ELSEVIER

Polymer 42 (2001) 6669–6671

polymer

www.elsevier.nl/locate/polymer

Polymer Communication

Ruthenium initiated ring opening metathesis polymerisation of amino-acid and -ester functionalised norbornenes and a highly selective chain-end functionalisation reaction using molecular oxygen

Stefano C.G. Biagini[a], R. Gareth Davies[a], Vernon C. Gibson[b,*], Matthew R. Giles[b], Edward L. Marshall[b], Michael North[a,1]

[a]*Department of Chemistry, King's College London, Strand WC2R 2LS, UK*
[b]*Department of Chemistry, Imperial College of Science, Technology and Medicine, Exhibition Rd, South Kensington SW7 2AY, UK*

Received 13 December 2000; received in revised form 19 February 2001; accepted 22 February 2001

Abstract

[Ru(=CHPh)(PCy_3)$_2$$Cl_2$] is shown to initiate the living ring opening metathesis polymerisation of amino-acid and -ester functionalised norbornenes; treatment of the living polymers with molecular oxygen gives rise to a highly selective chain-end functionalisation reaction.

Keywords: Ruthenium; Polymerisation; Metathesis

Living ring-opening metathesis polymerisation (ROMP) of norbornenes is a versatile method for the preparation of synthetic polymers with controlled molecular architectures [1]. A wide range of functionalised norbornenes have been investigated using well-defined molybdenum [2] and, more recently, ruthenium initiators [3,4]. We are interested in the synthesis of protein mimics via ROMP and have described previously the polymerisation of amino-ester [5,6] and peptide [7] derivatised norbornenes using well-defined molybdenum initiators. In furthering our studies on protein mimics we wished to study monomers bearing amino acid groups. In this case, it is necessary to employ the hydroxyl tolerant ruthenium initiator system which has been shown previously to polymerise monomers bearing penicillin [8], nucleic-acid base [9] and carbohydrate [10–13] functionalities. Here, we report the successful polymerisation of amino-acid (and -ester) functionalised norbornenes using [Ru(=CHPh)Cl_2(PCy_3)$_2$] and a remarkably selective end-functionalisation reaction using molecular oxygen.

The amino-acid and -ester monomers **2**–**9** were prepared as reported previously [14]. Initially, a series of NMR scale polymerisations were carried out in which 10 equiv. of monomer were added to initiator **1** in thf-d_8. For each reaction the formation of a 'living' chain-end was confirmed by the observation of propagating carbene resonances in the ^{1}H NMR spectrum (Table 1), the polymerisations all being completed within 15 min. The presence of two carbene signals is common to all the spectra recorded using monomers **2**–**9**. The two signals arise from mono- and bis-phosphine species [15]; the mono(phosphine) propagating species affords a lower intensity signal at ca. 18.5 ppm, the predominant bis(phosphine) resonance occurs at 19.6–19.8 ppm. The assignment was confirmed by adding one equivalent of PCy_3 to the NMR sample whereupon the resonance at 19.6 ppm is enhanced at the expense of the resonance at 18.5 ppm.

The polymerisations were then scaled-up (in THF solvent for the amino acid monomers, CH_2Cl_2 for the ester monomers) using 50–100 equiv. of monomer. After 4 h the reactions were terminated by treatment with ethylvinylether and, after precipitation from hexane, the homopolymers were isolated in typically >75% yield. The *cis*/*trans* alkene ratio for each homopolymer was determined by ^{1}H NMR spectroscopy (Table 1), and in every case a polymer with predominantly *trans*-double bonds was formed (81–87%). Comparison of the ^{13}C NMR spectra of the polymers derived from monomers **4** and **5** (and **8** and **9**) showed

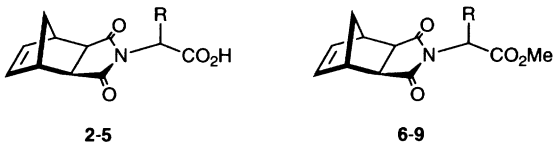
* Corresponding author. Tel.: +44-020-7594-5830; fax: +44-020-7594-5810.
E-mail addresses: v.gibson@ic.ac.uk (V.C. Gibson), michael.north@kcl.ac.uk (M. North).
[1] Tel.: +44-020-7848-1164.

0032-3861/01/$ - see front matter
PII: S0032-3861(01)00146-X

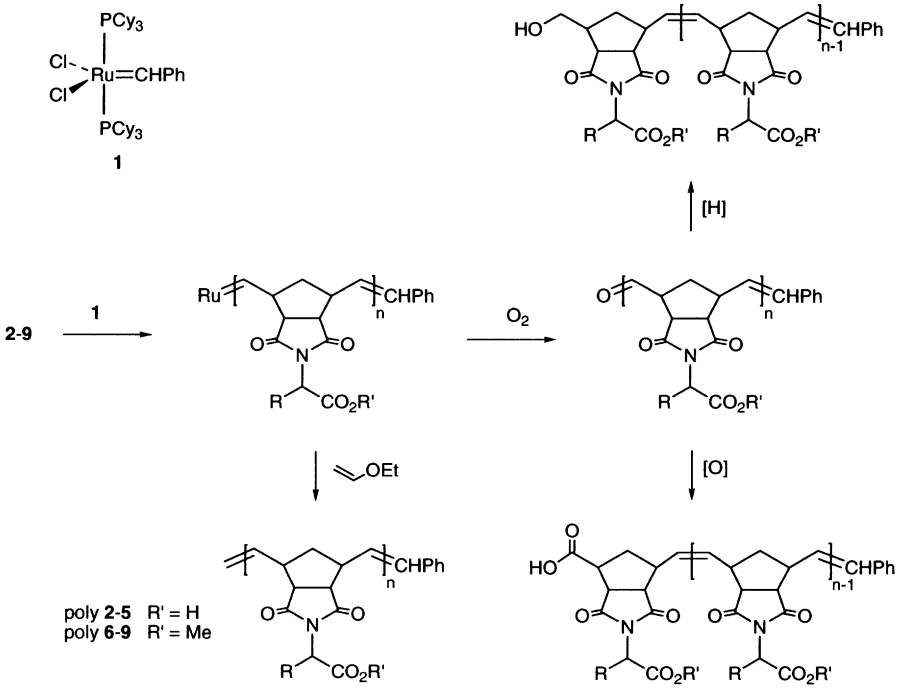
Table 1
Characterisation data for poly-**2**–**9**

Monomer	δ_H Ru=CH (ppm)	σ_t	M_n (calc[a])	M_n[b]	M_w[b]	M_w/M_n	T_g (°C)	$[\alpha]_D^{25}$	Yield (%)[f]
2	19.58[c], 18.53	87	29,500	32,400[d]	43,100[d]	1.33	204	–	77
3	19.56[c], 18.49	85	35,300	35,900[d]	48,500[d]	1.35	216	− 31[d]	96
4	19.72[c], 18.58	84	18,200	26,700[d]	36,600[d]	1.37	188	− 52[d]	89
5	19.83[c], 18.64	84	20,000	20,100[d]	27,300[d]	1.36	193	–	65
6	19.58[c], 18.52	87	23,400	23,200[e]	34,300[e]	1.48	130	–	75
7	19.57[c], 18.52	84	37,400	32,900[e]	40,100[e]	1.22	141	− 35[d]	97
8	19.75[c], 18.63	85	15,000	15,000[e]	16,500[e]	1.11	137	− 59[d]	73
9	19.82[c], 18.53	81	13,800	23,800[e]	34,500[e]	1.45	138	–	70

[a] Based upon monomer to initiator ratio.
[b] Determined by GPC relative to polystyrene standards; GPC was performed using two PSS SDV 10 μm linear columns connected to a Gynkotek Model 300 HPLC pump and a Knauer differential refractometer.
[c] Signal of highest intensity.
[d] Using tetrahydrofuran as the solvent.
[e] Using chloroform as the solvent.
[f] After precipitation from hexane.



2, **6** R = H
3, **7** R = Me(*S*)
4, **8** R = CHMeEt(*S*,*S*)
5, **9** R = CHMeEt(*RS*,*RS*)



Scheme 1.

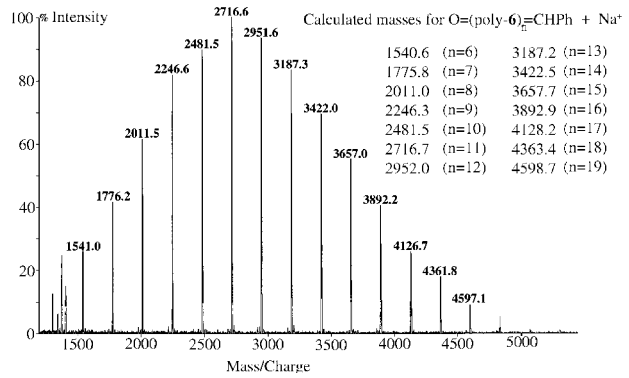


Fig. 1. MALDI–TOF mass spectrum obtained from poly-**6** terminated by reaction with oxygen.

that no epimerization of either of the stereocentres had occurred during the polymerisation.

The polymers derived from enantiomerically pure monomers (**3**, **4**, **7** and **8**) are optically active (see Table 1) with specific rotations of the polymers derived from monomers **7** and **8** being identical to those recorded for the same polymers prepared using molybdenum initiators [3,4]. This demonstrates that the specific rotation of these polymers is not sensitive to the *cis*/*trans* vinylene content within the polymer backbone. The amino-acid functionalised polymers display higher Tg's than the ester derivatives, most likely due to the presence of intermolecular hydrogen bonding between the pendant carboxylic acid groups.

The termination of the polymerisation by addition of ethylvinylether affords methylidene end-groups. However, if a solution of the living polymer is exposed to molecular oxygen for 24 h, an aldehyde end-group is introduced in high yield [16]. The ^{1}H NMR spectrum arising from treatment of living poly-**6** with oxygen affords several overlapping resonances due to the aldehyde end-capped polymer chains at ca. 9.7–9.8 ppm and a singlet at 10.09 ppm attributable to benzaldehyde arising from the reaction of oxygen with unconsumed **1**. Further evidence is provided by a MALDI–TOF spectrum of poly-**6** (Fig. 1) obtained from the reaction of 5 equiv. of **6** with **1** and terminated by introducing an atmosphere of O_2, followed by stirring of the solution for 1 h. The spectrum is in good agreement with oligomers bearing an oxo and a benzylidene end-group (each oligomer carrying a sodium cation).

In order to investigate the fate of the ruthenium species, **1** was stirred in CH_2Cl_2 under an atmosphere of oxygen for 6 h, by which time approximately 50% conversion had occurred. Evidently, the ruthenium initiator species reacts more slowly with oxygen than the propagating carbene species. The initially magenta-coloured solution of **1** changes to dark purple-brown and ^{1}H NMR analysis confirms that the benzylidene unit is converted cleanly to benzaldehyde. The ^{31}P NMR spectrum reveals two phosphorus-containing species, at 50.75 and 29.73 ppm. The resonance at 50.75 ppm is due to $Cy_3P{=}O$; the other signal is consistent with a tertiary phosphine group bonded to ruthenium. To date, it has not proved possible to isolate and identify this species.

The aldehyde end-group provides a versatile functionality for further end-functionalisations of these polymers. For example, reduction of poly-**6**-CHO with sodium borohydride affords the primary alcohol (CH_2OH) chain-end (Scheme 1), the hydroxyl group of which appears as a broadened resonance at 8.95 ppm in the ^{1}H NMR spectrum ($CDCl_3$); consistently, this signal is quenched upon shaking with D_2O. The aldehyde-capped polymer can also be oxidised to the corresponding carboxylic acid by treatment with sodium chlorite and hydrogen peroxide in a potassium phosphate buffer. This remarkably selective end-functionalisation process thus allows hydroxyl, aldehyde or acid functionalities to be introduced into ROMP products generated by ruthenium initiators, a process not available to well-defined initiators based on other metals.

Acknowledgements

The authors thank the EPSRC for financial support and Novartis for a CASE studentship (to M.R.G.). Thermomechanical analyses were carried out by the ULIRS service at Birkbeck College, University of London.

References

[1] Ivin KJ, Mol JC. Olefin Metathesis and Metathesis Polymerisation. London: Academic Press, 1997.
[2] Schrock RR. Acc Chem Res 1990;23:158.
[3] Schwab P, France MB, Ziller JW, Grubbs RH. Angew Chem, Int Ed Engl 1995;34:2039.
[4] Schwab P, Grubbs RH, Ziller JW. J Am Chem Soc 1996;118:1003.
[5] Coles MP, Gibson VC, Mazzariol L, North M, Teasdale WG, Williams CM, Zamuner DJ. J Chem Soc, Chem Commun 1994:2505.
[6] Biagini SCG, Coles MP, Gibson VC, Giles MR, Marshall EL, North M. Polymer 1998;39:1007.
[7] Biagini SGC, Davies RG, Gibson VC, Giles MR, Marshall EL, North M, Robson DA. J Chem Soc, Chem Commun 1999:235.
[8] Biagini SGC, Gibson VC, Giles MR, Marshall EL, North M. J Chem Soc, Chem Commun 1997:1097.
[9] Gibson VC, Marshall EL, North M, Robson DA, Williams PJ. J Chem Soc, Chem Commun 1997:1095.
[10] Mortell KH, Gingras M, Kiessling LL. J Am Chem Soc 1994;116:12053.
[11] Fraser C, Grubbs RH. Macromolecules 1995;28:7248.
[12] Mortell KH, Weatherman RV, Kiessling LL. J Am Chem Soc 1996;118:2297.
[13] Nomura K, Schrock RR. Macromolecules 1996;29:540.
[14] Biagini SGC, Bush SM, Gibson VC, Mazzariol L, North M, Teasdale WG, Williams CM, Zagotto G, Zamuner G, Zamuner D. Tetrahedron 1995;51:7247.
[15] Robson DA, Gibson VC, Davies RG, North M. Macromolecules 1999;32:6371.
[16] This reaction appears to be a unique feature of the ruthenium initiator system since termination of molybdenum-initiated polymerisations by molecular oxygen results in the formation of a polymer with double the expected molecular weight; this is due to a further reaction between the aldehyde end-group and the molybdenum alkylidene remaining in solution: Feast WJ, Gibson VC, Khosravi E, Marshall EL, Mitchell JP. Polymer 1992;33:872.