Feature Article

Step-growth polymerization and 'click' chemistry: The oldest polymers rejuvenated

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ABSTRACT

Since its discovery in 2001, copper catalyzed azide–alkyne 'click' chemistry has been extensively used in polymer chemistry to modify polymeric materials and create advanced polymer structures by efficient coupling reactions. Surprisingly, the contribution of this Huisgen cycloaddition reaction to industrially important commodity polymers, prepared by step-growth polymerization, was not existing until recently. Nevertheless, since many decades academic and industrial research was focused on finding attractive synthetic pathways to introduce large contents of different reactive functional groups in several polymer classes such as polyesters and polyurethanes. Because of the high tolerance of azide–alkyne coupling reactions to a wide variety of functional groups and to extreme reaction conditions often used in step-growth polymerizations, the straightforward synthesis of alkyne-containing building blocks created an ideal platform to modify and broaden the physico-chemical properties of step-growth polymers by choosing readily available low and high molecular weight azide components. This feature article provides a comprehensive review covering the strategies toward 'click'-functionalization of several classes of industrially important step-growth polymers.

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1. Introduction: toward the revival of step-growth polymers

Step-growth polymers have been known since the discovery of synthetic polymers as useful polymeric materials within wide application areas. Nowadays, they have a huge industrial impact and it would be difficult to imagine life without them. It all began with the Belgian chemist Baekeland, who discovered the Bakelite resins from the condensation of phenol and formaldehyde in 1907 [1]. It was the pioneering work of Wallace Carothers and his research group at DuPont that led to the discovery of two of the 20th century's most widely used synthetic polymers: nylon and polyester [2]. He elucidated the fundamental principles of step-growth polymers and paved the way for the later work of Whinfield and Dickson in which poly(ethylene terephthalate) (PET) was discovered [3].

In step-growth polymerizations, any species (monomers, dimers, trimers, etc.) can react at any time in consecutive reactions, leading to an increase in macromolecules of high molecular weight. In general, two classes of step-growth polymerization (SGP) reactions are considered: polycondensations and polyadditions.

Polycondensation reactions, including the formation of polyesters and polyamides, are accompanied by the elimination of a small molecule (e.g. water, methanol) as a by-product. Typical step-growth polymerizations of the polyaddition type are the formation of polyurethanes and polyurea in which monomers react without the elimination of a small molecule. However, some experimental criteria must be fulfilled in order to achieve well-defined compositions and predictable molecular weights of polymers prepared by SGP. High reaction conversions, monomer functionality equal to two, functional group stoichiometry equal to one, absence of side reactions and an efficient removal of the by-products are essential criteria for the preparation of high molecular weight polymers [4].

Numerous materials synthesized by SGP find notable applications in textiles, car industry, packaging, coatings and many others. The industrial applications mainly depend on the chemical nature of the starting components and on the industrial process. Nevertheless, for more specific applications, many of these polymers are limited in scope because of the lack of functionalities on the backbone for further modification and tailoring [5]. Their potential applications could be greatly broadened with the incorporation of pendant groups onto the polymer backbone. In general, to introduce functional moieties, two techniques are considered: chain-end and side-chain functionalization. The first route involves the use of monofunctional compounds, leading to polymer chain

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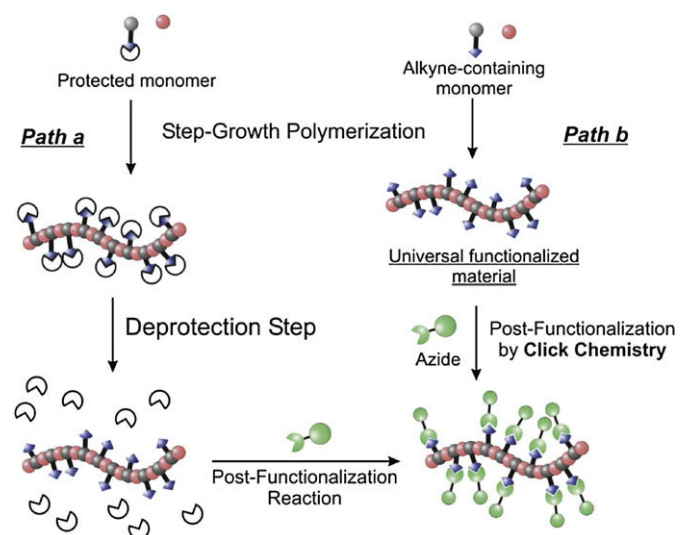E-mail address: filip.duprez@ugent.be (F. Du Prez).

Fig. 1. Functionalization of materials *via* step-growth polymerization. *Path a*: using the common protection and deprotection strategy. *Path b*: using a universal approach involving 'click' chemistry.

terminations with the desired functional group at the chain end and a reduced molecular weight. In an alternative way, the chain-end modification can also be performed after the synthesis of the materials. Side-chain functionalization is the most promising

strategy. A large amount of functional groups can be directly incorporated during the polymerization by using a functional monomer. This pre-functionalization technique is more mainstream to obtain functional materials with well-defined chemical structures. On the other hand, the introduction of functional side groups by SGP is in general not straightforward as the reaction conditions can be drastic (high temperatures, vacuum). At this point of view, the most reported strategies require additional protecting and deprotecting steps (path a, Fig. 1), which may be an important restriction for industrial manufacturing. Moreover, the chemical modification of functional polymers can suffer from a lack of efficiency because the reactivity of functional groups may be affected by the structure of the polymer and by the efficiency of the modification reactions used.

Because of these limitations, the focus on the research of functionalization of polymers has been moving during the last decade toward the use of highly efficient combination approaches, often referred to as 'click' chemistry. In 2001, Sharpless and coworkers introduced this term to assign reactions with high selectivity, quantitative yields, mild reaction conditions, absence of by-product and inertness toward other functional groups [6]. Among the listed 'click' reactions, the most popular one is the copper(I) catalyzed dipolar Huisgen cycloaddition reaction between an azide and a terminal alkyne leading to a 1,2,3-triazole ring. The use of the copper catalyst leads to a tremendous acceleration of the cycloaddition at room temperature [7,8]. Often, the reaction is referred to as CuAAC (copper catalyzed azide–alkyne cycloaddition). Nowadays, 'click' reactions have become a very powerful tool in polymer
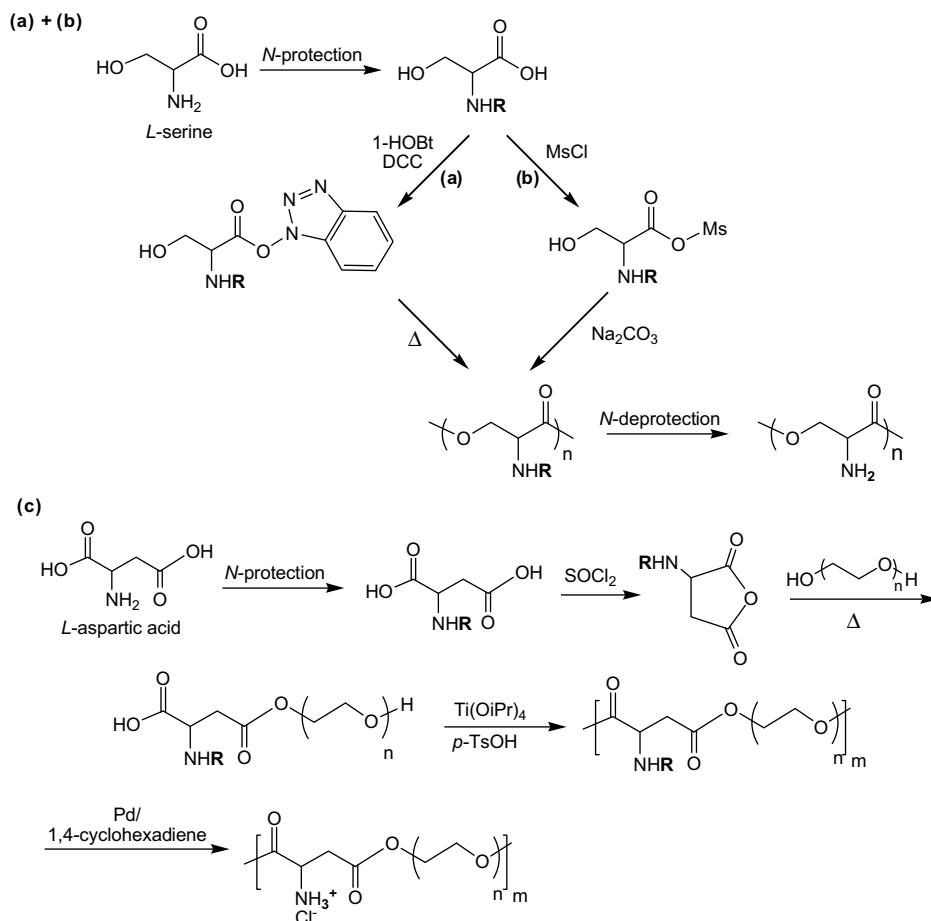
Scheme 1. Synthetic schemes for the preparation of amine-functionalized polyesters by polycondensation reactions including a protection/deprotection strategy.

chemistry for functionalizing synthetic macromolecules and synthesizing a wide range of polymer architectures [9–14].

Despite the amazing growth of scientific contributions in this field since 2002, to our surprise the possibilities to combine step-growth polymerizations with click chemistry were not explored until about 2 years ago. The objective of the present feature article is to highlight the efforts dealing with the functionalization of step-growth polymers by CuAAC (path b, Fig. 1). In particular the functionalization of two types of step-growth polymers, obtained by a polycondensation reaction on one hand and a polyaddition reaction on the other hand, will be discussed in detail. For this, alkyne-functionalized polyesters and polyurethanes and their further modifications by CuAAC will be considered [15,16]. It will be demonstrated that this promising concept of the in situ incorporation of alkyne functions creates a unique advantage to obtain materials with easily adaptable physical properties.

2. Functionalization of step-growth polymers: life before 'click' chemistry

2.1. Polyesters

Polyesters are one of the most versatile classes of polymers ever produced and nowadays, aliphatic polyesters are one of the most promising alternatives to commodity plastics. They can be obtained by a wide range of reactions, the most important being the polyesterifications between diacids and diols or their derivatives. Depending on the nature of alkyl groups in both diacid and diol, an enormous wide variety of structures, architectures, properties and applications are available [4]. The low melting points of aliphatic polyesters have prevented their wide usage as polymeric materials for a long time. However, because of their characteristic biodegradability and the ongoing environmental concerns, aliphatic polyesters are now in the middle of the spotlight [17].

As previously mentioned, chain-end functionalization only yields a limited amount of functional groups per polymer chain. These end capped materials are mostly used for specific applications such as curing and coating technology. For example, in the field of aliphatic polyesters prepared by SGP, hydroxyl-functionalized polyesters were functionalized with citric acid by Noordover et al., yielding slightly branched, acid functionalized materials used for coating applications [18]. End group modification is also an often used technique to introduce functionalities in hyperbranched polymers. As an example, very recently, hydroxyl-terminated hyperbranched polyesters were reacted with a urethane mono-methacrylate compound, yielding hyperbranched polyurethane methacrylates suitable for UV-curable systems [19].
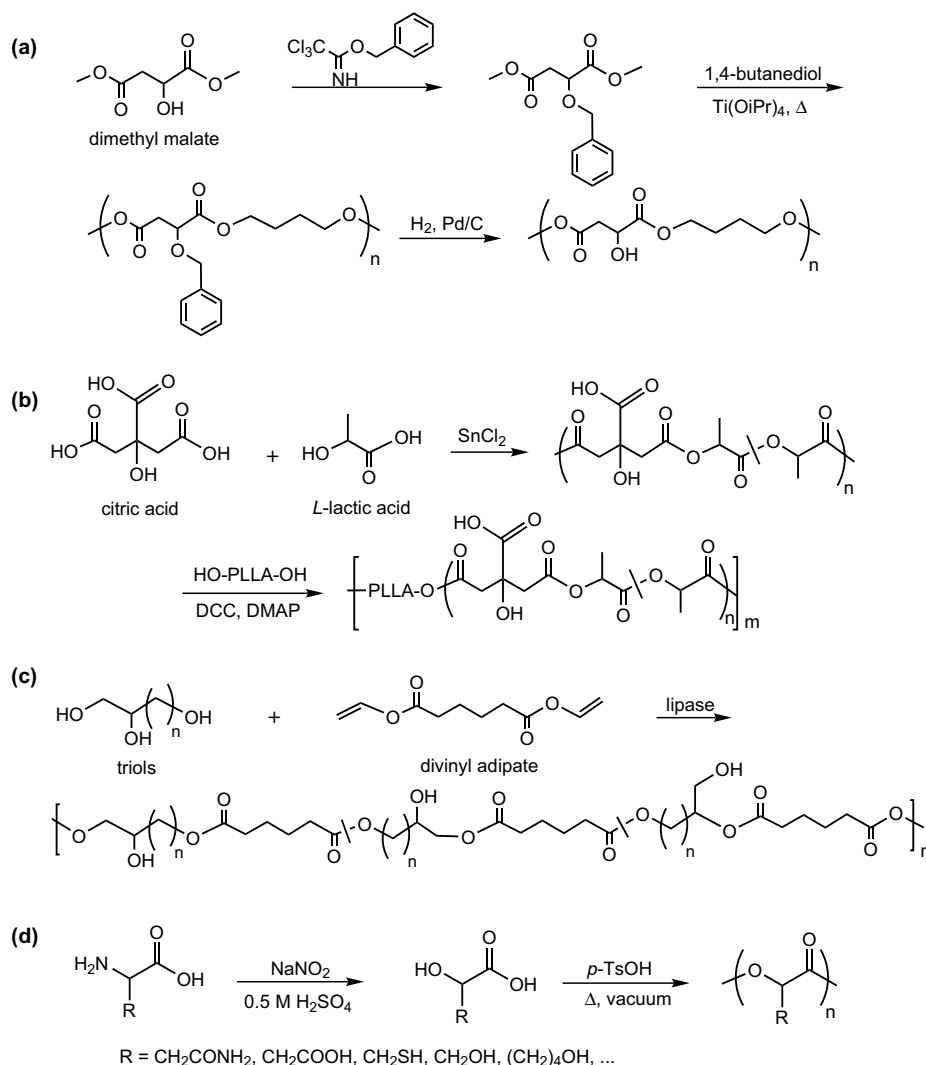

Scheme 2. Synthetic schemes of side-chain functionalized polyesters prepared by polycondensation reactions.

A conventional strategy for the introduction of a high content of functional pendant groups along a polyester backbone involves the preparation of protected functional monomers, followed by polymerization of the monomers and finally a deprotection step [20]. In this way, amine-bearing polyesters were prepared by polycondensation of linear N-protected serine, the carboxyl end of which was activated with benzotriazole (Scheme 1(a)) [21] or methanesulfonyl groups (Scheme 1(b)) [22]. In another example, prior to polymerization with poly(ethylene glycol) (PEG), the diacid, N-protected L-aspartic acid, was converted into N-protected L-aspartic acid anhydride. Subsequently, the benzyloxycarbonyl-protecting group was removed by hydrogenolysis, as shown in Scheme 1(c) [23].

A hydroxyl-functionalized poly(butylene succinate) based polyester was prepared by conventional polycondensation of benzyl-protected dimethyl malonate and 1,4-butanediol (Scheme 2(a)) [24a]. Yao et al. reported on the direct polycondensation of L-lactic acid and citric acid with the formation of poly[(L-lactic acid)-co-(citric acid)], obtaining a polyester oligomer with both pendant carboxylic and hydroxyl groups [24b]. This PLCA oligomer was reacted with dihydroxylated PLLA as a macromonomer, yielding a PLCA–PLLA multiblock copolymer as shown in Scheme 2(b). While lipases have been investigated for the ring-opening

polymerization (ROP) of cyclic ester monomers [25,26], they have also been used for the preparation of polyesters by polycondensation reactions. The advantage of this technique is that these enzyme-catalyzed reactions proceed without protection of the pendant functional groups. In this field, hydroxyl-bearing polyesters have been synthesized by the copolymerization of divinyl adipate with various triols (e.g. glycerol, 1,2,4-butanetriol) as represented in Scheme 2(c) [27] and by copolymerizations of 1,8-octanediol with adipic acid and several alditols [28]. Very recently, several α-hydroxy acids derived from amino acids were homo- and copolymerized with lactic acid by polycondensation in bulk without protected monomers (Scheme 2(d)) [29]. Biodegradable polyesters with various pendant groups were obtained, although the molecular weights remained low (1000–3000 g mol^{-1}).

Nevertheless, these strategies suffer from a few limitations. Besides the possible additional protecting and deprotecting steps, a specific monomer must be considered and synthesized for each functional group, resulting in labour-intensive procedures if the introduction of several types of functionalities is envisaged. Using one universal pendant group, that can be easily converted into the desired functionality, would simplify the synthetic procedures.
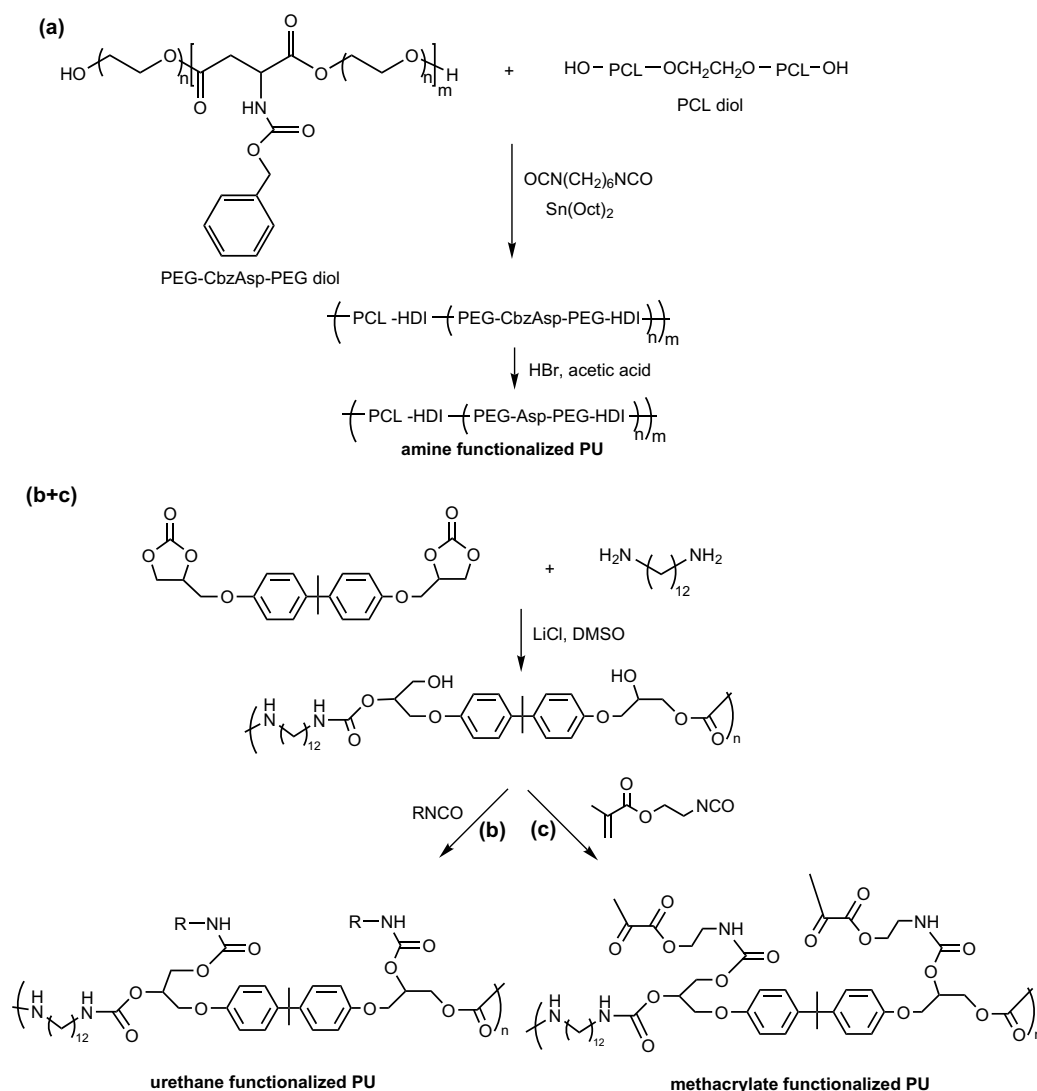
Scheme 3. Synthetic schemes for the preparation of functionalized polyurethanes.
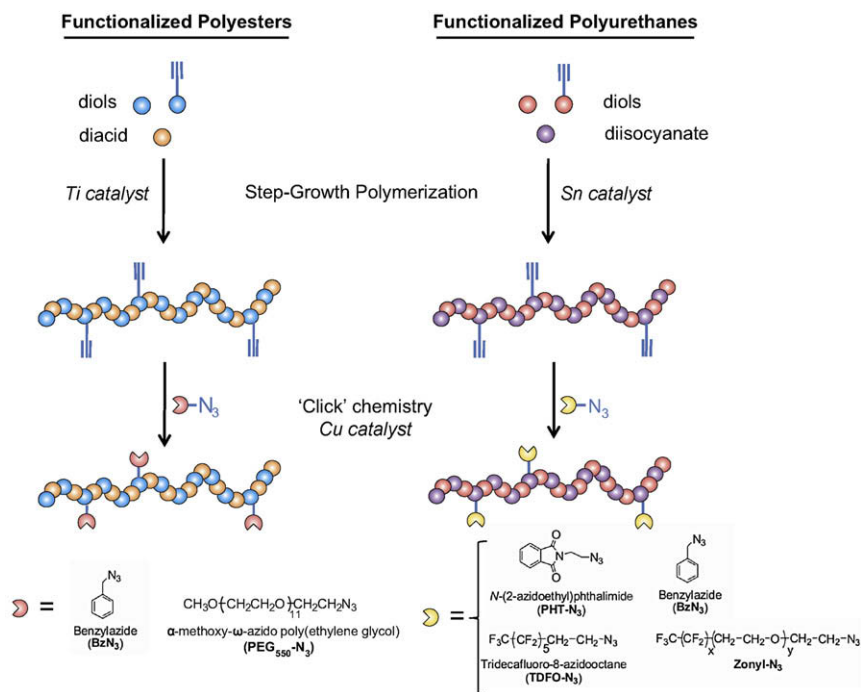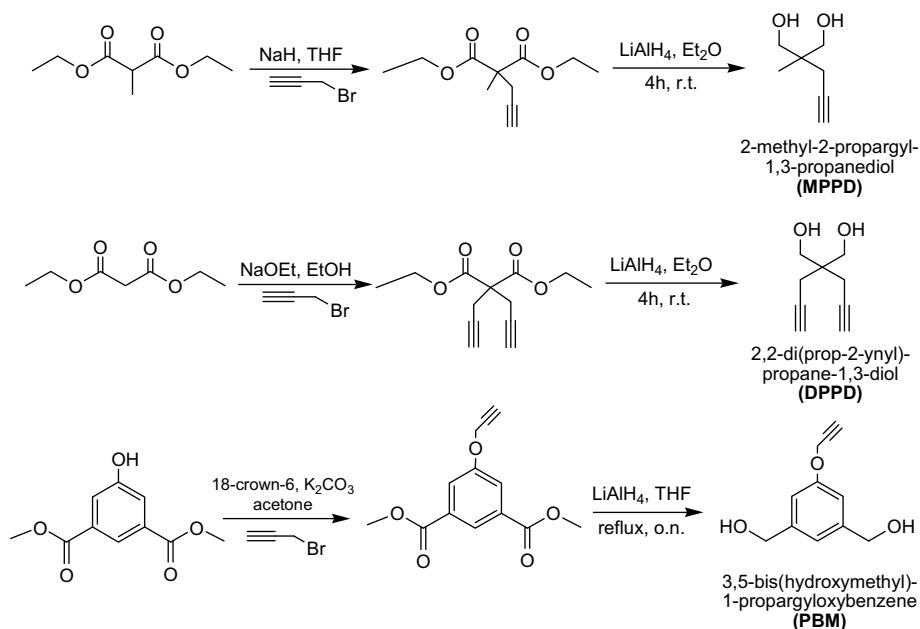
Scheme 4. Strategy for the synthesis of alkyne-functionalized step-growth polymers and their post-functionalization by CuAAC [15,16].

2.2. Polyurethanes

Polyurethanes are a versatile class of polymers of which the urethane group imparts most of the important physical properties [4]. Due to the presence of the hydrogen bonding, polyurethanes are often the best choice in demanding, high-performance applications. They are typically prepared through the polyaddition of low and/or high molecular weight diols and diisocyanates. The high reactivity and poor selectivity of the diisocyanates have limited the introduction of functional groups onto polyurethane backbones. Recently, much attention is again going to the development of functional polyurethanes because applications that are outside of

the classical polyurethane market can be anticipated. One route to obtain functional polyurethanes is the use of monofunctional compounds (alcohol or isocyanate), leading to polymer chain terminations with the functional group at the chain end and to a reduced molecular weight. The chain-end modification can also be performed after the polymerization. As an example, hydroxy-ethyl (meth)acrylate has been employed for the modification of an NCO-functionalized polyurethane, leading to UV-crosslinkable polyurethane (meth)acrylate [30,31].

Various functionalities have also been introduced as side chains onto the polyurethane backbone. As an example, PCL–PEG-based polyurethanes with pendant amine groups were synthesized by

Scheme 5. Synthesis strategy for the alkyne diols involved in polyester (MPPD) and polyurethane (PBM and DPPD) syntheses.

direct coupling of a PEG ester of NH₂-protected aspartic acid (CbzAsp), leading to PEG–CbzAsp–PEG diols, and PCL diols with hexamethylene diisocyanate (HDI), followed by a subsequent deprotection step as shown in Scheme 3(a) [32]. At the same time, Endo et al. prepared hydroxyl-bearing polyurethanes by polyaddition of a bifunctional cyclic carbonate with a diamine. Afterwards, the hydroxyl groups were converted into urethane groups with a functionalized isocyanate (Scheme 3(b)) [33] or into methacrylate groups with 2-methacryloyloxyethyl isocyanate (Scheme 3(c)) [34].

3. Examples of functionalization of step-growth polymers by 'click' chemistry

As previously mentioned, side-chain functionalization is the most applied technique to introduce functional groups along a polymer backbone. From this point of view, 'click' chemistry became of high relevance in polymer science. Until now, the combination of polymers prepared by SGP and click chemistry is still far from being explored. Since 2005, a few reports describing the combination of aliphatic polyesters and 'click' chemistry attracted our attention [35–38]. However, these polyesters have been synthesized by ROP, including the complex multistep synthesis of the azide- or alkyne-based cyclic monomers (i.e. lactones, lactides), sometimes accompanied by low yields. In contrast, SGP starts from readily available monomers and, despite the non-controlled reaction conditions, the structure of such polyesters and polyurethanes can be more easily tuned as a function of their application.

The actual research carried out in our group involves the synthesis of alkyne-functionalized aliphatic polyesters and polyurethanes by the use of SGP and their further post-functionalization by CuAAC [15,16]. In this strategy, that can also be more widely applied to other industrially relevant step-growth polymers and with new types of 'click' chemistry, first a non-protected monomer is prepared by convenient, upscalable organic synthesis. Subsequently these monomers were copolymerized with other diols and diacids in the case of polyesters and diols and diisocyanates for polyurethanes. In the last step, specific azide-functionalized molecules, giving enhanced properties to the polymers, are reacted with the alkyne groups of the polymers (Scheme 4). The choice for the alkyne groups as pendant groups along the backbone was made by considering the incompatibility of the potentially explosive low molecular weight azides with SGP (often high temperatures).

3.1. The choice of the alkyne-containing building blocks

The first crucial point in this strategy is the choice of the appropriate alkyne-containing monomer. To incorporate the pendant alkyne groups, it must contain the desired functionalities to react with the complimentary functionalities. In the case of polyesters or PU's, a bifunctional diol, dicarboxylic acid or diisocyanate provided with an alkyne group are possible candidates. Some additional conditions that need to be fulfilled are straightforward synthesis routes with good yields from readily available compounds. Scheme 5 shows the chemical structure of three building blocks that have been carefully selected. Two monoalkyne diols, 2-methyl-2-propargyl-1,3-propanediol (MPPD) and 3,5-bis(hydroxymethyl)-1-propargyloxybenzene (PBM) and one dialkyne diol, 2,2-di(prop-2-ynyl)propane-1,3-diol (DPPD) meet the abovementioned criteria and were synthesized in a large scale (up to 1 kg) via a two-step reaction, according to the procedures available in the literature [39–42].

PBM and DPPD have been applied in the synthesis of alkyne-functionalized polyurethanes. While PBM yields polyurethanes containing one alkyne function per repeating unit, the use of DPPD further enhances the functionality. Preliminary results

Table 1
Synthesis of PBM-based polyurethanes (entries 1–4) and PBAd-based polyesters (entries 5–8) with pendant alkyne groups.

Entry	Reference[a]	Experimental composition[b]	Mn[c] (g mol⁻¹)	$T_{5\%}$[e] (°C)
		HDI/BDO/PBM		
1	PU–PBM-0	1.0/1.0/0	_[d]	299
2	PU–PBM-8	1.0/0.84/0.16	6000	304
3	PU–PBM-25	1.0/0.50/0.50	14700	303
4	PU–PBM-50	1.0/0/1.0	8100	302
		AdA/BDO/MPPD		
5	PBAd-0	1/1.00/0	6800	353
6	PBAd-5	1/0.98/0.07	7900	354
7	PBAd-15	1/0.90/0.15	5000	342
8	PBAd-25	1/0.82/0.28	10900	352

[a] Indicated value in the reference names relates to the amount of incorporated mol% PBM (entries 1–4) or MPPD (entries 5–8) in the PU or polyester.
[b] Final composition determined by ¹H NMR in DMSO-d_6.
[c] Determined by DMA–GPC calibrated with PMMA standards (entries 1–4) and THF–GPC calibrated with polystyrene standards (entries 5–8).
[d] Not soluble in GPC solvent.
[e] Temperature at 5% weight loss, as determined by TGA. Heating ramp: 10 °C/min under air from 25 °C to 800 °C.

revealed that DPPD was not suitable for copolymerization of diols and dicarboxylic acids to synthesize aliphatic polyesters with pendant alkyne groups. In contrast to the synthesis of polyurethanes that are catalyzed by a tin catalyst, crosslinking was obtained during the polyester formation under the influence of
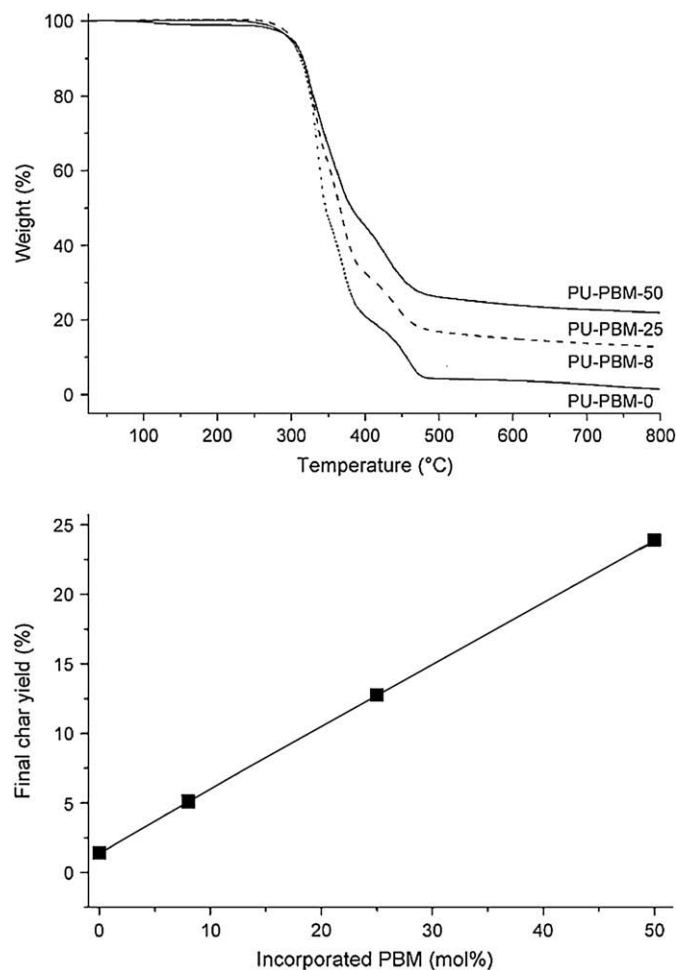

Fig. 2. TGA curves of the PU–PBM (top) and the char yield of the PU–PBM series versus the mol% of PBM incorporated in the material (bottom).

the applied titanium catalyst. In combination with this catalyst, DPPD was converted into a 1,3-dimethylenecyclopentane derivative, leading to Diels–Alder reactions between the polyester chains. To avoid this undesirable side reaction, MPPD was synthesized and copolymerized with other diols and dicarboxylic acids to obtain fully aliphatic polyesters with alkyne-containing side chains.

3.2. Synthesis and characterization of alkyne-functionalized polyesters and polyurethanes by step-growth polymerization

In our attempts to synthesize highly functionalized materials in a facile route, series of 'clickable' polyurethanes and polyesters, e.g. poly(butylene adipate) (PBAd) and poly(ethylene succinate) (PESu), were prepared. Although both types of polymers were synthesized by SGP, reaction conditions strongly differ.

In order to obtain pendant alkyne groups along the polyurethane backbone, a predetermined mixture of diols, consisting of 1,4-butanediol (BDO) and the alkyne-containing diol (PBM or DPPD), and hexamethylene diisocyanate (HDI) was reacted in ethyl acetate at 50 °C with dibutyltin dilaurate as catalyst. In this solvent, the polyurethanes precipitate during their formation, which facilitate the characterization afterwards. On the other hand, polyesters are generally obtained by polycondensation of diols and dicarboxylic acids with a two-step melt polycondensation method at high temperatures (160–200 °C). In the first esterification stage, the dicarboxylic acid (adipic acid, AdA or succinic acid, SuA) reacts with the diol mixture, consisting of the alkyne diols MPPD and BDO, while water is eliminated as by-product. Besides the use of titanium(IV) *n*-butoxide as catalyst, hydroquinone was added to prevent cross-linking in the polycondensation stage as already reported elsewhere [43,44]. Alkyne groups are known to act as a crosslinker upon heating
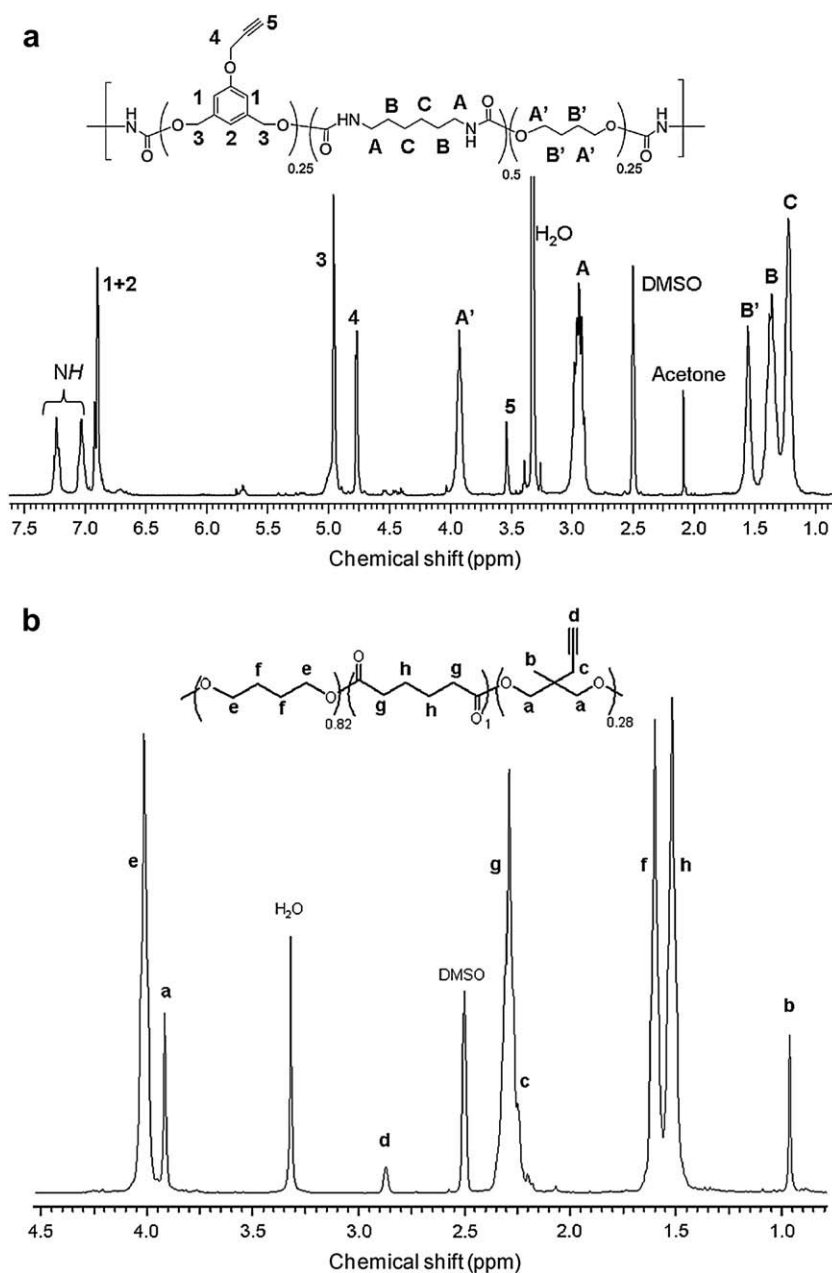

Fig. 3. ^{1}H NMR spectra (300 MHz, DMSO-d_6) of PU–PBM-25 (a) and PBAd-25 (b).

Table 2
Results of the click reactions onto the MPPD-based poly(butylene adipate) (entries 1–6) and PBM-based polyurethane (entries 7–13).

Entry	Sample	Azide compound	Catalyst	M_n[a] (g/mol)	Conversion[b] (%)
1	PBAd-5	BzN$_3$	CuBr/PMDETA	7000	>99
2		PEG$_{550}$N$_3$	CuBr/PMDETA	8000	>99
3	PBAd-15	BzN$_3$	CuBr/PMDETA	7100	>99
4		PEG$_{550}$N$_3$	CuBr/PMDETA	13 800	>99
5	PBAd-25	BzN$_3$	CuBr/PMDETA	14 800	>99
6		PEG$_{550}$N$_3$	CuBr/PMDETA	28 600	>99
7	PU–PBM-25	BzN$_3$	CuBr/PMDETA[c]	24 700	>99
8		PHT-N$_3$	CuSO$_4$/Na$_{asc}$.[d]	18 300	>99
9		TDFO-N$_3$	CuSO$_4$/Na$_{asc}$.[d]	16 000	>99
10	PU–PBM-50	BzN$_3$	CuBr/PMDETA[c]	11 600	>99
11		PHT-N$_3$	CuSO$_4$/Na$_{asc}$.[d]	11 400	>99
12		TDFO-N$_3$	CuSO$_4$/Na$_{asc}$.[d]	7800	>99
13		Zonyl-N$_3$	CuSO$_4$/Na$_{asc}$.[d]	14 100	–[e]

Starting materials: PBAd-5: M_n = 7900 g/mol. PBAd-15: M_n = 5000 g/mol. PBAd-25: M_n = 10 900 g/mol. PU–PBM-25: M_n = 14 700 g/mol. PU–PBM-50: M_n = 8100 g/mol.

[a] Determined by GPC using THF as solvent, calibrated with polystyrene standards (entries 1–6) and DMA as solvent with PMMA standards (entries 7–13).
[b] Determined by ^{1}H NMR in DMSO-d_6.
[c] CuBr/PMDETA: 0.1 eq, DMSO, 50 °C.
[d] CuSO$_4$/Na$_{asc}$.: 0.05 eq and 0.1 eq respectively, DMF, 60 °C.
[e] Partially soluble in DMSO-d_6.

by creation of reticulated alkenes and can participate in a cyclotrimerization reaction [43]. In order to increase the molecular weight, the oligomers were condensed in a second stage at 200 °C under vacuum during the polycondensation step. In this feature article, only the results related to the synthesized PBM-based (co)polyurethanes and the PBAd-based (co)polyesters with different amounts of respectively HDI/BDO/PBM and AdA/BDO/MPPD are presented in

Table 1. All other experimental data about the polyurethane synthesis can be found in reference [15], for the polyesters in reference [16].

All synthesized materials were intensively purified to remove unreacted components and dried prior to analysis by ^{1}H NMR, GPC, FTIR and TGA. As shown in Table 1, all polyurethanes are stable up to 300 °C and the polyesters even up to 340–350 °C. The initial decomposition temperatures, defined as 5% weight loss, do not depend on the PBM or MPPD content, showing that the incorporation of the alkyne group in these materials does not affect the thermal behavior at the early stage of the thermal decomposition process. A peculiarity that was only observed for the alkyne-containing polyurethanes, was an increased char yield with increasing amount of incorporated PBM. Indeed, alkyne groups are known to act as a crosslinker upon heating by creation of reticulated alkenes and can participate in a reaction of cyclotrimerization making the materials flame-retardant. This is ascribed to the formation of char on the upper part of the material, which prevents the formation of volatile compounds from the inner part. In addition, terminal alkynes have also been used to elaborate high-performance polymers and composites [45]. When these char yields were plotted against the amount of incorporated PBM (Fig. 2, bottom) in the polyurethanes, surprisingly a linear relationship was observed, meaning that a structure–property relationship may exist that can justify the abovementioned explanation about the thermal stability of alkyne-functionalized materials.

The ^{1}H NMR spectra obtained from PU–PBM-25 (Fig. 3, top) and PBAd-25 (Fig. 3, bottom) demonstrate the successful polymerizations. The typical resonance of the alkyne proton at 3.55 ppm in PU–PBM-25 and at 2.87 ppm in PBAd-25 (in DMSO-d_6) proves that the functionalized diol has been in both cases fully incorporated in the polymers without any side reaction as confirmed by the integrations. The other peaks belonging to the alkyne diol appear in both spectra, clearly indicating that these free alkyne groups
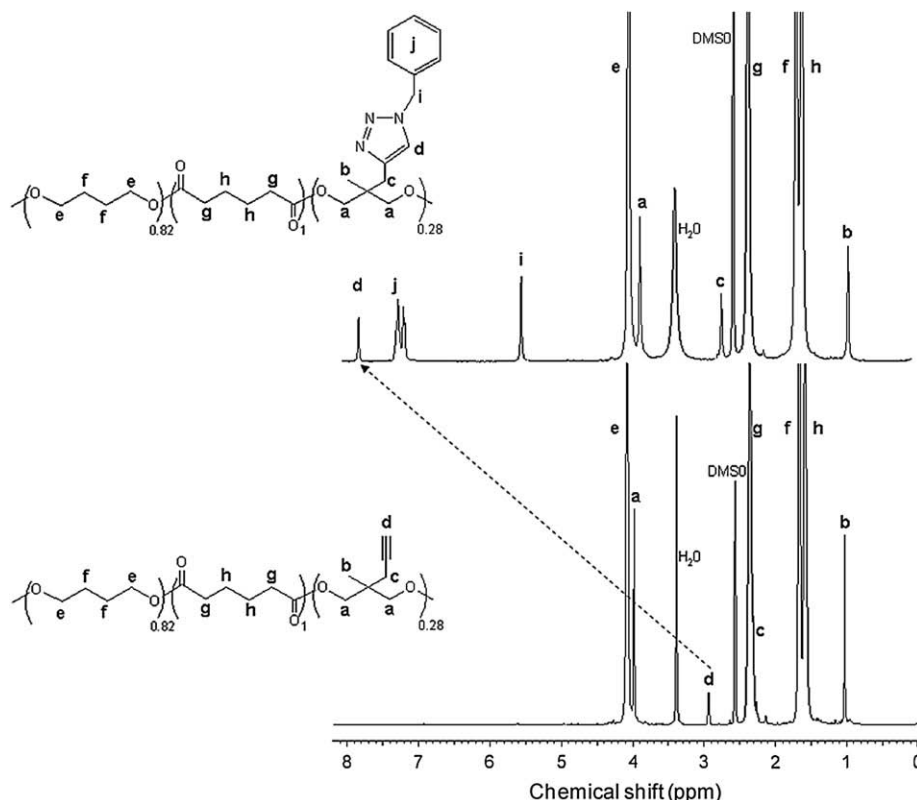

Fig. 4. ^{1}H NMR spectra of the starting polyester PBAd-25 (lower spectrum) and the polyesters after the click reaction with BzN$_3$ (upper spectrum).

withstand the copolymerization conditions, even when applying high polymerization temperatures without any additional protecting and deprotecting steps. Control over pendant acetylene concentration in the materials was tailored by varying the BDO/PBM and BDO/MPPD molar ratios during the copolymerization. The exact amount of incorporated alkyne diol into the polymers was calculated by the integration of the ^{1}H NMR signal from the alkyne at (C≡C–$\underline{H}$) against the signal of BDO (C$\underline{H}_2$CH$_2$CH$_2$C$\underline{H}_2$). As presented in Table 1, the calculated amounts of incorporated alkyne diols fit well with the predetermined feed ratios.

Thus, polyesters and polyurethanes with pendant alkyne groups are synthesized in a straightforward way, which opens the door for new industrially relevant materials. As SGP covers a wide market of end products, these universally alkyne-functionalized materials provide a promising platform as they can be reacted with a broad range of compounds to obtain functionalized polyesters and polyurethanes. A similar strategy, starting from azide-functionalized backbones, has been very recently applied to polysiloxanes, a class of step-growth polymers that is known for its extreme hydrophobicity [46].

3.3. 'Click' chemistry: a versatile functionalization method for materials prepared by SGP

In order to obtain functionalized materials from the previously alkyne-containing polyurethanes and polyesters, they were successfully reacted with a number of azides via the CuAAC cycloaddition reaction. Since 2002, this technique has been extensively used for post-polymerization modification, because it provides high yields under mild conditions in aqueous and in organic media [47]. Several azides have been screened during this post-modification step (Scheme 4) among which are benzyl azide (BzN$_3$), α-methoxy-ω-azido-PEG (PEG$_{550}$N$_3$), N-(azidoethyl)phthalimide (PHT-N$_3$), tridecafluoro-8-azidooctane (TDFO-N$_3$) and Zonyl-N$_3$ (Scheme 4). They were all synthesized in high yields from readily available compounds by a nucleophilic substitution reaction with sodium azide, in the case of PEG$_{550}$N$_3$ and Zonyl-N$_3$ preceded by a mesylation. As previously mentioned, one of the main advantages of this CuAAC chemistry is its tolerance toward a variety of functional groups, such as hydroxyl and carboxylic groups [7]. The CuAAC reactions with the polyesters were carried out in THF at 50 °C in combination with the common copper catalyst system Cu(I)Br/PMDETA (1 eq each), which has proved its efficiency towards the click reaction [48]. The reactions with the polyurethanes were carried out either in DMSO at 50 °C with 0.1 eq of Cu(I)Br/PMDETA or in DMF at 60 °C with CuSO$_4$/Na$_{asc}$ (0.05 eq and 0.1 eq respectively) as catalyst. In all reactions, the azide compounds were used in a two-fold excess. The results of the 'click' reactions between the alkyne-containing materials and the azides are reported in Table 2.

For both types of materials, the quantitative character of the 'click' reaction could be determined by ^{1}H NMR, as demonstrated in Fig. 4 where the ^{1}H NMR spectra of PBAd-25 before and after CuAAC with BzN$_3$ are shown. In this example, the arrow indicates the shift of the alkyne signal to the proton of the formed triazole ring. Also new peaks are appearing ascribed to the aromatic groups in BzN$_3$ while the signal integrations prove the efficiency of this reaction.

PEG-grafting has also been applied to the polyesters. Pegylation has been extensively used in drug delivery systems as a result of the physical properties of PEG such as non-toxicity, high water solubility, FDA approved and resistance to protein adsorption [49,50]. Graft copolymers are obtained by the reaction between the previously synthesized alkyne-containing polyesters and PEG$_{550}$N$_3$. As a result, PEG grafted PBAd-25 (Table 2, entry 6) becomes water-soluble.

Besides BzN$_3$ as a first model compound, several other functionalized azides have been used for click reaction with the alkyne-
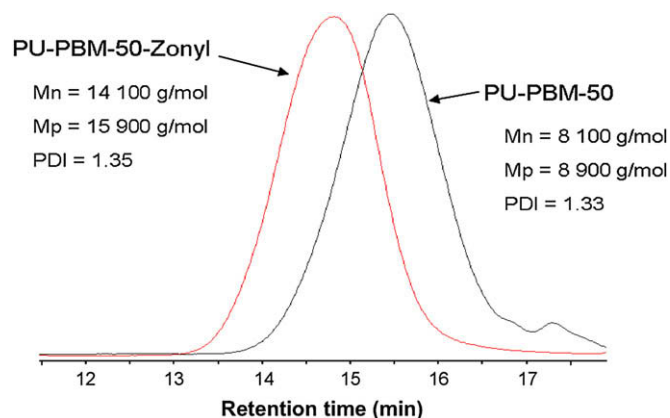

Fig. 5. GPC traces of the starting material PU–PBM-50 and PU–PBM-50–Zonyl. Reproduced from reference [15]. Copyright 2008 American Chemical Society.

functionalized polyurethanes. Phthalimide-based compounds were used as an amine-protecting group [51–53] and a deprotection step via treatment with hydrazine was performed [54] leading to ethyl-amino-functionalized PU. A direct anchoring of an amine to the PU via the cycloaddition process could also be considered with the help of 1-azidoethylamine. Nevertheless, this azide is explosive and therefore difficult to obtain because of the low C/N ratio [6] (i.e., 2/4). On the other hand, fluorinated azide compounds have been coupled to control the hydrophobicity. While tridecafluoro-8-azidooctane (TDFO-N$_3$) was synthesized from the iodide derivative [15], a higher molecular weight fluor-containing product, Zonyl-N$_3$, was synthesized from hydroxy-functionalized Zonyl FSO-100. This is a low molecular weight block copolymer having a first block based on a perfluoroalkyl chain followed by a second poly(ethylene glycol) block (see Scheme 4). Zonyl FSO-100 is currently widely used in several applications, e.g. improved wetting agent, lubricant, anti-fogging and pigment compatibilizer in inks [55]. As can be observed from Fig. 5, the grafting could be confirmed by the overlay of the GPC traces of PU–PBM-50 and the resulting PU. A shift of the compound toward lower retention time is clearly shown.

4. Conclusions and outlook

All possibilities and results discussed above show that CuAAC is a straightforward and versatile technique for industrially relevant polymers. With an alkyne diol incorporated in the polymer backbone, further efficient cycloaddition reactions with azides can be performed without any additional protecting and deprotecting steps, even in combination with drastic reaction conditions. In only three reaction steps, highly functionalized step-growth polymers can be obtained by the combination of SGP and 'click' chemistry. With regard to CuAAC, depending on the nature of the used azide compound, properties and characteristics of the polymer backbone can be tuned. At this moment, other clean and efficient functionalization reactions, such as thio-click chemistry, are explored in polymer science, which will certainly find their way in this particular research field.

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