALLS of *b*-PCL

Previous work has shown that the plot of R_g against elution volume should be linear for straight chain polymers.⁵¹ Analysis of Figure 5.17 indicated that branched architectures were present, because the plot was not linear at high molecular weights. The linearity of the low molecular weight region indicated that some linear PCL chains were present, which was also observed in the GPC-RI traces (Figure 5.16).

The gradient of the slope taken from the conformation plots of R_g against M_w is known to provide information on the polymer architecture,⁵¹ where values greater than 0.5 are attributed to linear polymers and less than 0.5 indicate a branched structure. The conformation plots of R_g against M_w provided in Figure 5.18 and the gradient is given in Table 5.3.

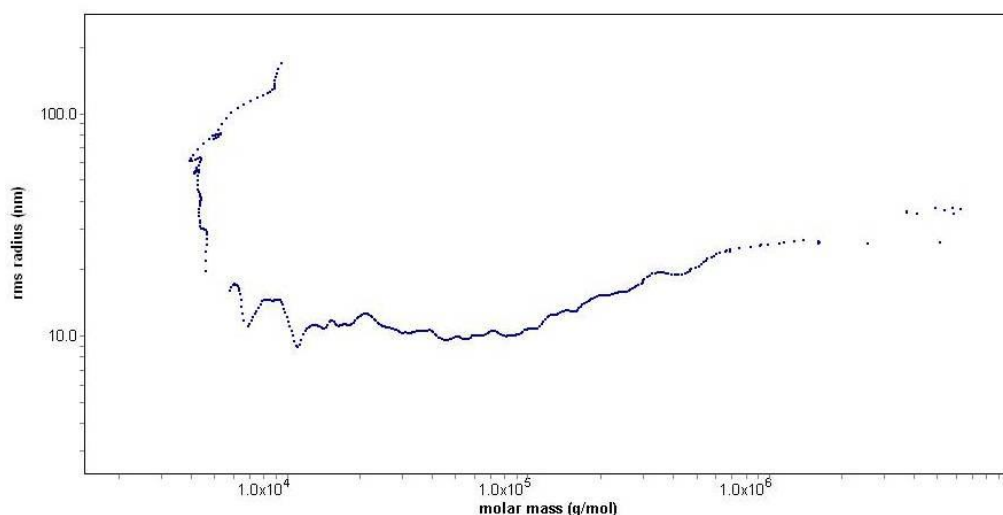


Figure 5.18: The conformation plot of the RMS R_g against M_w for b -PCL

The low gradient value given in Table 5.3 of 0.30 is indicative of a branched structure. Indeed, the shape of the plot in Figure 5.18 is typical of a non-linear polymer,⁵¹ as has been observed in previous studies into b -PCL.³⁷ This data may also suggest that star polymers were formed, with different arms growing away from the BOD units. The small amount of BOD in the reagent feed could mean that not enough linkages for present to form a highly branched species.

The DSC analysis of the final product was conducted and compared with a linear PCL sample of similar molecular weight. The b -PCL had a $T_g = -59.7\text{ }^{\circ}\text{C}$, which is the similar to that of the linear analogue. Again, this was consistent with previous work where the degree of branching was too low to have a significant impact upon the amorphous region of the polymer.³⁷ However, the T_m of the b -PCL was noted to be at lower temperature ($51.03\text{ }^{\circ}\text{C}$) and less energy of crystallisation (52.24 J/g) of the branched material than the linear analogue ($57.54\text{ }^{\circ}\text{C}$; 73.99 J/g respectively). This was caused by the branching regions restricting the ability of the PCL backbone to align with

itself. Thus, the fact that crystallisation was disrupted supports the view that BOD was successfully used as the branching agent to create *b*-PCL for the first time via ROMBP using MWH.

The CH equivalent experiment (Entry 2, Table 5.1) was undertaken to gain a comparison with the MWH. Figure 5.19 presents the GPC traces of samples taken at various stages in the reaction with a view to establish the onset of branching.

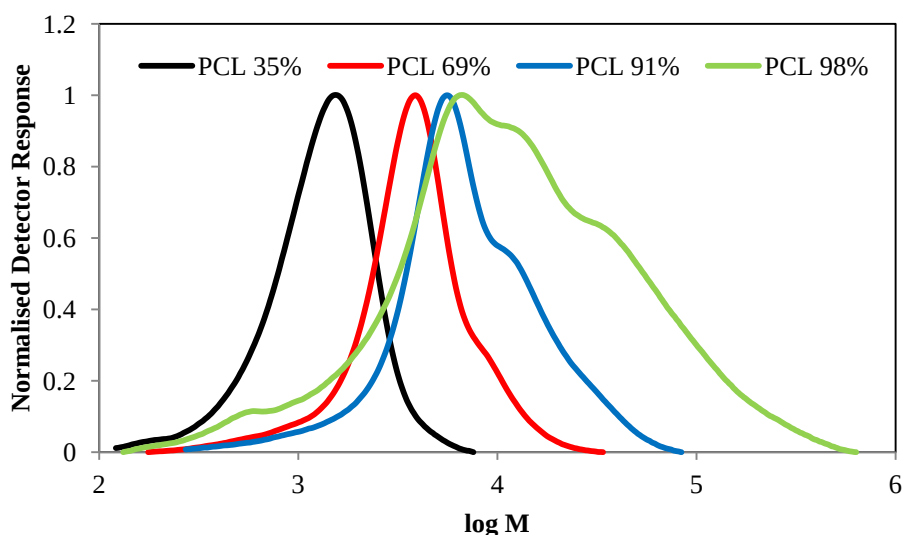


Figure 5.19: GPC trace overlay of samples taken during the ROP reaction forming *b*-PCL using CH at 160 °C

The synthesis of *b*-PCL using CH was observed to follow a slightly different reaction profile (Figure 5.19) to the MWH reaction discussed above. After 3 hours, with PCL conversion at 69 %, there was evidence that the BOD was undergoing ROP but there was little evidence branching occurring. Additionally, the GPC trace was almost symmetrical, with only a slight

increase in M_w due a small shoulder similar to that at 50 % conversion in the MWH experiments.

It was only when ϵ -CL reached high conversion (> 90 %) there was a broad $\bar{D}$ and a large amount of branching observed, as indicated by the presence of a significant high M_w shoulder. After this point, transesterification reactions occurred, with the typical drop in M_n alongside the formation of large macromolecules.

Therefore, the successful formation of *b*-PCL using the BOD as a branching agent was achieved using both MWH and CH. Although it was interesting to note that the onset of branching was observed to occur earlier in the reaction profile for MWH than with CH, typically at conversion levels that are 20 % less in MWH. From the ^1H NMR data, BOD was incorporated into the growing PCL chains early in the reaction for both heating methods, but the pendent BOD ring reacted earlier (i.e. when less ϵ -CL had been converted) in MWH than in CH.

This effect was attributed to the selective heating of the BOD moiety and/or the Sn species. This focussed input of energy may lead to increased flexibility within the pendent BOD ring, compared to the polymeric structure that surrounds it. This may have relieved some of the steric hindrance around this second ring and as a result may be the cause of its higher reactivity in MWH than in CH. Alternatively the Sn catalyst may also be being selectively heated making it more likely to overcome the barriers to its approach to the pendant BOD ring. The dielectric measurements in Section 5.3.1 showed that the PCL

was not susceptible to MWH energy as it had a relaxation time far greater than the oscillating field. This was because the PCL polymer was constructed of many monomer units, thus the individual dipoles cannot align easily with the applied field. Furthermore, the intermolecular forces between adjacent polymer chains will further hinder the ability of the molecule to rotate to align with the oscillating field. The pendant BOD moiety, however, is not as restricted, and will be able to be selectively heated by the MWH due to its enhanced flexibility over its surrounding polymer. CH was unable to replicate this phenomenon because the heating energy is not directed specifically at these reactive groups, and as such, branching was delayed in the CH reaction until > 90 % ϵ -CL conversion. At this point, the monomer can be regarded as being depleted, thus inter-chain reactions are all that is available to the Sn catalyst.

5.3.2.2 BOD Addition at 70 % ϵ -CL Conversion

Further experiments were undertaken to establish if the use of MWH, and the in-depth knowledge of the reagents' dielectric properties, could be exploited to modify and shorten the time needed for the synthesis of *b*-PCL. From the previous experiments, it was noted that adding the BOD co-monomer at the outset of the reaction extend the reaction time, however, the onset of significant branching was not observed until after the reaction system had exceeded 70 % conversion. Thus, it was postulated that the reaction time could be shortened by adding the BOD as a second addition of monomer when the “linear” PCL system had reached 70 % conversion. At this point there should also be limited

advent of transesterification reactions. Therefore, a series of experiments were conducted in which a PCL reaction was commenced in a standard “linear” method and BOD was added at approximately 70 % conversion using both MWH and CH, in a one-pot, two step method. The polymer data acquired from these experiments is shown in Table 5.1 as Entries 3 and 4 to enable comparison with the reactions in which BOD was added at the outset of the polymerisation.

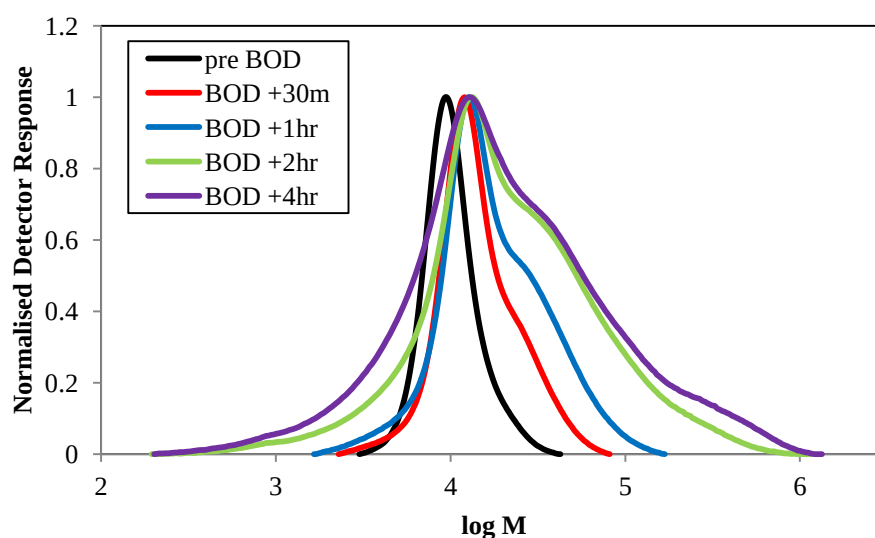


Figure 5.20: GPC trace overlay of samples taken during the MWH ROMBP reaction at 160°C forming *b*-PCL with BOD addition at 70 % PCL conversion

In the MWH reaction, the BOD was added after 50 minutes of homo-PCL growth, with the system analysed to have attained conversion of 70 % and the polymer exhibited a $\bar{M}_w$ was 1.15 (Figure 5.20). The fact that 70 % PCL conversion was reached in only 50 minutes, compared with 150 minutes needed when BOD was present from the start of the reaction, shows that BOD inhibited the ROP process. The bulky BOD unit was thought to slow down ROP when present on the active chain end. Therefore BOD addition later in the

reaction process may be the route to fast formation of *b*-PCL. It was observed that the BOD units rapidly underwent ROP and branching was evident immediately as $\bar{D}$ increased and a multimodal peak was observed in the GPC trace after 30 minutes with BOD added, at which point the PCL had reached > 90 % conversion. Again it was observed that branching dominated over transesterification reactions whilst the BOD was consumed, as the peak after BOD + 1hr minutes indicated a large increase of M_w without a drop of the lower M_n values.

After BOD +2hr, the reaction reached its maximum level of branching. This was when both ϵ -CL and BOD have reached full conversion. The M_w was 55,020 g mol⁻¹, considerably more than a theoretical linear value of 9,700 g mol⁻¹. When the reaction as continued for 2 more hours (BOD +4hr), the high molecular weight shoulders did not increase in size (no further branching). However, M_n decreased and $\bar{D}$ increased, relating to the transesterification mechanisms now becoming evident as the monomers are depleted.

The GPC-MALLS data for these experiments are presented in Table 5.4 alongside the GPC-RI data, to enable further understanding of the polymer architecture.

Table 5.4 Comparison of GPC-RI and GPC-MALLS data of the *b*-PCL formed in MWH with BOD addition at 70 % PCL conversion (Entry 3, Table 5.1).

	$M_{n\text{ THEO}}$ (g mol ⁻¹)	M_n (g mol ⁻¹)	M_w (g mol ⁻¹)	$\bar{D}$	R_g (nm)	R_g/M_w slope
GPC-RI ^a	9,700	10,410	56,050	5.38	n/a	n/a
GPC-	9,700	15,800	84,600	5.30	19.4	0.28

MALLS

^a Determined using GPC-RI ($500 < M_n < 2,000,000 \text{ g mol}^{-1}$, calibrated with PS standards).

It can be concluded from the GPC-MALLS data that *b*-PCL was synthesised in the one-pot, two step ROMBP reaction using BOD as the branching agent with pre-formed linear PCL chains. The large $\bar{D}$ value of 5.30 indicated a branched structure with the M_w value of $84,600 \text{ g mol}^{-1}$ much larger than the linear equivalent size for at the same conversion. The plot of R_g against elution volume is provided in Figure 5.21, from which the size and structure of the various polymer fractions can be deduced.

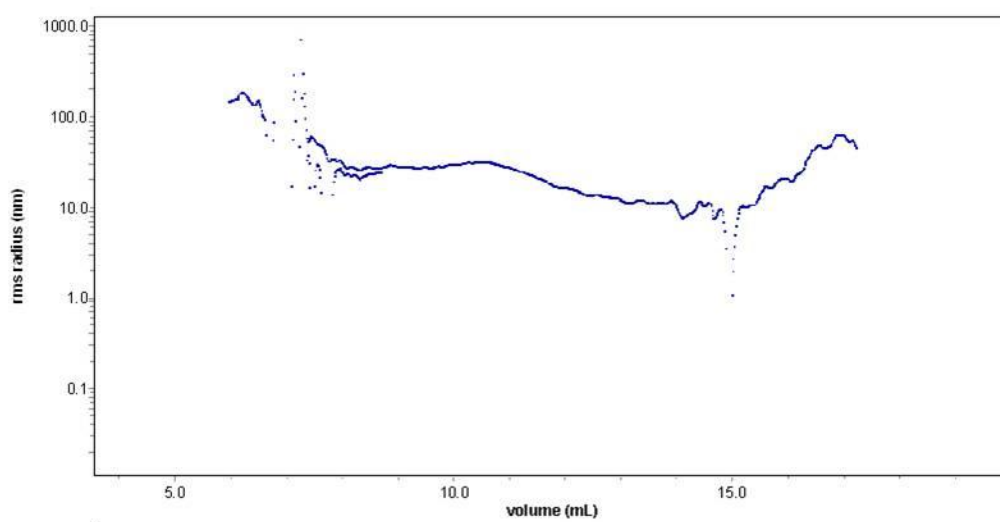


Figure 5.21: The radius of gyration (R_g) against elution volume as calculated by GPC-MALLS of *b*-PCL; Entry 3, Table 5.1

The plot in Figure 5.21 was similar to the analysis of the one-step *b*-PCL method (Figure 5.17). The non-linear plot, particularly at high molecular weight polymers, confirmed that branched architectures were synthesised. However, some linear chains were also present. The gradient of the conformation plot of R_g against M_w is provided in Figure 5.22.

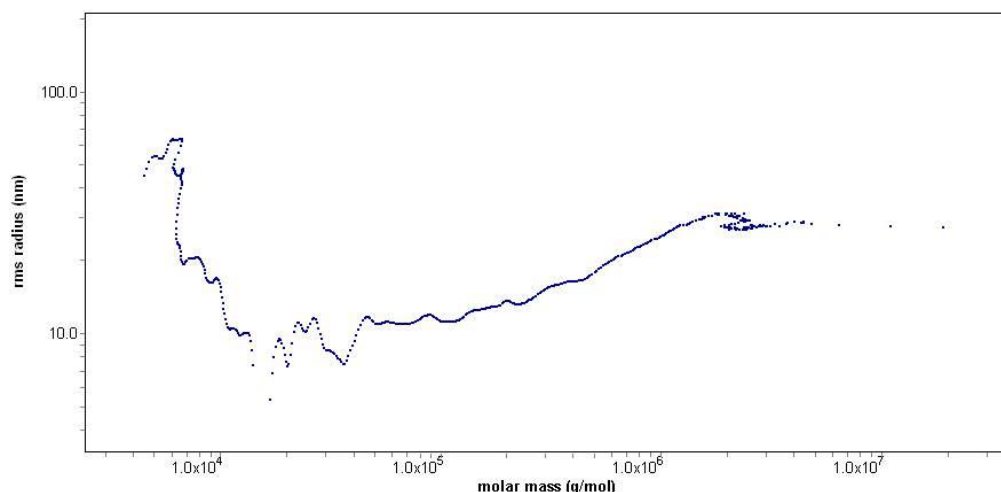


Figure 5.22: The conformation plot of the RMS R_g against M_w for b -PCL for Entry 3, Table 5.1

The non-linear, ‘looped’ shape in Figure 5.22 provided evidence of the formation of b -PCL. This was supported by the gradient of the R_g against M_w slope, which calculated to be 0.28.

The DSC analysis supported the proposition that BOD had undergone ROMBP to create b -PCL. As was noted in the one-pot, one step reaction, the T_g value was not affected by branching ($T_{g \text{ } b\text{-PCL}} = -59.91 \text{ } ^\circ\text{C}$; $T_{g \text{ PCL}} = -60.13 \text{ } ^\circ\text{C}$). However, the crystallinity was affected by the formation of the branched architecture. Indeed, the $T_{m \text{ } b\text{-PCL}} = 51.12 \text{ } ^\circ\text{C}$ with an energy of crystallisation = 55.23 J/g, which were found to be different than the linear equivalent. (57.54 $^\circ\text{C}$; 73.99 J/g).

The GPC traces (Figure 5.23) indicate that the CH reaction also had incorporation of BOD into the linear PCL, forming b -PCL (Entry 4, Table 5.1).

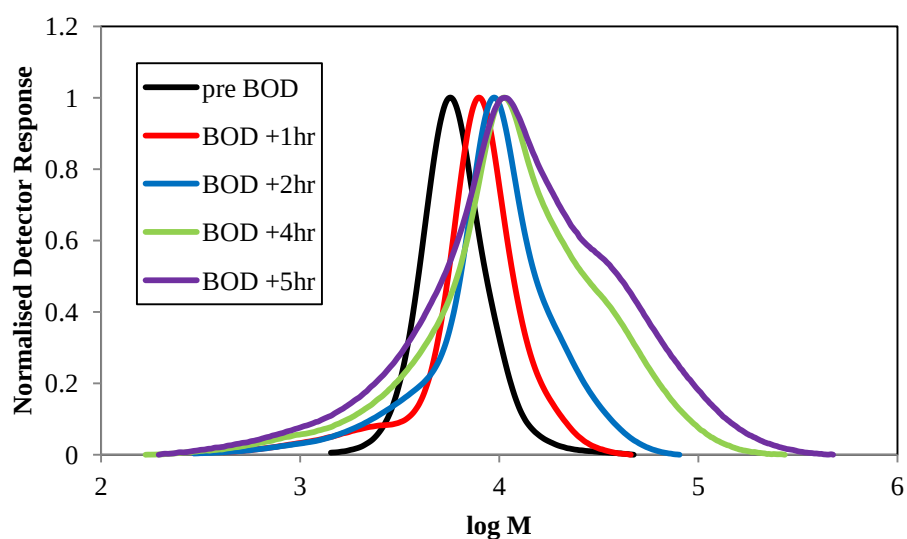


Figure 5.23: GPC trace overlay of samples taken during the CH ROMBP reaction at 160 °C forming *b*-PCL with BOD addition at 70 % PCL conversion.

The final product (BOD +5hr) had a large $\bar{D}$ with an M_w value much greater than a linear comparison. However the main difference between CH and MWH was the relative rates of branching vs transesterification. Unlike in the MWH experiment, where branching dominated until complete monomer depletion, when the mixture was heated using CH, the onset of transesterification appeared much sooner and as a result significantly less branching had been achieved. Indeed, when BOD was reacted for 2 hours with the pre-formed linear PCL (BOD +2hr), the PCL conversion was calculated to be 85 % and the $\bar{D}$ increased to 1.71. There was a large amount of lower M_n polymer present in the GPC trace, formed by the inter-chain scission mechanism.

The cause of the preference of branching over transesterification in MWH (compared with CH where transesterification is prominent) may be explained by the dielectric properties of the BOD and catalytic species, as has been discussed above. The main difference between BOD addition at 0 % and 70 %

monomer conversion in the case of the MWH system, was a reduction in reaction time. The materials produced are largely the same but in only 50 minutes when using the two-step step method. However, in the CH case the final materials are not identical. Rather the 70 % product exhibits a degree of branching which is not as high as the 0 % equivalent. Therefore, the reduction in reaction time, with increased k_p PCL for the period of linear PCL growth, whilst retaining the target high molecular weight product, suggests that an one-pot, two step MWH process will create larger quantities of the desired products if the process is scaled up.

5.3.2.3 BOD Addition at 100 % ϵ -CL Conversion

Finally, an investigation into the possibility of branching being introduced retrospectively to linear PCL that had undergone ROP to full conversion was undertaken with both MWH and CH (Entries 5 and 6, Table 5.1). If the BOD was being selectively heated it was postulated that it may be able to invoke controlled branching of linear PCL polymer to create organic soluble branched materials.

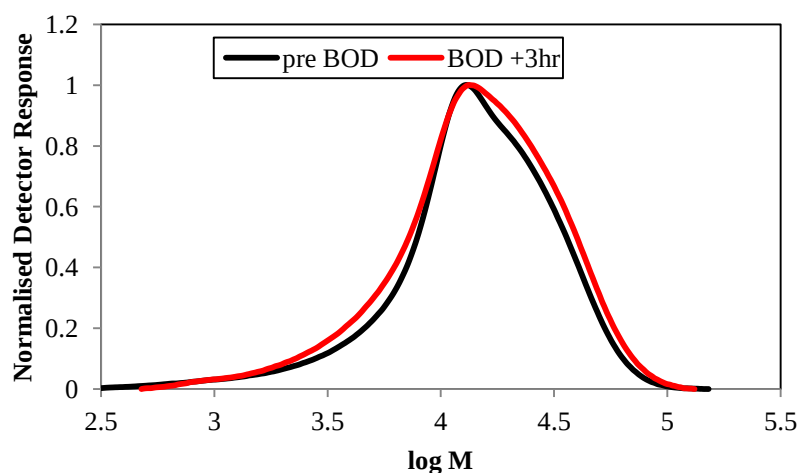


Figure 5.24: GPC trace overlay of samples taken during the MWH ROP reaction at 160 °C forming PCL with BOD addition at 100 % PCL conversion.

However, it was found that neither heating method was able to create *b*-PCL from the linear PCL. In MWH (Entry 5), the $M_w = 19,100 \text{ g mol}^{-1}$ and $\bar{D} = 1.61$ when the PCL was reacted to > 98 % conversion (Figure 5.24). These values did not significantly increase after 3 hours of reacting with BOD. The final M_w value was only 19,900 g mol^{-1} and $\bar{D}$ was 1.71.

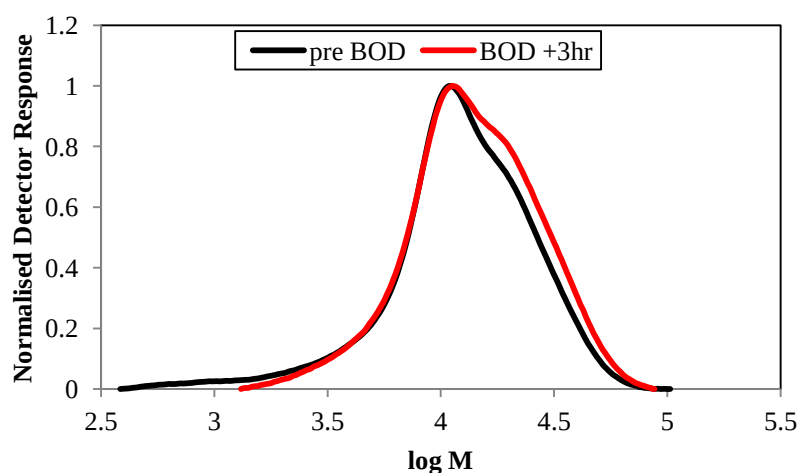


Figure 5.25: GPC trace overlay of samples taken during the CH ROP reaction at 150 °C forming PCL with BOD addition at 100 % PCL conversion.

The CH reaction followed a similar profile (Figure 5.25), with M_w increasing from 17,400 g mol⁻¹ to 18,600 g mol⁻¹ and $\bar{D}$ changing from 1.56 to 1.58 after the addition of BOD. In both cases the slight increase in M_w (BOD +3hr) was attributed to the action of transesterification reactions. Therefore neither heating method was able to create branched links between linear PCL chains with retrospective addition of BOD after full ϵ -CL conversion had been achieved.

5.3.3 Effect of Temperature upon Synthesis of *b*-PCL: Target Degree of Polymerisation = 20

Having noted cycle time differences between the MWH and CH processes when targeting a DP of 87, an additional study was conducted to further investigate the effect of temperature on the rate of reaction, k^{app} values, when heated with MWH and CH methods. From the dielectric data investigated in Section 5.3.1, it was known that BOD exhibited a high susceptibility to microwave energy at high temperatures (> 160 °C) but that it was very unresponsive below that temperature. Indeed, above 160 °C BOD had a higher $\tan \delta$ value than ϵ -CL, Sn(Oct)₂ and BnOH. However below this temperature, (< 150 °C), BOD had a relatively small $\tan \delta$ value, and thus should not undergo efficient dielectric heating.

A series of experiments were conducted both above and below the temperature that BOD becomes highly susceptible to microwave energy (180 °C and 150 °C

respectively). The target DP for these reactions was lowered to be 20, thus enabling a higher level of clarity in the ^1H NMR spectrum. By doing this it was experimentally found that the ϵ -CL and PCL peaks no longer overlapped the BOD peak which thus made interpretation easier. Thus the reagent ratio was set at $[\epsilon\text{-CL}]_{20} : [\text{BnOH}]_1 : [\text{Sn}(\text{Oct})_2]_{0.02} : [\text{BOD}]_{0.6}$ and $M_{n \text{ Theo}}$ was $2,000 \text{ g mol}^{-1}$. All reagents were present at the start of the reaction. Identical reaction conditions were ensured in both CH and MWH to enable an accurate comparison between the effects of the heating method on BOD reactivity to be made. The data obtained from these experiments is summarised in Table 5.5.

Table 5.5: NMR data from the studies into the effect of temperature on the synthesis of *b*-PCL: Target degree of polymerisation = 20.

Entry	Heating method	Reaction Temp ($^{\circ}\text{C}$)	Conv (%) ^a	Conv (%) ^a	Reaction time (min)	k_p (min^{-1})		$k_p \text{ PCL}/k_p \text{ BOD}$
			$\epsilon\text{-CL}$	BOD		PCL	BOD	
1	MWH	150	92	53	20	0.0938	0.0326	2.88
2	CH	150	88	58	30	0.0482	0.0184	2.62
3	MWH	180	91	69	2	0.7705	0.8343	0.92
4	CH	180	93	73	5	0.4208	0.1647	2.55

^a Determined by ^1H NMR.

Analysis of the k_p values (MWH (Entry 1) and CH (Entry 2)) at 150°C demonstrated that for both heating methods, the PCL was formed faster than the rate of BOD conversion. This was similar to the observations made in the DP 87 experiments in Section 5.3.2.1. This difference in monomer conversion rate at this temperature was partly attributed to the relative concentrations of both $\epsilon\text{-CL}$ and BOD within the system. Also, on closer inspection of the $k_{p \text{ PCL}}$ and $k_{p \text{ BOD}}$ values, it was observed that they were both faster in MWH

compared to the CH at both temperatures. Consequently, it was observed that the $k_{p \text{ PCL}} / k_{p \text{ BOD}}$ ratios at 150 °C were very similar, with 2.88 in MWH and 2.62 in CH. Interestingly, there was a significant difference between the $k_{p \text{ PCL}} / k_{p \text{ BOD}}$ ratios observed when the reactions were conducted at 180 °C, i.e. the temperature where BOD was noted to be much more susceptible to microwave heating. In this case the ratio is approximately three times smaller for the MWH. Figure 5.26 and Figure 5.27 display this data in a graphical manner.

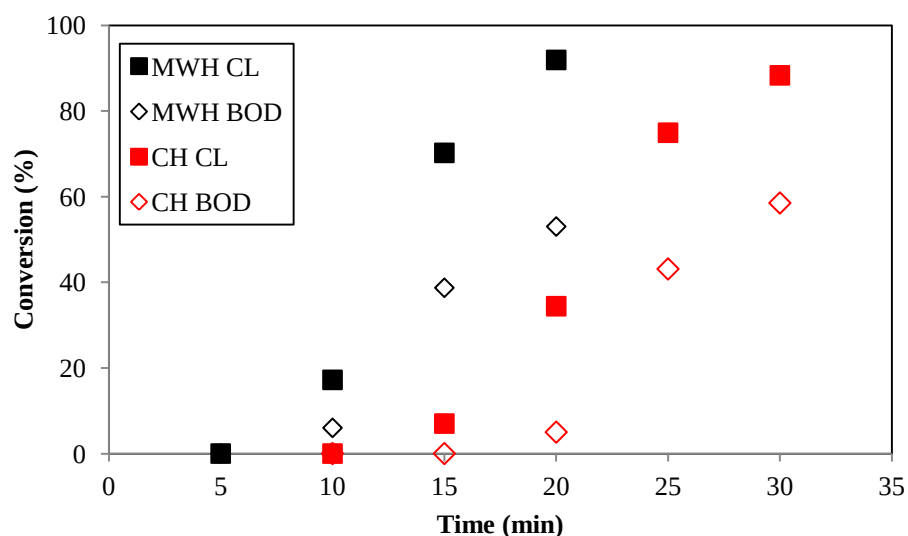


Figure 5.26: Kinetic plots of ϵ -CL (■ MWH ; ■ CH) and BOD (◇ MWH ; ◇ CH) conversion against time for ROP of ϵ -CL at 150 °C. Determined by ^1H NMR.

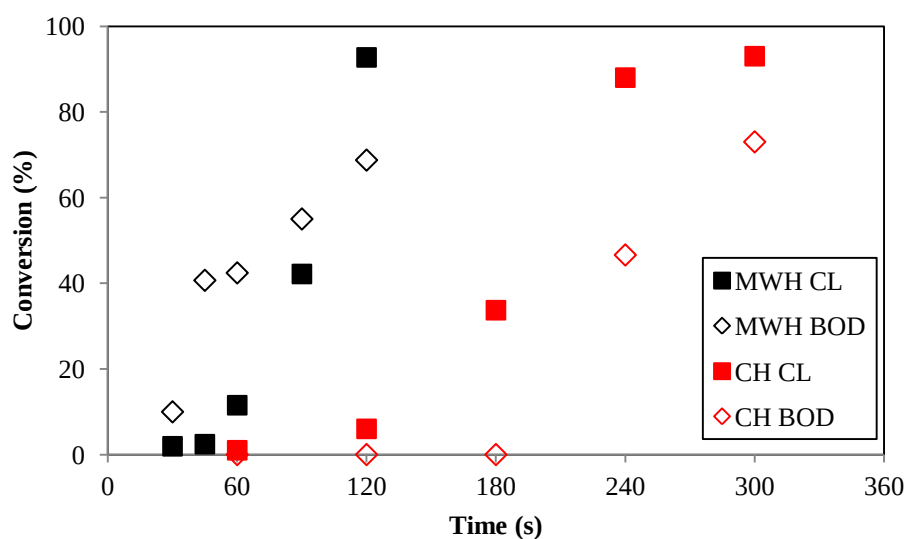


Figure 5.27: Kinetic plots of ϵ -CL (■ MWH ; ■ CH) and BOD (◇ MWH ; ◇ CH) conversion against time for ROP of ϵ -CL at 180 °C. Determined by ^1H NMR.

Furthermore, it is clear that, unlike the previous experiments at 150 °C, the BOD experienced conversion faster than the ϵ -CL units at 180 °C (Figure 5.27) in the MWH experiment alone, as the $k_{\text{p BOD}}$ was greater (0.8843 min^{-1}) than the $k_{\text{p PCL}}$ (0.7705 min^{-1}). After 60 seconds of reaction, less than 10 % of PCL had experienced ROP, whilst almost half the BOD had reacted. The ratio of $k_{\text{p PCL}} / k_{\text{p BOD}}$ was 0.92, indicative of the higher reactivity of BOD at higher temperatures in MWH. The BOD dielectric properties suggested that it should be the most susceptible species to microwave energy within the reaction mixture at this temperature. This is a further clear indication of selective, volumetric heating influencing the course of the reaction mechanism. The argument that specific heating only to present in MWH is also supported by comparing this result with the CH equivalent reaction at 180 °C (Entry 4, Table 5.5).

The ratio of $k_{p \text{ PCL}} / k_{p \text{ BOD}}$ using CH at 180 °C was 2.55, which was very similar to both MWH and CH reactions at 150 °C. Therefore increased temperature was not able to significantly alter the relative monomer reactivity ratios using CH, unlike in MWH.

The fact that both MWH and CH reactions at 150 °C had similar $k_{p \text{ PCL}} / k_{p \text{ BOD}}$ ratios indicates that for the reaction in MWH at 150 °C, even though the BOD is solvated by the ϵ -CL monomer, its ability to undergo selective heating appears not to be as great as at 180 °C. Thus the melting point of the species which are to undergo selective heating would seem to be an important parameter. Thus this implies that reaction mixtures could be designed to target specific molecular entities within the medium by careful consideration of the physical properties of the moieties.

5.3.4 *b*-PCL Studies: Target Degree of Polymerisation = 5

Due to the fact that different rates of BOD uptake were observed to be dependent on both temperature and heating method adopted, a further study was conducted to investigate the rate of BOD incorporation into growing polymer chains. A much lower DP = 5 was targeted to enable clearer spectroscopic analysis of the exact rates of BOD conversion.

As BOD is constructed of two ϵ -CL units joined together, it was important to examine the rate that each ring undergoes ROP. The BOD resonance in the

^1H NMR represents an amalgamation of data from both rings, thus the conversion obtained *via* ^1H NMR cannot differentiate between the relative rates at which these individual rings are involved in the ROP process. Consequently, GC-MS analysis was used to compliment the ^1H NMR data and thus to determine the actual rate of free BOD depletion relative to branching. Therefore, a low DP targeted was required in order to allow for the samples to be analysed *via* GC-MS with a high level of accuracy, and give a clear comparison between the relative reagent depletion ratios.

Reactions were conducted at 160 °C using MWH and CH, with the reagent ratio of $[\epsilon\text{-CL}]_5 : [\text{BnOH}]_1 ; [\text{Sn}(\text{Oct})_2]_{0.02} : [\text{BOD}]_1$. The temperature was chosen to be 160 °C so that, in MWH, the BOD moiety would have a high $\tan \delta$ value relative to the other reagents. The results from the MWH reaction are given in Figure 5.28, which represents both the levels of $\epsilon\text{-CL}$ and BOD conversion estimated by NMR analysis and the rate of free BOD conversion obtained *via* GC-MS analysis.

The BOD was represented in the GC-MS spectra as the peak at 41.13 minutes. The area of this peak dropped dramatically from the sample taken at 20 seconds compared at 40 seconds. This indicates that over 90 % of the free BOD in the reaction mixture had been incorporated into a chain and indicated that one of the BOD rings had undergone ROP. The enhanced rate of BOD interaction with the Sn catalytic species at the start of the reaction supported the conclusion drawn earlier in Section 5.3.2.1 on why the initiation/induction period for ROMBP was longer than ROP for linear PCL. It was postulated that the BOD 1-mer is more sterically hindered than a PCL 1-mer, thus when BOD is at the reactive chain end, the k_p PCL will be decreased as the following monomer units are less able to react with the more sterically hindered BOD chain end active species. Therefore the initiation/induction periods of PCL were extended when BOD was present at the start of the reaction. This supports the observation that a sequential monomer addition was the faster method for synthesising *b*-PCL.

It is interesting to note that after 40 seconds, the formation of the catalytically active species had not reached full conversion. It is clear from the ^1H NMR that almost 20 % of the BnOH was still present at this point. Therefore ϵ -CL and BOD were undergoing ROP before complete formation of the $\text{Sn}(\text{OBn})_2$ active species (as was noted in the induction period studies in Section 3.3.5.2). Indeed both monomers had achieved over 80 % conversion when all BnOH had been consumed after 90 seconds.

It is clear from the ^1H NMR analysis that the rate of the pendent BOD rings undergoing ROP was much slower than the initial “free monomer” BOD ring,

with over 60 % of the pendent rings still visible in the NMR spectrum after 40 seconds. Therefore intermolecular branching would occur later in the reaction timeline.

The identical reaction was conducted in CH, Figure 5.30 contains the NMR data and Figure 5.31 displays the GC-MS analysis.

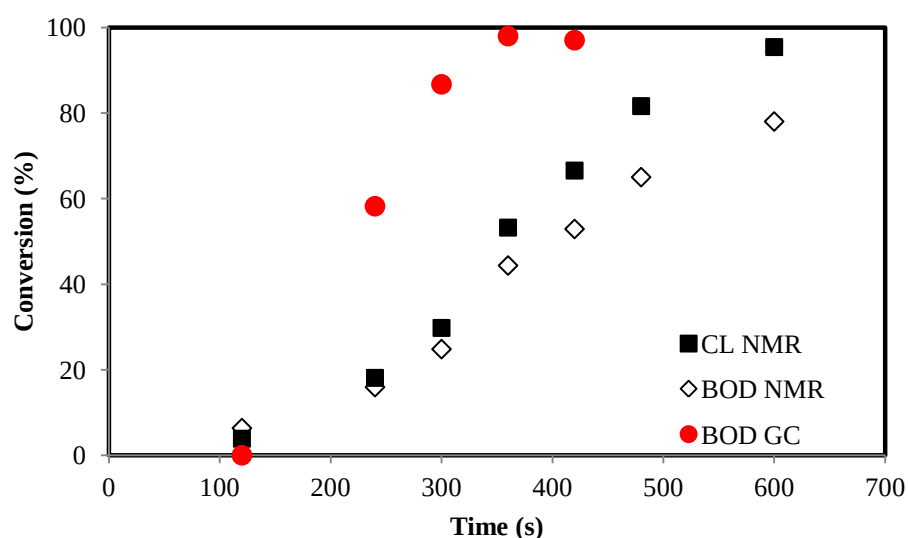


Figure 5.30 Kinetic plots of reagent conversion and monomer depletion against time for the ROP of ϵ -CL and BOD in CH at 160 °C. Conversion of ϵ -CL (■) and BOD (◇) calculated from NMR. BOD depletion (●) calculated by GC-MS.

As expected, the k_p PCL and k_p BOD were slower than the MWH reaction (0.1958 min^{-1} and 0.1187 min^{-1} respectively). The reason why the k_p PCL / k_p BOD ratio was almost 2 (compared with 3 for the DP 20 reaction in Section 5.3.3) was attributed to the increased level of tin moieties relative to the monomer.

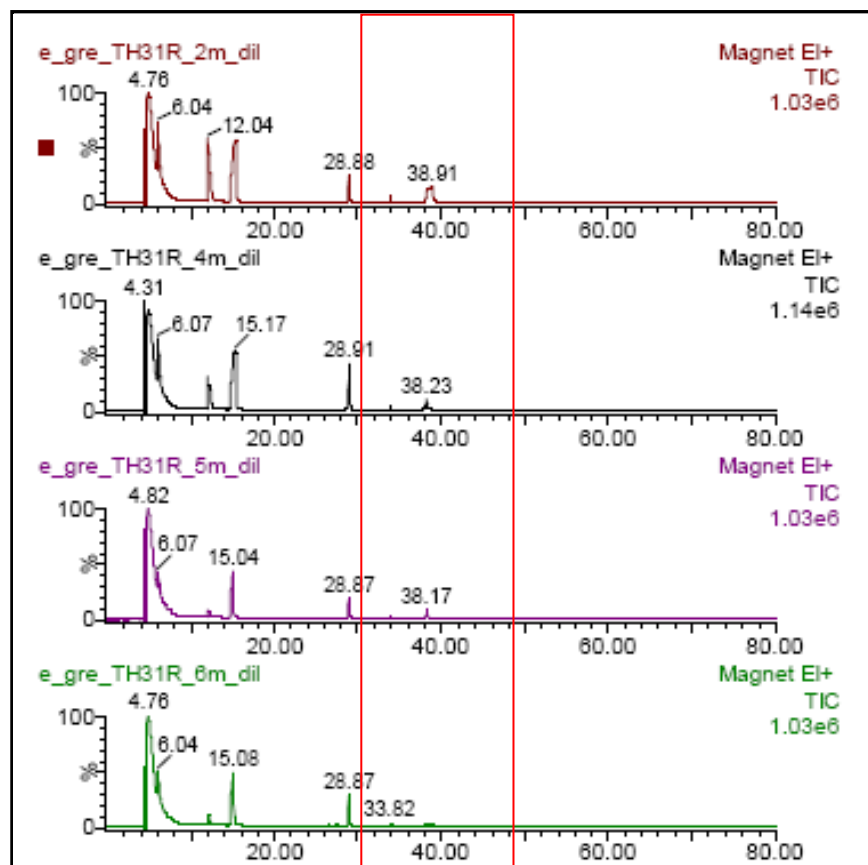


Figure 5.31: GC-MS analysis of the ROP of ϵ -CL and BOD in CH at 160 °C. Samples taken after 120 s, 240 s, 300 s and 360 s. The ϵ -CL peak is at 15.17 min and the BOD peak is highlighted at 38.91 min, the peak at 28.98 min is the oligomeric species.

The level of free BOD depletion, derived from the GC-MS data, indicated a slower rate of BOD reactivity than in the MWH equivalent reaction. The slow incorporation of BOD in CH was indicated in the GC-MS spectrum where after 5 minutes of heating at 160 °C, 20 % of “free-monomer” BOD was present in the bulk, along with 80 % of ϵ -CL and 20 % of BnOH. This means that the ratio of free BOD to free ϵ -CL was higher in the CH reactions, again supporting the conclusion that BOD was incorporated into chains more quickly in the MWH reaction. In fact, the BOD peak was still present until the 6 minutes sample of the CH experiment. This slower level of BOD incorporation in the CH reaction further supports the claim that MWH was capable of

specifically heating the BOD units and increasing $k_{p \text{ BOD}}$ relative to $k_{p \text{ PCL}}$. The elevated $\tan \delta$ value of BOD at $> 160^\circ\text{C}$, observed in the dielectric property assessment of the individual monomers, suggest that BOD could have led to a higher affinity for MWH and thus these units may have achieved a higher temperature than the bulk. This localised heating may result in the observed increase in the $k_{p \text{ BOD}}$ in MWH, which cannot occur in CH.

5.3.5 *b*-PCL-co-PLA Synthesis

The final part of this branching project was targeted at the synthesis and analysis of BOD addition to a copolymerisation reaction of ϵ -CL and DLLA with CH. A DP of 50 was targeted with the same BnOH initiator and SnOct_2 catalyst concentration used as in previous sections, whilst the monomer feed composition was varied and the thermal properties were studied. Table 5.6 provides analysis on the various branched products formed. The synthetic procedure used in these experiments was similar to the one-pot, one step method discussed in the previous section. All the reagents were present at the start of the reaction before the ROMBP was commenced.

Table 5.6: Synthesis of *b*-PCL-*co*-PLA using various monomer feed ratios, with BOD at 150 °C in bulk.

Entry	Reagent Molar Ratio					GPC ^a (g mol ⁻¹)			DSC	
	DLLA	ε-CL	BOD	BnOH	SnOct ₂	M _{n obs} ^a	M _{w obs} ^a	Đ ^a	T _g (°C) ^b	T _g (°C) ^c
1	50	0	0.6	1	0.02	6,200	7,900	1.26	43.51	45.00
2	37	13	0.6	1	0.02	9,200	23,000	2.49	12.85	18.75
3	25	25	0.6	1	0.02	11,000	44,800	3.94	-15.29	-7.50
4	13	37	0.6	1	0.02	10,100	34,200	3.44	-46.83	-33.75
5	0	50	0.6	1	0.02	10,700	44,900	4.62	-59.65	-60.00

^a Molecular weights and dispersity of final sample determined using GPC (500 < M_n < 2,000,000 g mol⁻¹, calibrated with PS standards). ^b Determined using DSC (sample size = 0.5 - 3mg, heating rate = 10 °C min⁻¹); ^c Theoretical values calculated from the Fox equation, by using for the T_g of the homopolymers from the following literature values: PLA = 45 °C ; PCL = -60 °C.

The sample without any ϵ -CL (Entry 1) did not indicate that any of branching had occurred, suggesting that BOD was ineffective at forming branches between linear PLA primary chains. The $\bar{D}$ remained low (< 1.3) throughout this reaction supporting the conclusion that linear PLA had been synthesised.

However, it was observed that with the introduction of ϵ -CL, the BOD was able to achieve branching in the overall system. With the monomer ratio at $[\text{DLLA}]_{13}:[\epsilon\text{-CL}]_{37}$ (Entry 4 Table 5.6), evidence of branching was supported by the observed broadening of the $\bar{D}$ and higher M_w (Figure 5.32). The similarity of the structure of BOD and ϵ -CL could be the explanation for the ease of incorporation of BOD into the PCL chains which later act as branching points.

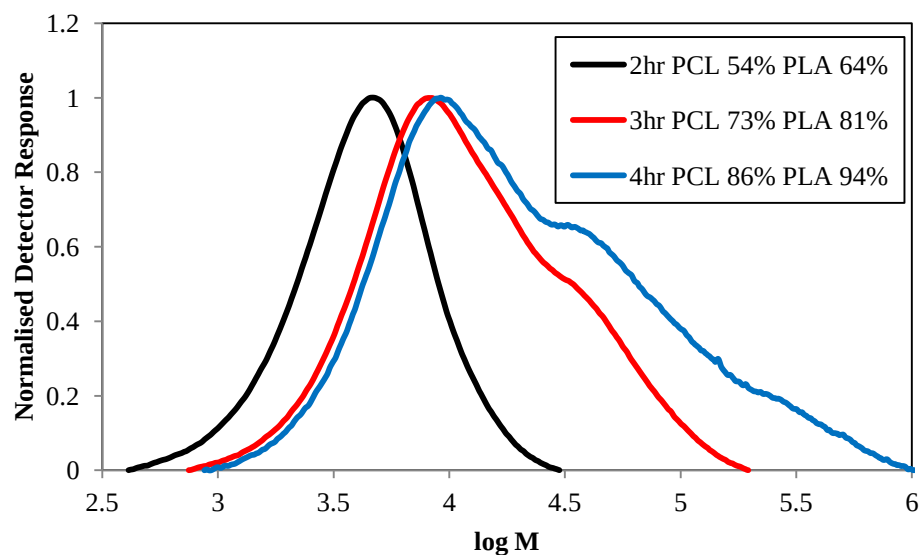


Figure 5.32: GPC traces of the progression of branched copolymer formation for ROMBP of DLLA and ϵ -CL using BnOH , $\text{Sn}(\text{Oct})_2$ and BOD with ratio $[\text{DLLA}]:[\epsilon\text{-CL}]:[\text{BnOH}]:[\text{BOD}] = [13]:[37]:[1]:[0.6]$. GPC ($500 < M_n < 2,000,000 \text{ g mol}^{-1}$, calibrated with PS standards).

The formation of a linear copolymer after 2 hours could be seen after 54 % of PCL and 64 % of DLLA had been converted into polymer with a $\bar{D}$ of 1.23. At

this point, BOD had started to undergo ROMBP and the pendent ring will have been situated within the copolymer primary chains. Branching was only observed to occur after 3 hours, when the unopened BOD rings reacted with active centres on a separate growing chain. The increased $\bar{M}_w$ of the broad peak at 3 hours was evidence for the branched structure.

The GPC results for the final product from the *b*-copolymerisation experiments which containing the various monomer ratios detailed in Table 5.6 are presented in Figure 5.33.

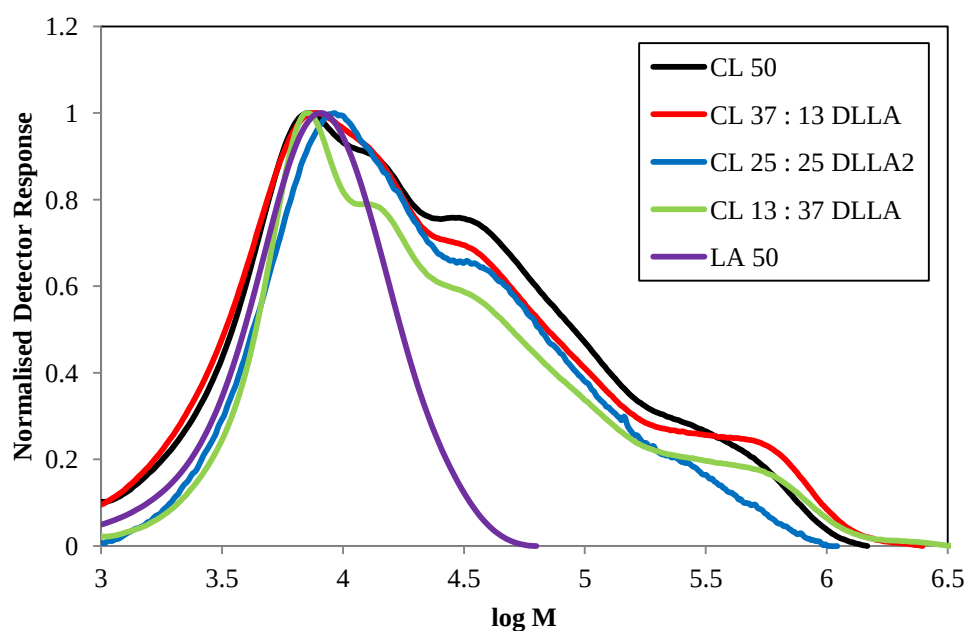


Figure 5.33 GPC traces of various branched copolymers formed by ROP of DLLA and ϵ -CL using BnOH, Sn(Oct)₂ and BOD with ratio [DLLA]:[ϵ -CL]:[BnOH]:[BOD] = [x]:[x]:[1]:[0.6]. GPC ($500 < M_n < 2,000,000 \text{ g mol}^{-1}$, calibrated with PS standards).

All the peaks of the high conversion product polymer were observed to have large shoulders in the peaks at high M_w regions, indicating branching had occurred producing high M_w *b*-copolymers. The linear peaks were still present

at low molecular weight levels. Samples with higher proportion of ϵ -CL in the monomer feed had shown higher levels of branching, possibly due to the higher affinity BOD will have had to ϵ -CL due to their similar structures. Indeed, increasing levels of ϵ -CL in the monomer feed caused higher M_w products with broader $\bar{D}$'s as is shown in Table 5.6. Included in Table 5.6 are the DSC results. The T_g values of the branched products are compared with their equivalent linear PCL analogues' T_g values in Figure 5.34.

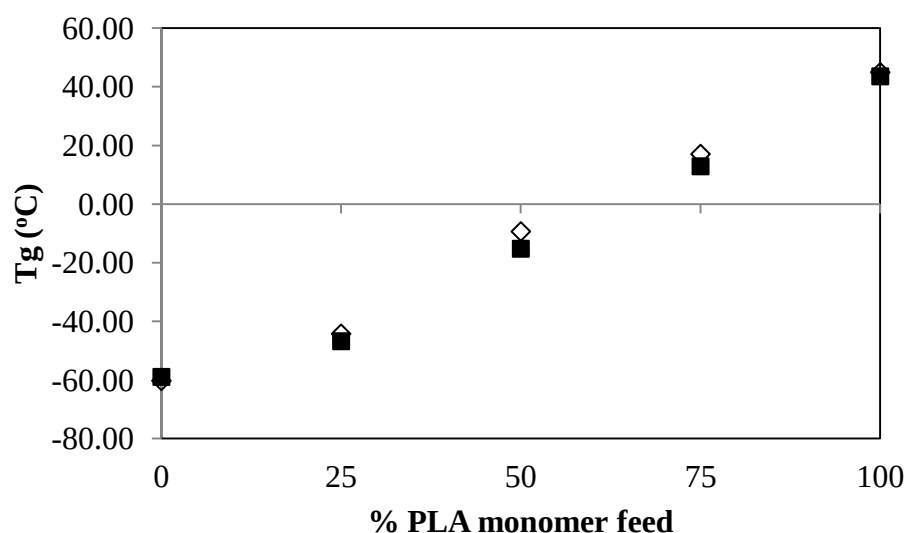


Figure 5.34 Plot of T_g against % of DLLA in the monomer feed for branched (■) and linear (◇) PLA-co-PCL using BOD crosslinker, BnOH and Sn(Oct)₂. Determined using DSC (sample size = 0.5 - 3mg, heating rate = 10 °C min⁻¹).

Figure 5.34 shows that the branched and linear copolymers have very similar T_g properties and follow a comparable trend. Additionally, the results were very close to the theoretical values calculated from the Fox equation, see in Table 5.6. This data suggests the synthesis of statistical branched copolymers where there is a random distribution of the PLA and PCL segments within the polymer.

Only the sample that contained 100 % ϵ -CL in the monomer feed was able to undergo crystallisation of the PCL chain segments. All the copolymerisation did not exhibit a T_m value. Figure 5.35 presents the comparison of the branched and linear DSC traces from the reactions conducted with a monomer feed of $[\epsilon\text{-CL}]_{37} : [\text{DLLA}]_{13}$ as a typical example of the copolymer data.

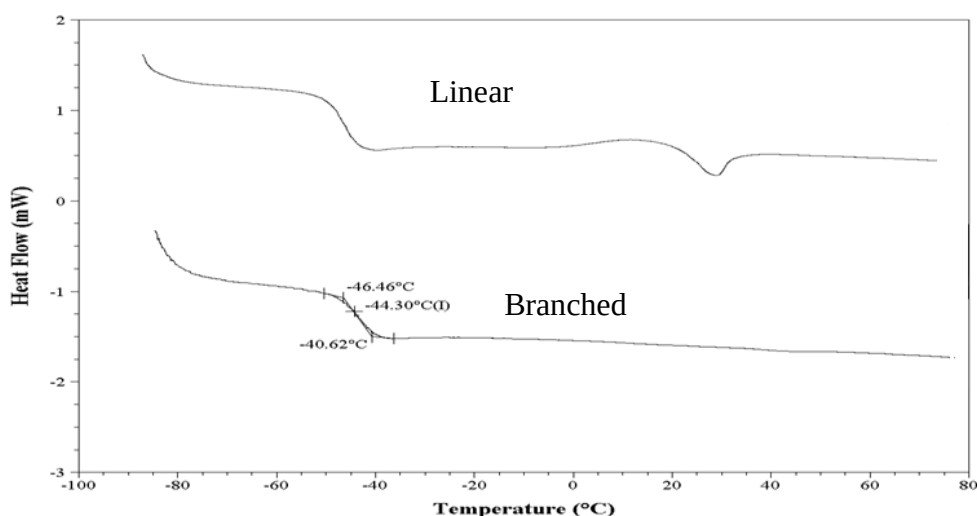


Figure 5.35 DSC comparison of linear (top) and branched (bottom) copolymers formed by ROP of DLLA and ϵ -CL in the absence and presence of BOD with ratio $[\text{DLLA}]:[\epsilon\text{-CL}]:[\text{BnOH}]:[\text{BOD}] = [13]:[37]:[1]:[0]/[0.6]$ at 150 °C in CH. Determined using DSC (sample size = 0.5 - 3mg, heating rate = 10°C min⁻¹).

The melting peak, corresponding to the crystalline area of PCL, was observed at approximately 30 °C for the linear sample. With the incorporation of BOD, the branched sample is unable to crystallise and there is no T_m present in the DSC spectrum. Additionally, the homopolymers of *b*-CL had also been shown to exhibit a T_m value in the DSC. Thus it would appear that the disruption of the crystalline regions cannot be achieved using branching alone with PCL, rather it requires inclusion of DLLA co-monomer. This is of particular interest in the applications of biodegradable, biocompatible polymers. The lack

of significant crystalline regions will result in a more linear degradation profile. Previous work has shown that the amorphous regions preferentially undergoes degradation, leaving clusters of high PCL crystallinity.⁵² Therefore incorporation of a small amount of branching could have significant implications in the future design and application of degradable polyesters.

5.3.5.1 Branched PCL-*co*-PLA Conclusions

Therefore, there is evidence that for the first time branched copolymers of ϵ -CL and DLLA have been synthesised in high yield using BOD as the branching agent. GPC analysis has provided evidence that linear random PCL-*co*-PLA was formed early in the reaction, before intermolecular branching reactions occur through the pendent BOD rings. The shoulders at high M_w suggested that *b*-PCL-*co*-PLA was being formed late in the reaction. No branching was achieved in an attempted ROMBP of DLLA indicating that ϵ -CL was required to achieve the incorporation of BOD. The higher ratio of ϵ -CL in the co-monomer reagent feed led to increased levels of *b*-copolymer being synthesised, as shown by increased $\bar{D}$ and higher M_w . The similarity in structure and reactivity of ϵ -CL and BOD provided the explanation for this enhanced level of branch polymer formation. As observed for the linear copolymers, DSC analysis suggested the formation of statistical copolymers. At the low targeted level of branching, *b*-homo-PCL was able to contain crystalline regions. The lack of a T_m peak when DLLA was incorporated was evidence that the presence of this co-monomer was necessary to disrupt the

b-PCL-*co*-PLA's ability to crystallise, whilst a T_m was observed in the linear analogue.

5.4 Conclusions

The work presented in this chapter studied the synthesis of branched biodegradable polymers using a di-functional monomer moiety. *b*-PCL and *b*-PCL-*co*-PLA have been produced using a di- ϵ -CL species (4,4-Bioxepanyl-7,7'-dione; BOD) as the branching agent.

The effect of the heating method upon the ROMBP synthesis of *b*-PCL was investigated, with a view to establishing if MWH had any specific effects on the kinetics and final product structures compared with CH. The dielectric properties of the BOD species were assessed and contrasted with the other reagents used in the study. It was suggested that BOD's high $\tan \delta$ values would make it susceptible to MWH energy. It was also observed that above 160 °C, BOD possessed a higher $\tan \delta$ value than the other reagents used in the synthesis of *b*-PCL. This could potentially lead to specific heating of the BOD moieties, resulting in enhanced rates of reaction and increased branching.

A series of experiments were conducted with BOD addition at varying levels of ϵ -CL conversion (0 %, 70 % and 100 %). When the BOD was present at the start of the reaction in a one-pot, one step synthesis, *b*-PCL was synthesised. GPC and NMR analysis showed that branching did not occur until at least 50%

ϵ -CL monomer conversion. However, the onset of branching was observed to occur at lower monomer conversion in MWH (> 50%) than in CH (> 70 %).

GPC-RI, GPC-MALLS and DSC data provided evidence for *b*-PCL formation. High molecular weight shoulders and an extremely broad $\bar{M}$ in the GPC-RI coupled with conformation plots in the GPC-MALLS showed branched architectures had been successfully achieved. In the homopolymerisations, T_m values at lower temperature than linear analogues were observed in the DSC traces, which proposed the view that branching had altered but not completely disrupted the crystalline state.

It was interesting to note that the presence of BOD slowed the k_{PCL}^{app} . This was because the BOD moiety would hinder the ϵ -CL units from reacting with the reactive site. A one-pot, two step reaction method was then adopted, which allowed for $\sim 70\%$ ϵ -CL linear conversion before BOD addition. The process created a fast formation of linear PCL chains before the successful formation of *b*-PCL. It was also observed that the MWH produced similar branched structures *via* both the 0 % and 70 % methods, whilst the CH did not achieve the same level of branching *via* the 70 % method. This was attributed to selective heating of the BOD increasing the reactivity of this moiety in the MWH reaction.

The effect of temperature and heating method on the BOD reactivity compared with that of ϵ -CL was studied, with reactions targeting a much smaller DP of 20. When the reaction temperature was 150 °C, MWH and CH had similar reactivity ratios, with the $k_{p\ PCL} / k_{p\ BOD}$ of 2.88 for MWH and 2.62 in CH.

However, when the reactions were conducted at 180 °C, which was observed to be a temperature both above the melting point of BOD and where the $\tan \delta$ of BOD indicated that it should be the most susceptible molecular species to selective heating within the mixture. At 180 °C, the reactivity ratios were determined to vary depending on the heating method used. In CH, the $k_p \text{PCL} / k_p \text{BOD}$ ratio was 2.55 (similar to the reactions at 150 °C). However, this ratio value dropped to 0.92 for MWH, supporting the postulation that MWH was selectively heating the BOD units at the elevated temperatures, increased the BOD reactivity with regard to the ϵ -CL.

GC-MS analysis of the initiation stage of the ROMBP of *b*-PCL with a target DP = 5 reactions supported the view that with MWH elevated BOD reactivity. It was found that free BOD in the bulk reaction mixture was depleted faster in MWH than in CH. Additionally, the ROP of BOD occurred before full formation of the true catalytic species had been achieved in MWH, which was not repeated in CH.

Finally, *b*-PCL-*co*-PLA was synthesised for the first time using the BOD species as the branching agent. It was observed that ϵ -CL was necessary in order to achieve BOD incorporation and that the increase of ϵ -CL in the monomer feedstock enhanced the amount of branching that was achieved. Indeed, larger $\bar{D}$ and M_w noted in the GPC traces for the *b*-PCL-*co*-PLA with higher ϵ -CL levels. It was also observed that branching alone did not disrupted crystallinity resulting in the loss on the T_m values. Rather, DLLA was required

to achieve this. This observation also confirmed that DLLA had been successfully incorporated into the branched copolymer.

5.5 References

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6 Conclusions and Future Work

This chapter draws together the research in this thesis and outlines the overall conclusions drawn from the ring-opening polymerisation system investigated. This chapter also provides possible routes of future work that may be explored for the further understanding and development of the topics discussed.

6.1 Thesis Summary

The work presented in the thesis attempted to gain in-depth understanding of the effect that the microwave energy has on various facets of the ring-opening polymerisation of cyclic esters with a view to synthesising novel bio-degradable homopolymers, branched structures and copolymers.

The effect that microwave heating has upon the homopolymerisation of poly(ϵ -caprolactone) was investigated initially. It was shown that the ROP of ϵ -CL could be enhanced with the use of MWH, especially during the early stages of the ROP reaction. This was rationalised using the dielectric properties of the reagents. Accurate temperature monitoring was applied during various stages of the reaction mechanism ensure experimental errors were avoided when comparing the two heating methods.

Copolymerisation reactions to form PLA-co-PCL were also found to be influenced by the heating method. In a one pot method, the relative reactivity ratios of the two monomers were influenced by MWH. The dielectric properties of the reagents and their polymer structures are used to rationalise these experimental observations. Further attempts to use this phenomenon using sequential monomer addition was unable to afford block copolymers as transesterification processes dominated at the high reaction temperatures.

Finally, branched polymers using a di-lactone branching agent, composed to two joined ϵ -CL units, were synthesised. The effect of microwave energy was scrutinised on the branching process. It was found that MWH affect the relative reactivity ratios of the monomer and branching agent, leading to faster incorporation of branching species in the growing polymer chain and an earlier onset of branching.

6.2 Chapter 3: Investigation into the Effect of Microwave Energy on the Ring-Opening Polymerisation of ϵ -Caprolactone

6.2.1 Conclusions

This chapter presents work carried out to establish the true cause for enhanced rates of reaction and shortened cycle time observed when the ROP of ϵ -CL was conducted using MWH. This was achieved *via* establishing a thorough

understanding of the various reagent dielectric properties coupled with accurate temperature monitoring of the reactions in real time.

The work in this chapter highlighted that various experiment and procedural errors were present in many of the literature reported studies. Many of these had led from inconsistent and inaccurate temperature monitoring in MWH reactions. Consequently, conclusions that were focused on the presence of a specific microwave effect were shown to be incorrect. A FO probe placed into the reaction medium emphasised the erroneous temperature reading from an external IR sensor built into the equipment by the manufacturer, which may have led to exaggerated rates of reactions calculated in MWH in previous work because the conventionally heated reactions had not been conducted at the same temperature.

This work demonstrated that reduction of the induction and initiation stages of the reaction were a key element to the shortening of the cycle time in MWH. A large temperature overshoot was observed to occur and the delay before PCL growth was diminished in MWH. The dielectric properties of the monomer and the tin pre-catalyst were used to rationalise these enhancements. It was also concluded that the formation of the true catalytic species was enhanced in MWH, and ϵ -CL units were observed to undergo ROP prior to complete true catalyst formation, thus reducing the initiation period with MWH, backed up with ^1H NMR.

MWH was found to have less of an improvement over CH during the propagation stage, as the less ‘microwave susceptible’ PCL became a more

significant component of the ROP mixture. However, there was evidence that the active species were still able to experience selective heating as the rate of propagation was determined to be faster in MWH.

Overall, it was shown that MWH was able to synthesise PCL in a controlled manner with faster rates of reaction compared with CH. It was concluded that these improvements were caused by thermal effects due to targeted heating of key reaction reagents in the MWH reactions.

6.2.2 Future Work

The use of MWH technology to synthesise PCL in large quantity in a ‘green’ process is a key area of research that would follow on from the fundamental understanding achieved in the small scale system used in this thesis.^{1, 2} The National Centre for Industrial Microwave Processing (NCIMP) at the University of Nottingham contains experts in the field of large scale MWH synthesis.³ The work contained in this chapter in this thesis investigated the MWH effects on the batch process to ROP ϵ -CL. Collaborative efforts with the chemical engineers within NCIMP to construct continuous flow PCL equipment is potential future work. Using the conclusions from this thesis, potential routes forward may involve microwave energy being used specifically for the induction and initiation stage of the process, where the reagents were revealed to be most susceptible to MWH and the greatest enhancements were observed. For the next stage of the continuous reaction,

conventional heating, or the latent heat in the bulk, could keep the mixture at reaction temperature during the propagation stage in a continuous process.

The method of introducing the microwave energy into the reaction mixture may be an interesting line of future work. If the power was pulsed into the system, the active species may be the only component able to experience the inputted energy, thus selective heating may be possible even at high monomer conversion and increased bulk viscosity.⁴ This would result in less overall energy required and a 'greener' process.⁵

6.3 Chapter 4: Synthesis of Biodegradable Copolymer, PLA-co-PCL, using Microwave Heating

6.3.1 Conclusions

The research in Chapter 4 relates to the novel synthesis of PLA-co-PCL copolymers using MWH. Following detailed analysis of the reagent dielectric properties, attempts were conducted to synthesise block-copolymers via selective heating of reagents that were known to be highly susceptible to microwave energy.

Initial work studied the effect of MWH on the homopolymerisation of DLLA. It was found that MWH was able to extend the window of controlled ROP of DLLA to a higher level of monomer conversion than detected using CH. The

selective heating of the remaining DLLA units and the tin active species was given for the ability of MWH to encourage propagation and suppress unwanted transesterification reactions.

In a one-pot, one step methodology, a statistical PLA-co-PCL copolymer was formed using both heating methods. It was noted that MWH enhanced the rate of DLLA polymerisation compared to ϵ -CL, rationalised by the high dielectric properties of the DLLA units leading to selective heating. Toward the end of the reaction profile, at very low levels of un-reacted monomer, there was evidence that MWH encouraged transesterification.

Various sequential monomer addition methods were attempted from PLA macro-initiators, with and without isolation of the first block. When attempting re-growth from a PLA macro-initiator, MWH appeared to promote transesterification process which resulted in a mixed statistical copolymer material. With the CH method, the PLA initiated copolymerisation strategies led to a chain transfer dominated system which produced separate homopolymers.

The ability of the heating method to affect the final product structure and properties was rationalised by the ability of MWH specifically target specific reactions between reagents that have high dielectric values within a multi-component reaction mixture.

6.3.2 Future Work

An interesting route for the future work from Chapter 4 is a comprehensive study into the mechanical properties and degradation rates of the copolymeric structures that were synthesised in this chapter. The ability of MWH to target precise and reproducible structures with pre-determined degradation rates and mechanical properties could lead to the synthesis of bio-degradable statistical copolymers for interesting applications.⁶⁻⁸

It would be interesting to examine the effect of MWH on the copolymerisation of DLLA and/or ϵ -CL with other bio-renewable monomer for the synthesis of bio-degradable polyesters, for example L-lactide or glycolide.⁹ A careful investigation into the various monomer dielectric properties could lead to choosing co-monomers with differing susceptibility to MWH energy, thus the ability to alter the copolymeric structure *via* selective heating.

6.4 Chapter 5: Synthesis of Branched Poly(ϵ -Caprolactone) using Microwave Heating

6.4.1 Conclusions

The work presented in this chapter studied the synthesis of branched biodegradable polymers using a di-functional monomer moiety (4,4-

Bioxepanyl-7,7'-dione; BOD). *b*-PCL and *b*-PCL-*co*-PLA were demonstrated to have been produced using a di- ϵ -CL species as the branching agent.

For the first time, MWH was used to synthesise *b*-PCL using BOD as a branching agent. Initial research used ^1H NMR, GPC-RI, GPC-MALLS and DSC analysis to prove that *b*-PCL had been synthesised from a one-pot one step approach. MWH appeared to encourage branching at a lower level of ϵ -CL conversion than in the CH equivalent reaction, however it was noted that the presence of BOD lowered the rate of PCL polymerisation.

Hence, a two step method was attempted, with linear PCL polymerised before the addition of BOD and 70 % ϵ -CL conversion. Again, various analytical techniques were used to study the formation of *b*-PCL, but the two step method was observed to have a shorter cycle time with no loss of branching compared with the one step process. Finally, retrospective branching was attempted, with BOD added to PCL with 100 % ϵ -CL conversion, however no evidence of branching was observed.

The effect of temperature and heating method on the relative rates of BOD and ϵ -CL conversion was investigated. Reactions targeting a lower DP were conducted above and below the temperature that the dielectric property measurements indicated that BOD would be highly susceptible to MWH. It was found that below this key temperature, the ratio of BOD to ϵ -CL reactivity was the same for each heating method. At the elevated temperature, this ratio remained constant for the CH reaction. However, in the MWH reaction at the elevated temperature, the BOD units were observed to have a significantly

enhanced rate of reaction, which was proposed to be caused by selective heating in MWH, as supported by the dielectric property analysis.

Finally, DLLA was introduced to synthesise *b*-PLA-*co*-PCL for the first time using BOD as the branching agent in CH. It was observed that ϵ -CL was necessary in order to achieve BOD incorporation and that the increase of ϵ -CL in the monomer feedstock enhanced the amount of branching that was achieved.

6.4.2 Future Work

As branched materials are known to exhibit interesting properties compared with their linear counterparts, a thorough mechanical and rheological investigation into the *b*-PCL and *b*-PLA-*co*-PCL produced would be interesting future work.¹⁰ It would be important to establish if the heating method produced branched structures with vastly differing properties as this would lead to attractive applications.

It would be extremely interesting to investigate the effect of MWH on the synthesis of *b*-PLA-*co*-PCL using BOD. From the dielectric studies it was noted that the three monomers have significantly higher $\tan \delta$ values at different temperature windows. Thus, it is postulated that careful control over the exact reaction temperature (with a FO probe) could have an important effect on the relative rates of reaction, resulting in structural manipulation. Future work could also study similar branching agents, for example di-lactide

unit or variations on the BOD di-lactone species.¹¹ Also, branching agents with differing dielectric properties and physical state at the reaction temperature may result in selective heating and offer control over the degree of branching.

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