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Towards degradable polyethylene: end-functionalised polyethylene (PE-X) and PE-I/LDPE blends from iron-catalysed chain growth of ZnEt₂ with ethylene†

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A series of end-functionalised polyethylene materials (PE-X) has been prepared *via* the catalysed chain growth (CCG) reaction of diethyl zinc with ethylene, catalysed by a bis(imino)pyridine iron catalyst activated by MAO. This CCG catalyst system enables the *in situ* formation of long alkyl chain zinc species Zn(PE)₂, which are subsequently quenched to form PE-X. Quenching with oxygen results in PE-OH, but the functionalisation appears to be limited to approximately 80% due to the formation of mixed [ZnR(OR)]_n clusters. Functionalisation with sulfur leads to polysulfides, PE-S_k-PE, whereby k is affected by temperature. Functionalisation with iodine leads to PE-I with high conversion, but the degree of functionalisation appears to be chain length dependant. PE-I has been blended with LDPE, either through solution mixing or *via* melt blending to give PE-I/LDPE blends with different chain lengths. Characterisation of the PE-I/LDPE blends has been carried by IR spectroscopy and thermal analysis (DSC). Surface analysis by FIB-SEM and EDX analysis up to 6 μm into the surface has shown a uniform distribution of PE-I within the LDPE matrix. The propensity of alkyl iodides to undergo photolytic cleavage makes these PE-I/LDPE materials interesting candidates for degradable PE.

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Introduction

Polyethylene (PE) is currently the most widely used synthetic polymer on the market and accounts for almost one third of the total global plastics production, which translates to approximately 90 Mt per annum.^{1–3} A wide range of different types of PE are available, all with polymer properties designed for specific applications. Many of these properties cannot easily be obtained by other polymers at a reasonable cost, including polymers from bio-derived or renewable resources. The unique and tuneable properties of PE-based materials and their versatility, combined with their low cost and ease of production, have made PE the most successful polymer on the

market and the material of choice for many applications today and for some time to come.

The main classes of polyethylene, LDPE, LLDPE, HDPE and UHMWPE, are prepared using different catalyst systems and, in the case of LLDPE through incorporation of co-monomers.⁴ Post-functionalisation of polyethylene can be carried out to modify certain polymer properties using a range of methods,⁵ for example through oxidation or chlorination of surface C–H bonds to prepare oxygenated or chlorinated PE.⁶ An alternative strategy to introduce specific functionality into polyolefins like PE is through melt-blending with end-functionalised polyethylene. In this context, well-defined functionalised polymers, so called smart materials, have become increasingly important targets in recent years.^{7–10}

Commercially available end-functionalised alkanes are only up to C₁₈. A convenient method to generate longer polyethylene chains with reactive chain ends (PE-X) is *via* reversible coordinative chain transfer polymerisation.^{9,11} This method uses a polymerisation catalyst (M¹) in combination with a chain transfer agent (M²) and makes use of a very fast and reversible exchange of the growing polymer chains (P¹ and P²) between the catalyst and a transfer agent (see eqn. (1)). A range of transition metal catalysts can be used, whereby transfer

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Table 1 Chain length variations in Zn(PE)₂ at different Zn/Fe ratios

Run	ZnEt ₂ [mmol]	ZnEt ₂ Equiv.	Activity [g mmol ⁻¹ h bar ⁻¹]	λ ^a	C _n ^b
1	0	0	PE ^c	—	—
2	2.5	250	PE ^c	—	—
3	3.0	300	1380	31	64
4	3.5	350	1420	21	44
5	4.0	400	820	14	30
6	4.5	450	600	11	24
7	5.0	500	690	8	18
8	5.5	550	482	7	16
9	6.0	600	500	4	10

Conditions: catalyst **1** (10 μmol), MAO (100 eq.), toluene solvent (30 mL), room temperature, 1 barg ethylene, 1 hour reaction time. ^a λ = mean number of ethylene units inserted, determined by GC analysis. ^b C_n = mean chain length, determined by ¹³C-NMR analysis. ^c No exchange to zinc is observed.

0.30 ppm in the ¹H NMR and at 16.3 ppm in the ¹³C NMR spectrum, as well as the in-plane rocking vibration at 628 cm⁻¹, typical for ZnCH₂ units.⁵⁹ The high reactivity of the Zn–C bond can be exploited to prepare a range of end-functionalised PE-X compounds, as illustrated in Scheme 2

Hydrolysis of Zn(PE)₂ results in a distribution of linear alkanes. The Poisson distribution of the *n*-alkane oligomers allows quantitative ¹³C NMR analysis to be used to estimate the mean chain length C_n by comparing integrals for CH₃ with those for CH₂ signals (Table 1, last column). Further analysis can be achieved by GC-FID. The average molecular weight is generally too low for accurate GPC analysis, whereas analysis by GC-FID will only capture part of the total distribution, because the longer alkanes are only partially soluble and insufficiently volatile for GC analysis, as illustrated in Fig. 1. Only the first part of the total distribution is therefore quantifiable, and these values can be used as inputs for the Poisson equation (eqn. (2)) to extract λ, the mean number of inserted ethylene units (*L* is the amount of catalyst used). The total amount of each alkane of chain length *n* obtained at the end of the reaction can then be calculated.^{60,61} For example, the calculated value of λ = 14 for run 5 in Table 1 suggests an average chain length of 30 carbons which is very close to the value of 30 carbons determined by ¹³C NMR spectroscopy (see Table 1 for other values). Comparison of the average chain lengths determined by GC and NMR analysis shows excellent agreement (Fig. 2). This fitting method allows the entire product distribution to be determined from a subset of experimental data obtained by GC analysis.

$$\text{Poisson equation: } \text{mol}(n)_{\text{tend}} = \frac{L\lambda^n}{n!} e^{-\lambda} \quad (2)$$

There appears to be no convenient nomenclature to describe mixtures of compounds with long alkyl chains, where the length of the chains follows a Poisson distribution, other than quoting an M_n value. In order to describe the chain length in our product mixtures, we will henceforth use the italicised *n* value (*n*) to describe an average chain length, *i.e.*



Fig. 1 Experimentally determined *n*-alkane distribution by GC-FID (blue) versus calculated distribution based on the Poisson equation (red, data from run 5 in Table 2).

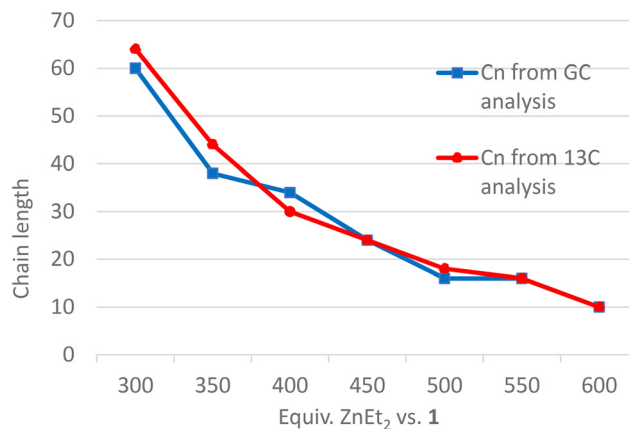


Fig. 2 Zn(PE)₂ chain length (C_n) as a function of Zn/Fe ratio.

C_nH_{2n±2} to describe a mixture of alkanes with an average chain length *n*. We will use the same nomenclature for other related compounds, *i.e.* Zn(C₃₀H₆₁)₂ will result in C₃₀H₆₂ upon hydrolysis, or C₃₀H₆₁I upon reaction with iodine. C₃₀H₆₁I is thus a mixture of alkyl iodides with chain lengths clustered around C₃₀, whereas C₃₀H₆₁I would be the pure compound.

End-functionalisation with oxygen

Initial experiments with dipentylzinc as a model compound for Zn(PE)₂ and synthetic air (80% N₂/20% O₂, dry) resulted in a mixed alkyl alkoxide complex, [Zn(OPent)Pent]_n, according to NMR analysis (see Fig. S4 and 5[†]), presumably a tetramer (*n* = 4) as seen in related examples.^{62,63} Hydrolysis of the zinc



cluster resulted in pentanol with 78% selectivity, the remainder being pentane. A reaction with pure oxygen instead of air gave similar results but was subsequently avoided for safety reasons. Subsequently, CCG reactions using ZnEt₂ and catalyst **1** (Zn/Fe = 300) have been carried out at 1 bar ethylene pressure and the product Zn(PE)₂ was reacted with air prior to hydrolysis (see Table 2). Reactions were carried out using different amounts of catalyst, which did affect the activity somewhat. The products in both reactions have a similar average chain length, analysed as C₆₈H₁₃₇OH according to ¹³C NMR with 65–74% OH-functionalisation, the remainder of the product mixture being linear alkanes.

The formation of end-functionalised PE-OH from the reaction of Zn(PE)₂ with oxygen has been investigated previously using Ziegler–Natta catalysts and metallocenes,^{45,46,64} titanium guanidate catalysts,⁴¹ and also with the Fe/Zn catalyst system use here.^{36–40} In all these reports, the degree of OH-functionalisation is less than 80%, with the remainder being alkanes (PE-H) formed upon hydrolysis. The incomplete reaction of zinc alkyls with oxygen is likely due to the formation of mixed zinc alkyl alkoxide “ZnR(OR)” clusters, as reported by Lewinski.^{62,65,66} For example, the reaction of ZnMe₂ with oxygen has been reported to generate [Zn(OMe)₂(Zn(OMe)Me)₆], which upon hydrolysis would only yield 57% MeOH. It is possible that for ZnR₂ with longer alkyl chains, similar [Zn(OR)_xR_y] clusters are generated which upon hydrolysis will generate different yields of ROH.^{62,67,68} We can thus conclude that end-functionalisation of Zn(PE)₂ to generate PE-OH appears to have an upper limit of approximately 80% selectivity, because this functionalisation suffers from an inherent problem due to the formation of stable mixed alkyl/alkoxide zinc clusters upon reaction with oxygen.

End-functionalisation with sulfur

The incorporation of sulfur into polymers, for example the vulcanisation of rubber, has been an important aspect in polymer chemistry for a long time, and is currently finding renewed interest for other polymers.^{69–71} The reaction of main group alkyls with elemental sulfur has been known for some time and generally results in the formation of dialkyl polysulfides R-S_k-R.⁷² Boisson *et al.* have shown that Mg(PE)₂ reacts with sulfur to generate PE-S_k-PE polysulfide polymers, where *k* =

1–8. Previous studies on the reaction between ZnEt₂ with sulfur in equimolar amounts resulted in the formation of [Zn(SET)Et]_n clusters such as [Zn(SET)Et]₁₀,⁷³ similar as for the reaction with oxygen discussed in the previous section. Increasing the ratio of sulfur to zinc leads to the formation of [(ZnS)Zn(SET)₂]_n clusters, together with the formation of SET₂ and S₂Et₂.⁷⁴

Initial reactions of dipentylzinc with sulfur in an equimolar ratio showed the formation of C₅H₁₁-S_k-C₅H₁₁ (where the ratio of *k* = 1 : 2 : 3+ was 21 : 42 : 37), together with unreacted dipentylzinc (see Fig. S6†). The reaction of excess sulfur (4 equiv.) with Zn(PE)₂ resulted in the formation of PE-S_k-PE polymers with 71% functionalisation, the remainder being linear alkanes formed upon hydrolysis. Analysis by ¹H NMR reveals a ratio between PE-S-PE, PE-S₂-PE and PE-S₃₊-PE of 11 : 42 : 47 (see Fig. 3). Considering an average chain length of C₂₂ in this case, an average value of *k* = 4 could be calculated from elemental analysis (see Table S1†). Analysis of PE-S_k-PE by Raman spectroscopy (Fig. S8†) has shown a characteristic C–S vibration at 744 cm⁻¹.⁷⁵ When PE-S_k-PE was heated in toluene at 80 °C for one hour a reduction of *k* was observed, specifically in the amount of PE-S_k-PE with *k* ≥ 3 (see Fig. S7†), in line with the general thermal instability of polysulfides with *k* > 3.⁷⁶

End-functionalisation with iodine and bromine

The reaction of Zn(PE)₂ with an excess I₂ results in 1-iodoalkanes (PE-I), together with ZnI₂. A range of 1-iodoalkanes with various average chain lengths has been prepared, a selection is shown in Table 3. The products have been analysed by GC, ¹H, ¹³C NMR and IR spectroscopy, as well as thermal analysis (Fig. S10–15†). Analysis of long chain 1-iodoalkanes by GC is reliable for short chain lengths up to C₂₀ and fitting of the GC results to the Poisson formula allows full characterisation of the distribution of chain lengths to be determined (see Fig. S14†). Average chain length values have been determined by ¹³C NMR analysis (see Fig. S11†). IR spectroscopic analysis can also be used for relatively short alkyl iodides, using the ratio of ν(C–H) signal at 3000 cm⁻¹ relative to the characteristic ν(C–I) stretch at 603 cm⁻¹ (see Fig. S15–17†).

Thermal analysis was carried out on a series of four longer chain PE-I samples with different chain lengths, ranging from C₄₈ to C₈₈ alkyl iodides. Analysis by DSC shows two endothermic processes (Fig. 4), one centred around 60–70 °C and another around 110–120 °C. The former signal is more dominant for the shorter chain alkyl iodides, whereas the latter becomes the main transition for the longer chain products. Melting points for linear alkyl iodides C_nH_{2n+1}I of different chain lengths follow a hyperbolic relationship (Fig. S20†), approaching the melting point of HDPE for *n* → ∞, and the melting points of pure C₄₈H₉₇I and C₈₈H₁₇₇I are 91 °C and 110 °C, respectively.^{77,78} The two transitions seen here are due to the fact that we have mixtures of linear alkyl iodides with different chain lengths that lead to the formation of solid solutions before complete melting of the material takes place. Similar complex behaviour has been reported for mixtures of alkanes and perfluorinated alkanes.^{79,80}

Table 2 Synthesis of PE-OH from Zn(PE)₂ upon reaction with air

Run	Yield [g]	Zn/Fe ratio	Activity [g mmol ⁻¹ h bar ⁻¹]	λ ^c	C _n ^d	Funct.(%)
1 ^a	3.84	300	384	33	68	74
2 ^b	19.9	300	497	33	68	65

^a Conditions: catalyst **1** (10 μmol), MAO (100 eq.), toluene solvent (30 mL), room temperature, 1 bar ethylene, 1 hour reaction time, quenched with air ^b Conditions: catalyst **1** (40 μmol), MAO (100 eq.), toluene solvent (120 mL), room temperature, 1 bar ethylene, 1 hour reaction time, quenched with air ^c λ = mean number of ethylene units inserted, determined by GC analysis ^d C_n = mean chain length, determined by quantitative ¹³C-NMR analysis



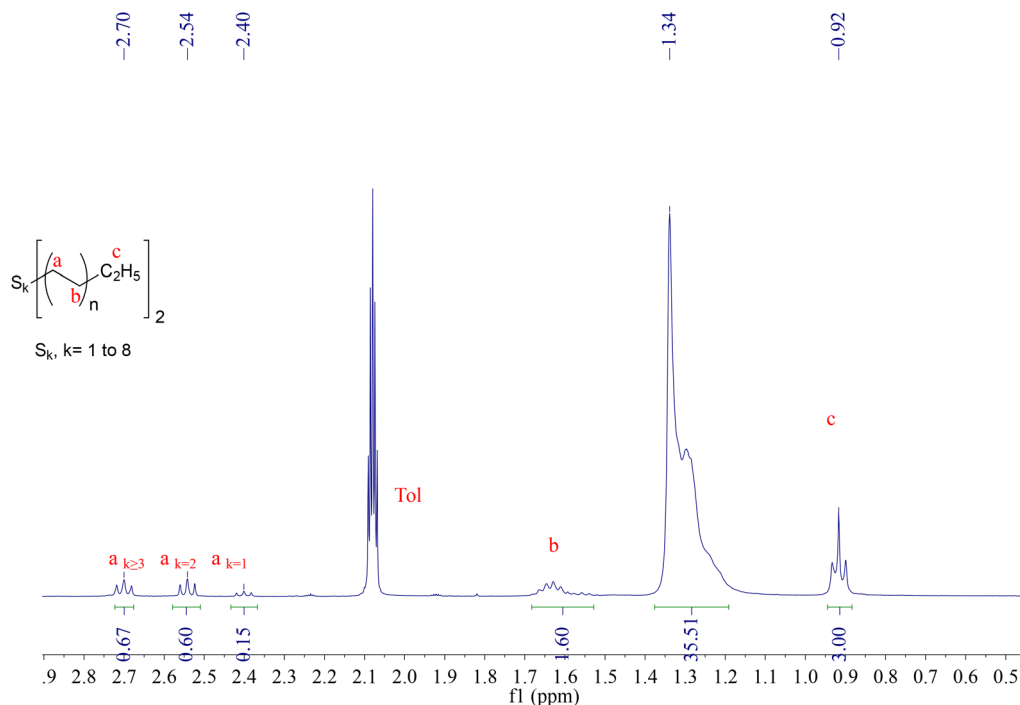


Fig. 3 ^1H -NMR spectrum in d_8 -toluene at 298K of PE- S_k -PE ($k = 1-8$) obtained from the reaction of $\text{Zn}(\text{PE})_2$ with 4 equiv. sulfur. $\text{Zn}(\text{PE})_2 = \text{Zn}(\text{C}_{22}\text{H}_{45})_2$ in this case.

Table 3 Synthesis of PE-I from $\text{Zn}(\text{PE})_2$ with various chain lengths

Run	Eq. Zn	Activity [g mmol ⁻¹ h bar ⁻¹]	Chain length ^a (C_n)	PE-I ^b (%)
1	300	1460	70	89
2	350	1220	46	96
3	450	950	40	97
4	500	900	30	98
5	650	640	12	100

Conditions for the polymerization reactions: catalyst **1** (10 μmol), MAO (100 eq.), toluene solvent (50 mL), 30 $^\circ\text{C}$, 1 barg ethylene, 1 hour reaction time. ^a C_n = average chain length, determined by ^{13}C NMR analysis. ^b Iodo-functionality yield determined by ^1H NMR analysis.

Whilst selectivities for the formation of PE-I are typically very high (>90%), the functionalisation appears to depend to some degree on the alkyl chain length, something that was also noted by Boisson in catalysed chain growth reactions of magnesium alkyls followed by iodine quenching.⁴⁸ For example, the degree of functionalisation is quantitative for $\text{C}_{20}\text{H}_{41}\text{I}$, but decreases to 97% for $\text{C}_{30}\text{H}_{61}\text{I}$ and 89% for $\text{C}_{70}\text{H}_{141}\text{I}$, the remainder being the corresponding alkanes (see Fig. S12[†]). This may be due to the reduced solubility of $\text{Zn}(\text{PE})_2$ with increasing chain length, or alternatively, encapsulation of the reactive zinc centres with increased PE chain length could result in restricted access to the metal centre and reduced reactivity with I_2 . Unreacted zinc-carbon bonds are eventually cleaved upon hydrolysis, resulting in the formation of alkanes.

Analogous to the reaction of $\text{Zn}(\text{PE})_2$ with iodine, reactions with bromine result in the formation of PE-Br. Upon addition of

Br_2 to a solution of $\text{Zn}(\text{PE})_2$ in toluene, $\text{C}_{32}\text{H}_{65}\text{Br}$ was obtained with 67% functionalisation, the remainder being $\text{C}_{32}\text{H}_{66}$ (see Fig. S18 and 19[†]). The reason for the lower functionalisation is not clear at this stage, but it should be noted that compared to iodine, the addition of bromine is considerably more reactive and may have led to some decomposition of alkyl zinc species.

Synthesis and characterisation of PE-I/LDPE polymer blends

A series of polymer blends has been prepared by incorporating PE-I into LDPE (SABIC N0W2021). The polymer blends were prepared by two different methods, either by solution mixing or melt blending. Solution mixing involved dissolving LDPE in hot toluene,⁸¹ followed by the addition of PE-I and precipitation of the resulting PE-I/LDPE polymer blend in methanol. Melt blending of PE-I and LDPE was carried out *via* co-extrusion at 130 $^\circ\text{C}$ (see ESI[†]). TGA analysis has shown that PE-I and LDPE are thermally stable up to 200 $^\circ\text{C}$ (Fig. S21[†]). LDPE was blended with $\text{C}_{18}\text{H}_{37}\text{I}$, $\text{C}_{30}\text{H}_{61}\text{I}$ and $\text{C}_{70}\text{H}_{141}\text{I}$ at 10 wt% loading. Analysis of the polymer blends was carried out by IR spectroscopy based on the characteristic signals at 1163 cm^{-1} for $\omega(\text{CH}_2\text{I})$ and 603 cm^{-1} for $\nu(\text{C-I})$ (see Fig. S15[†]). Despite dilution in the LDPE matrix the characteristic IR signals can be clearly observed (Fig. 5 for solution mixing and S22[†] for melt blending). Further characterisation was carried out by DSC analysis, which shows superposition of the DSC profiles for LDPE and PE-I (Fig. S23[†]).

In order to establish the dispersion of PE-I throughout the PE-I/LDPE polymer blend, surface analysis has been carried out on the material obtained through solution blending, using



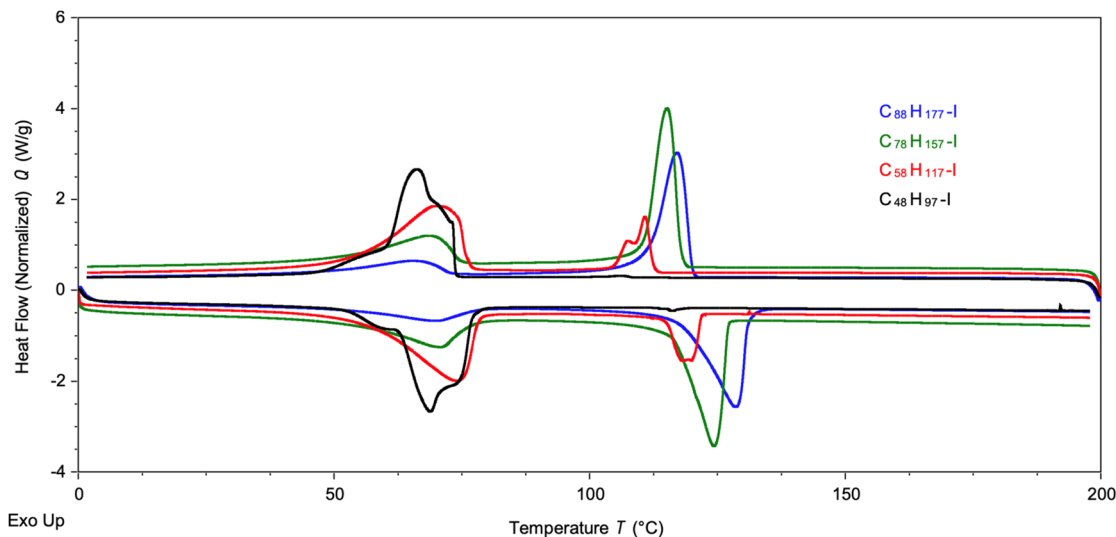


Fig. 4 DSC analysis of four PE-I samples of different chain length. Measurements shown were taken during the second heating cycle.

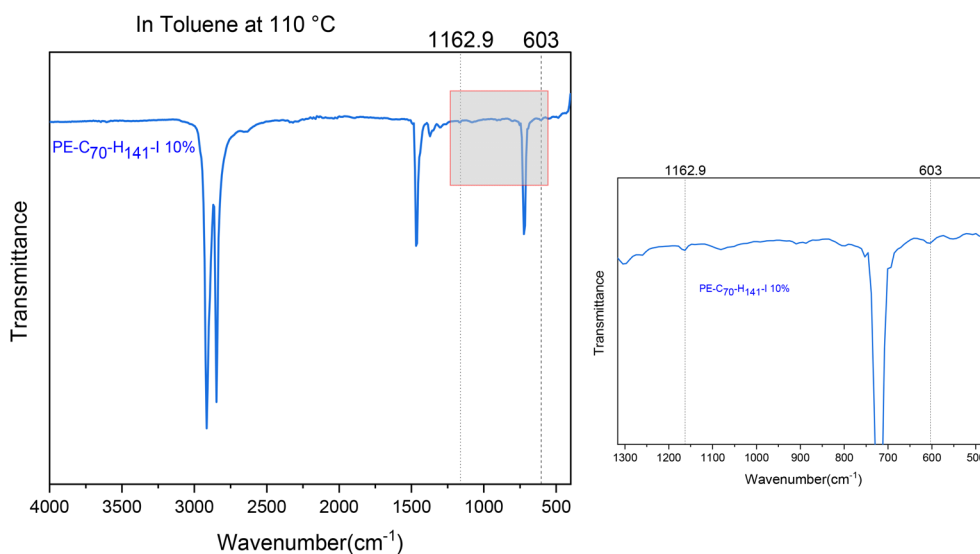


Fig. 5 FT-IR analysis of $C_{70}H_{141}I$ /LDPE polymer blend obtained via solution blending in toluene.

FIB-SEM and EDX analysis.^{82–84} The SEM image in Fig. 6 shows a magnification of the PE-I/LDPE polymer surface. A square hole of approximately $10 \times 10 \times 10 \mu\text{m}$ was cut by FIB micro machining using a gallium ion beam (see ESI for details[†]). EDX measurements were carried out at approximately $1 \mu\text{m}$ depth intervals up to $6 \mu\text{m}$ from the surface, as indicated in Fig. 6. Iodine was detected in all samples from its characteristic L_{α} signal at 3.937 keV , and there was no indication of a concentration gradient along this trajectory, indicating a random dispersion of PE-I, at least within $6 \mu\text{m}$ from the polymer surface.

In conclusion, we have shown that the CCG reaction of ZnEt_2 with ethylene, catalysed by the iron-based catalyst system $[(2,6\text{-diacetylpyridinebis}(2,6\text{-diisopropylanil}))\text{FeCl}_2]$ (**1**) and MAO gives access to ZnPE_2 , whereby the PE chain length can be controlled by the Zn/Fe ratio and the reaction time. The reaction of

ZnPE_2 with a variety of electrophiles leads to the formation of end-functionalised polyethylene PE-X. The selectivity for the formation of PE-OH appears to be limited to approximately 80%, probably due to the formation of zinc cluster $[\text{Zn}(\text{OR})\text{R}]_n$ intermediates. The reaction of ZnPE_2 with elemental sulfur results in the formation of polysulfides PE- S_k -PE. Polysulfides with $k > 3$ are thermally unstable and heating of PE- S_k -PE results in the elimination of sulfur and a lowering of k . The reaction of ZnPE_2 with iodine to generate PE-I is generally highly selective and is the preferred functionalisation method. Blends of PE-I and LDPE can be prepared by solution mixing or by melt blending through extrusion. These novel PE-I/LDPE polymer blends have been characterised by IR spectroscopy and DSC analysis. Surface analysis using SEM-EDX has indicated a uniform distribution of PE-I within $6 \mu\text{m}$ from the PE-I/LDPE surface.



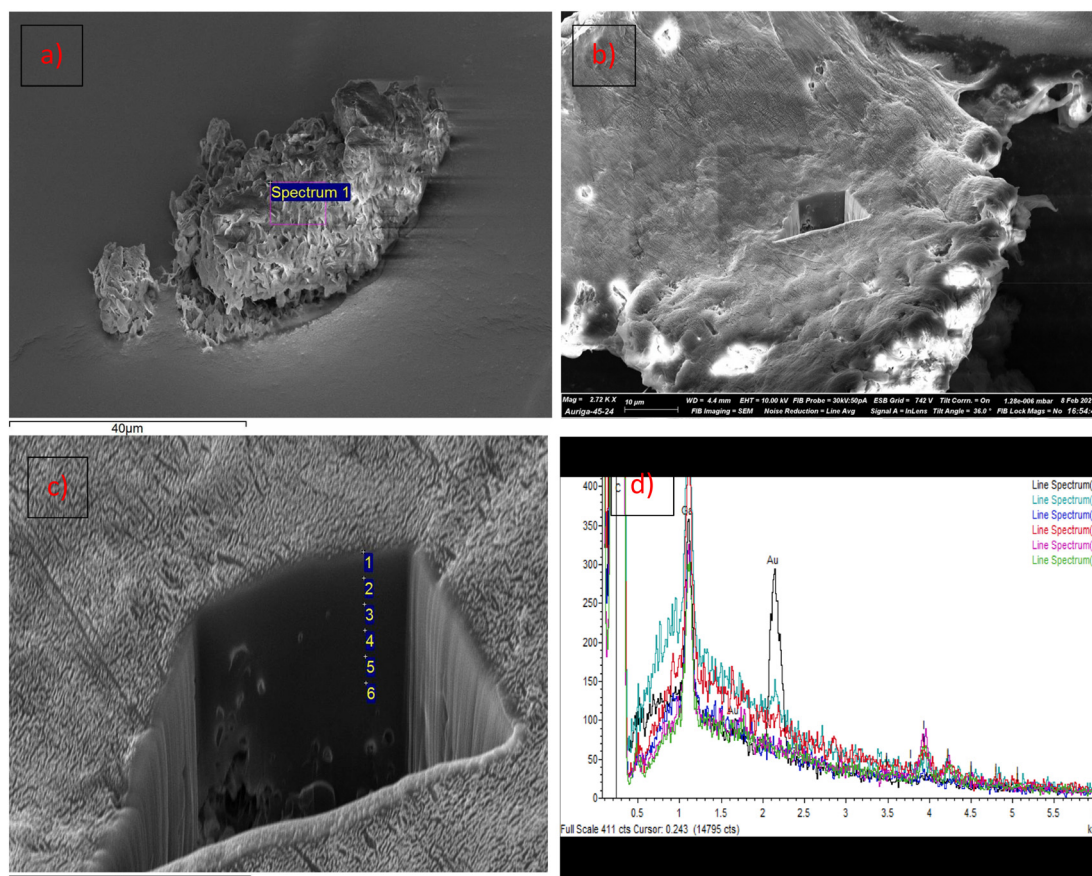


Fig. 6 (a) SEM image of PE-I/LDPE particle. (b) FIB-SEM image of PE-I/LDPE surface with square hole cut using FIB micro machining. (c) EDX analysis at $\sim 1 \mu\text{m}$ depth intervals. (d) EDX spectra taken at surface (spectrum 1) and at $\sim 1 \mu\text{m}$ depth intervals (SEM samples were Au-plated for conductivity).

Degradation studies of these novel PE-I/LDPE materials are currently underway and will be reported in due course.

Conflicts of interest

There are no conflicts of interest to declare.

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