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Electrospray Ionization–Mass Spectrometry for Molecular Level Understanding of Polymer Degradation

Minna Hakkarainen

Abstract The stability and durability of polymeric materials under different external influences (e.g., sunlight, humidity, heat, chemicals, or microorganisms) is of outmost importance in applications such as coatings, building materials, and automotive parts, whereas a rapidly degradable material is preferable in temporary short-term applications. There are considerable economic and environmental benefits if we can design polymers for short or long lifetimes as well as prevent the release of harmful substances from the materials during their lifetime. The recent developments in mass spectrometric techniques facilitate possibilities for molecular level characterization of the changes taking place in the polymer matrix as well as for identification of the released degradation products. This review presents an overview of the application of electrospray ionization–mass spectrometry (ESI-MS) for the analysis of polymer degradation. The great potential of the technique for revealing detailed insights into the degradative reactions taking place is demonstrated with examples ranging from degradable polymers and biomaterials to degradation of coatings, paints, polymer electrolyte membranes, food packaging, and materials in the nuclear industry.

Keywords Degradation · Electrospray ionization · Long-term properties · Mass spectrometry · Polymer

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Abbreviations

APCI-MS	Atmospheric pressure chemical ionization–mass spectrometry
a-PHB	Atactic poly(3-hydroxybutyrate)
APPI-MS	Atmospheric pressure photoionization–mass spectrometry
ATC	Acetyl tributyl citrate
BPA	Bisphenol A
CE	Capillary electrophoresis
CL	Caprolactone
CPLA	Cyclic polylactide
DESI-MS	Desorption ionization–mass spectrometry
EHA	2-Ethylhexyl-(4-dimethylamino)benzoate
EPR	Electron paramagnetic resonance
ESBO	Epoxidized soybean oil
ESI-MS	Electrospray ionization–mass spectrometry
FTIR	Fourier transform infrared
GC-MS	Gas chromatography–mass spectrometry
HALS	Hindered amine light stabilizer
HPLC	High performance liquid chromatography
ITX	Isopropylthioxanthone
LA	Lactide
LC	Liquid chromatography
MALDI	Matrix-assisted laser desorption ionization
MS	Mass spectrometry

MS^n	Multistage mass spectrometry
NMR	Nuclear magnetic resonance
PA	Polyacrylate
PBTA	Poly(1,4-butylene terephthalate)-*co*-(1,4-butylene adipate)
PCL	Polycaprolactone
PDLA	Poly(D-lactide)
PDXO	Poly(1,5-dioxepan-2-one)
PEG	Poly(ethylene glycol)
PHA	Polyhydroxyalkanoate
PHB	Poly(3-hydroxybutyrate)
PHBV	Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate)
PLA	Polylactide
PLLA	Poly(L-lactide)
PMMA	Polymethacrylate
PP-R	Polypropylene random copolymer
PTMG	Poly(tetramethylene glycol)
PVC	Poly(vinyl chloride)
TELNR	Telechelic epoxidized liquid natural rubber
TOF	Time-of-flight
UPLC	Ultra-performance liquid chromatography

1 Introduction

Depending on the application, the ideal lifetime of a polymeric product could vary from weeks to years. The stability and durability of polymeric materials during thermo-or photo-oxidation or under other external influences is of outmost importance in applications such as coatings, building materials, and automotive parts, whereas a rapidly degradable material is preferable in temporary short-time applications. There are considerable economic and environmental benefits if we can design polymers for short or long lifetimes as well as prevent the release of harmful substances from the materials during their lifetime. Mass spectrometry (MS) allows analysis of polymer microstructures, end-groups and molecular weights of the individual chains, information not obtained by other techniques. In polymer degradation studies, developments in mass spectrometric techniques can provide us with molecular level information about the smallest changes taking place in the polymeric materials as well as about the identity of the formed degradation products. During their lifecycle, polymeric materials are subjected to different harmful environments including high temperatures, chemicals, oxygen, sunlight, microorganisms, and/or humidity. Degradative reactions can take place during synthesis and processing of the materials and later during, e.g., the use outdoors or in contact with food, body fluids, or other corrosive liquids. Here the utilization of novel mass spectrometric techniques could provide better understanding of the influence of various environmental parameters on different polymeric

materials as well as an understanding of the stabilization mechanisms of antioxidants and light stabilizers. This in turn will provide tools for the development of materials for optimum lifetimes, whether we desire stable and durable materials or environmentally benign degradable materials.

In the 1980s it became possible to ionize large molecules into the gas phase, and soft ionization techniques like matrix-assisted laser desorption ionization–mass spectrometry (MALDI-MS) and electrospray ionization–mass spectrometry (ESI-MS) appeared. Recent developments in these techniques and MS of polymers in general have been reviewed in several papers [1–3]. Even though MALDI-MS has been more widely utilized for polymer characterization, in some applications ESI-MS poses advantages over MALDI-MS. It is easier to interface ESI-MS with separation techniques like liquid chromatography (LC) to provide both MS-based structural information, separation of the compound mixtures, and quantitative information from the LC analysis. ESI-MS analysis has also been shown to be more effective than MALDI-MS for determination of end-groups due to lower noise levels, absence of matrix ion interferences at lower m/z region and more effective ionization [4], and there are already many examples of the utilization of ESI–tandem mass spectrometry (ESI-MS/MS) and LC-ESI-MS/MS for the end-group characterization [5, 6]. ESI-MS has been applied for structural characterization of polymers in a number of studies, including monitoring of reaction pathways and detection of degradation reactions taking place during synthesis [7, 8]. Another very interesting and increasingly important application is the characterization of different biopolymers as well as their derivatives and hydrolysates [9, 10]. ESI-MS has not yet been widely utilized in polymer degradation studies even though the potential of the technique is great. In many cases, polymers are aged or used in different aqueous solutions, which could be analyzed by ESI-MS directly or after concentration and/or purification steps. This review presents an overview of the application of ESI-MS for the analysis of polymer degradation. The great power of the technique in providing deeper understanding of the degradation reactions is demonstrated with examples ranging from degradable polymers and biomaterials to degradation of coatings, paints, polymer electrolyte membranes, food packaging, and materials in the nuclear industry.

2 Degradation of Degradable Polymers and Biomaterials

Aliphatic polyesters are among the most promising materials for tissue engineering and degradable packaging applications. In both cases, the thorough understanding of degradation mechanisms, lifetime prediction and mapping of low molecular weight migrants is of outmost importance to ensure the safe use of the materials and their complete degradation to environmentally friendly products. Gas chromatography–mass spectrometry (GC-MS) [11, 12] and LC [13] have been successfully applied for identification and quantification of hydrolysis and biodegradation products. Both of these methods have their own advantages and limitations.

ESI-MS has emerged as an alternative effective and rapid tool for structural characterization of polyesters and copolyesters [14]. It also allows mapping of the whole water-soluble degradation product patterns up to molecular weights of 2,000 Da. Interesting ESI-MS work has also been performed to understand the molecular level structures of complex natural polyesters like suberin [15] and of linear and branched poly(ω-hydroxyacid) esters from plant cutins [16]. The main advantage of ESI-MS is the ease of sample preparation as the aging water can in many cases be directly analyzed after, e.g., addition of methanol. The technique also allows the analysis of longer water-soluble oligomers.

2.1 Side Reactions and Degradation During Synthesis of Polyesters

The physical properties of bacterial polyhydroxyalkanoates (PHA)s can be changed by addition of acids of different lengths. ESI-MS analysis has made it possible to show the incorporation of longer hydroxyacid units into the PHA chain during bacterial synthesis [17]. The analysis proved that PHAs could be synthesized from odd carbon atom *n*-alkanoic acids ranging from heptanoic to heptadecanoic acid. Ether bond fragmentation resulting in unsaturated end-groups was shown to take place during ring-opening polymerization of poly(1,5-dioxepan-2-one) (PDXO) at temperatures above 140 °C [18]. The formed double bonds could be further utilized for synthesis of crosslinked PDXO. ESI-MS also demonstrated the formation of vinyl ether end-groups during Na_2CO_3 promoted polymerization of poly(ethylene glycol) (PEG) [19].

Recently, a quantitative method for direct determination of residual monomers after polyester synthesis by ESI-MS was proposed [20]. This method allowed rapid quantification of terephthalic acid and sebacic acid after synthesis of copolyesters. Methanol was used to extract the monomers and 1,12-dodecanedioic acid was utilized as internal standard. The method was validated by comparing the obtained results with high performance liquid chromatography (HPLC) analysis. The detection limits were between 0.01 and 0.03 ppm. ESI-MS also showed that cyclization had taken place during synthesis of hydroxylated hyperbranched polyesters of fourth and fifth generation [21]. These cyclic structures were not detectable by nuclear magnetic resonance (NMR).

LC-MS and ESI-MS/MS methods were developed for the determination of low molecular weight cyclic polylactides (CPLA), which are formed as side-products during synthesis of polylactide (PLA) and could also be added to modify material properties [22]. The introduction of these cyclic compounds into the human body through migration from PLA biomaterials is undesirable as they may have negative effects such as lowering of the activity of pyruvate kinase and lactic hydrogenase. Linear and CPLA oligomers and their solvolysis products were also characterized by ESI-MS [23]. The study showed that solvolysis of the cyclic oligomers took

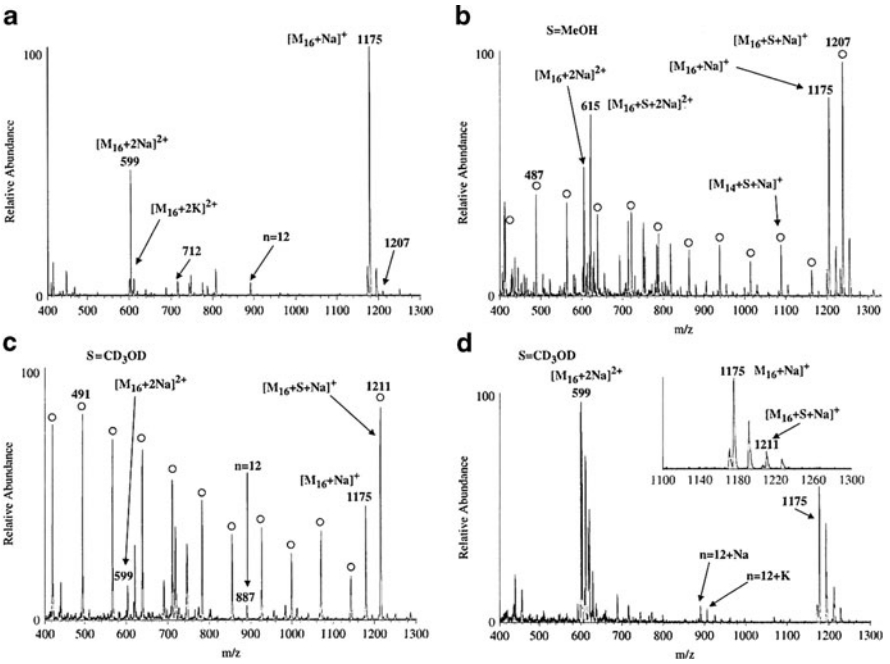

Fig. 1 ESI-MS spectrum obtained immediately after dissolving uniform CPLA ($n = 16$) in anhydrous MeOH (**a**). ESI spectrum of the solution after having been left standing for 1 day in anhydrous MeOH (**b**), CD_3OD (**c**), or 1/1 H_2O/CD_3OD (**d**). Reprinted from [23] with permission. Copyright 2006 John Wiley & Sons

place during overnight contact with anhydrous methanol and after shorter contact at an elevated temperature. This reaction resulted in appearance of methylated linear oligomers in the ESI-MS spectra (see Fig. 1). The reaction was, however, impeded by the presence of even small amounts of water. The presence of cyclic structures in poly(butylene adipate-*co*-butylene terephthalate) copolymers was also shown by LC-MS and LC-MS^n [24]. During aging in aqueous tetrabutylammonium hydroxide/methanol solution, these oligomers underwent methanol trans-esterification and formed linear oligomers with methyl ester end groups.

2.2 *Effect of Copolymer Microstructure and Composition on Hydrolytic Degradation*

ESI-MS clearly demonstrated the effect of microstructure and composition on the hydrolytic degradation pathways of polyesters and revealed molecular level information concerning the degradation process and susceptibility of different ester bonds [25]. The hydrolytic degradation of glycolide/caprolactone copolymer in

pH 7.4 phosphate buffer showed that not only the copolymer composition but also the microstructure influenced the degradation process. The ester bonds between the different monomer units seemed to be more susceptible to hydrolysis, leading to higher hydrolysis rate for more random copolymers, which could be partly related to the degree of crystallinity in the samples. The combination of high-resolution NMR spectroscopy and ESI-MS allowed detailed molecular level mapping of the degradation processes and release of degradation products from glycolide/caprolactone copolymers [26]. The influence of copolymer structure and crystallinity was evaluated in the compositions ranging from 70/30 to 30/70 glycolide/caprolactone. With the help of ESI-MS it was possible to follow in detail at molecular level the accumulation and/or further hydrolysis of water-soluble degradation products with different compositions and sequence distributions. The changes in the distribution of different oligomers during hydrolysis were demonstrated by illustrative planar projections.

The large effect of polymer architecture together with hydrophilicity of the monomeric building blocks was also clearly shown by ESI-MS analysis of hydrolysis products of different polycaprolactone (PCL) and PDXO copolymers [27]. In the case of the DXO–PCL–DXO triblock copolymers, the hydrophilic DXO blocks were rapidly hydrolyzed and released to the aging water, whereas the hydrolysis rate for the PCL blocks was similar to that for the PCL homopolymer. The more random distribution of the "weak" DXO linkages on the other hand also accelerated the hydrolysis of PCL sequences. This is clearly demonstrated in Fig. 2, which shows an expansion of the region m/z 1,040–1,320 from the mass spectra of the hydrolysis products of multi-and triblock copolymers. In the case of the triblock copolymer, the main hydrolysis products were the linear DXO oligomers, while mixed CL/DXO oligomers were released from the more random multiblock structures. The hydrophilicity of the building blocks is important for controlling the hydrolysis rate because it both regulates the water uptake by the materials and largely influences the water solubility of the resulting hydrolysis products.

2.3 Effect of Crosslinking on Hydrolytic Degradation

Following the hydrolysis process of crosslinked materials is complicated as the possible analyses are limited by the non-solubility of the material. Here, ESI-MS analysis of the water soluble products proved to be a valuable tool [28]. The hydrolytic degradation of crosslinked CL and/or DXO networks was followed and the results clearly showed differences in the hydrolytic degradation rate depending on the copolymer composition. At low degrees of degradation, the products patterns mainly consisted of linear CL and/or DXO oligomers, while at later stages oligomers with attached crosslinking agent were detected showing the point where the network structure started to disrupt. Figures 3 and 4 show, as an example, the water-soluble product patterns for crosslinked PCL homopolymer at low degree of degradation and at a later stage where oligomers with crosslinking

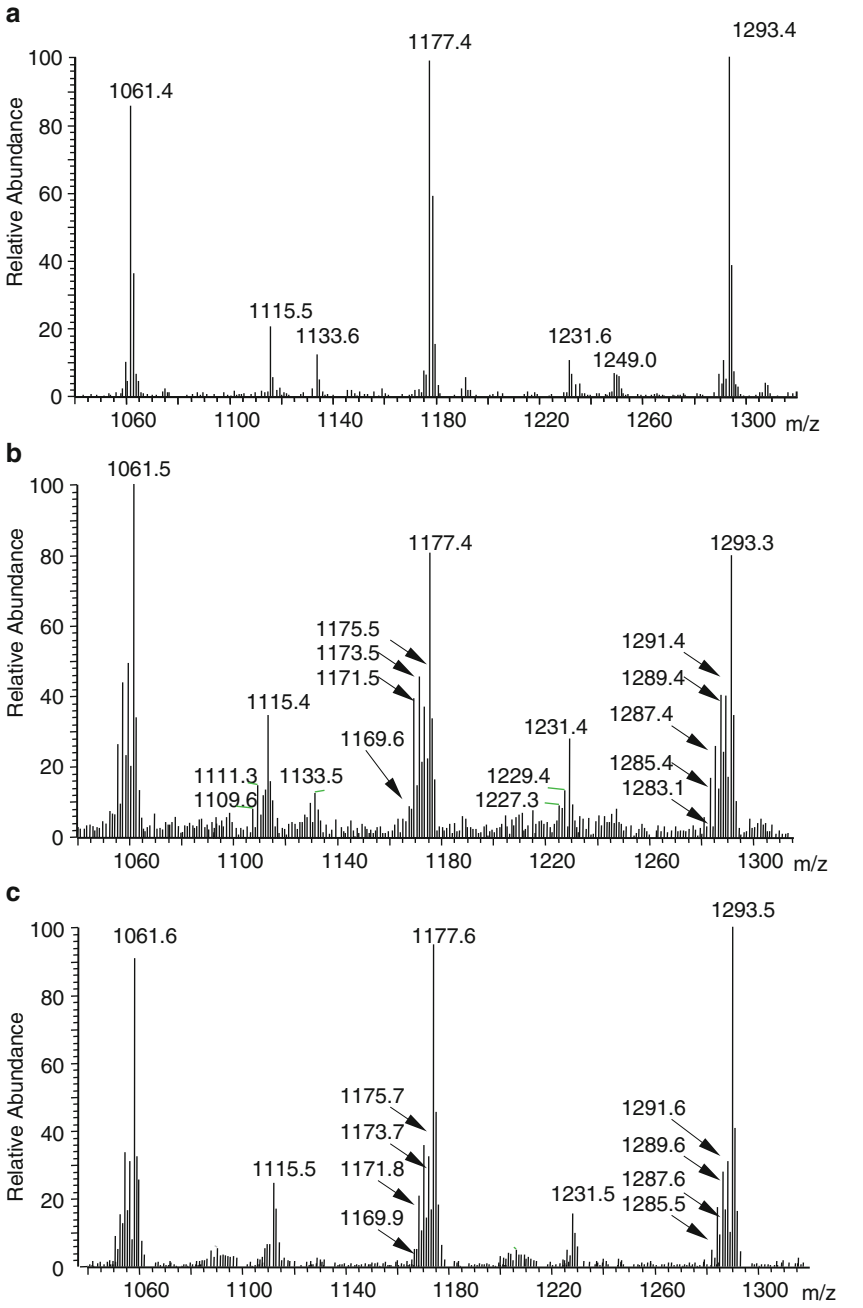

Fig. 2 Expanded region *m*/*z* 1,040–1,320 of the ESI-MS spectra of degradation products from (**a**) 60/40 CL/DXO triblock copolymer, (**b**) 60/40 CL/DXO multiblock copolymer, and (**c**) 75/25 CL/DXO multiblock copolymer. Reprinted from [27] with permission. Copyright 2008 American Chemical Society

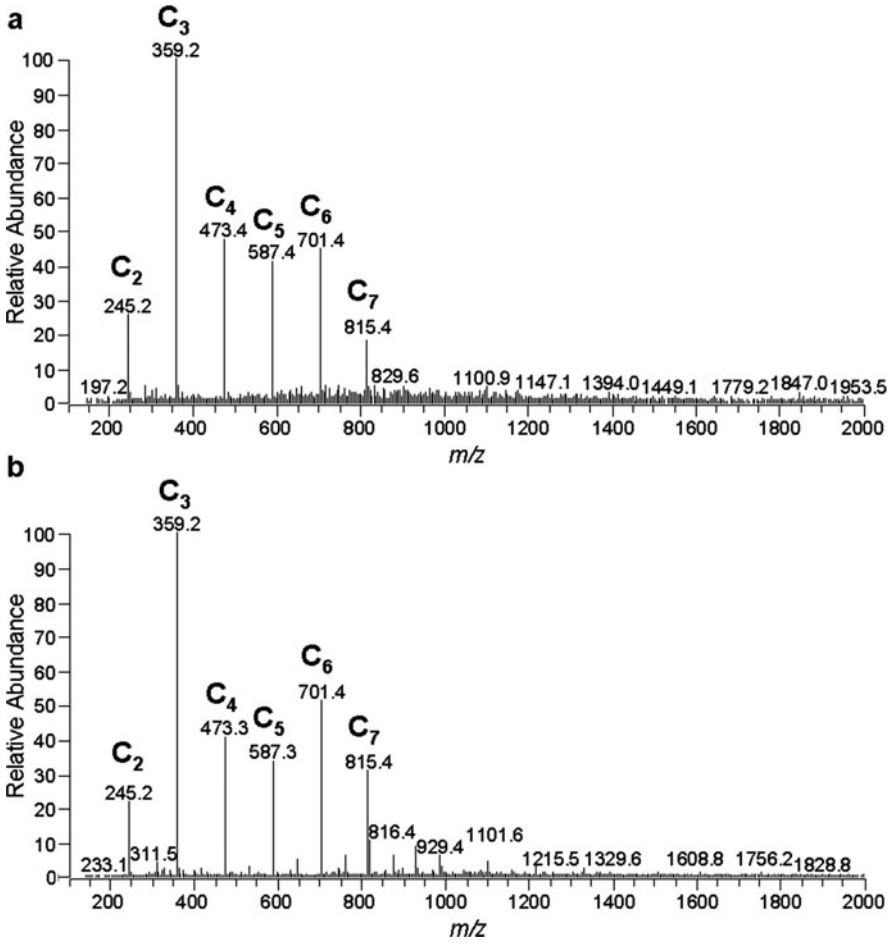

Fig. 3 Negative ESI-MS spectra of hydrolysis products from crosslinked PCL after (**a**) 1 day and (**b**) 21 days of hydrolysis in water at 37 °C showing linear caprolactone oligomers from dimer to heptamer. Reprinted from [29] with permission. Copyright 2008 John Wiley & Sons

agent are also detected. In another study PCL with acrylate end groups was crosslinked with amino-telechelic poly(tetrahydrofuran) and the in vitro degradation of the crosslinked PCL was evaluated by ESI-MS [28].

2.4 Effect of Blending on Hydrolytic Degradation

Several studies have applied ESI-MS to map the degradation process of PLA and different PLA modifications. Each material modification potentially affects the degradability, degradation rate, and degradation product patterns, which makes it

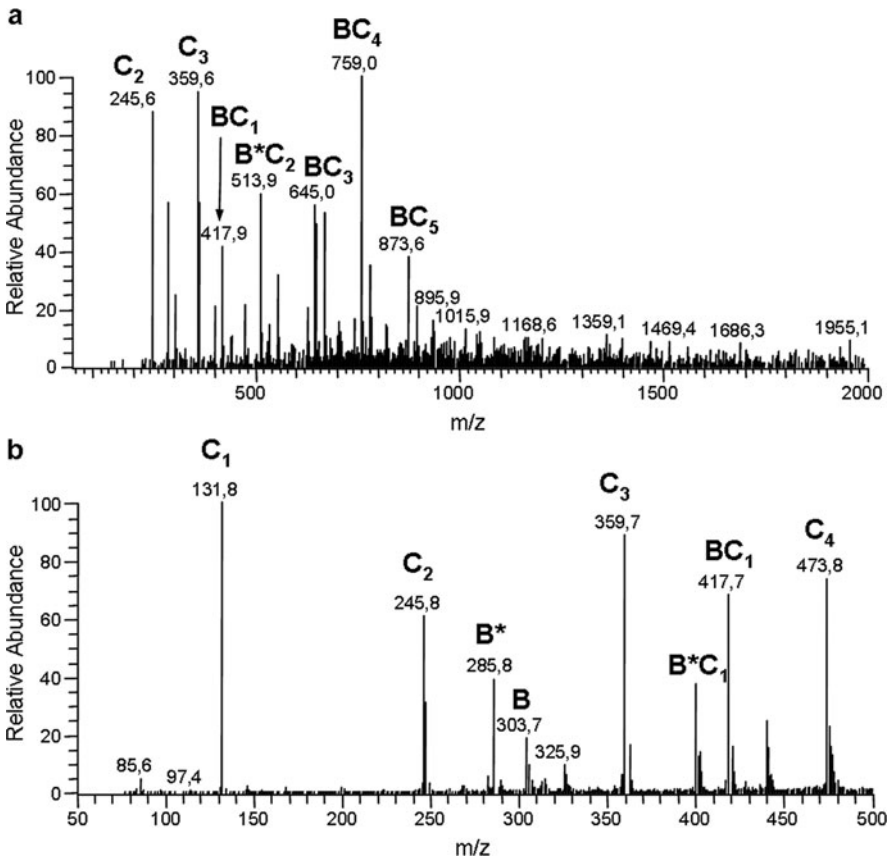

Fig. 4 Negative ESI-MS spectra of hydrolysis products from crosslinked PCL after 147 days of hydrolysis in water at 37 °C showing linear caprolactone oligomers as well as oligomers with the attached crosslinking agent (2,2′-bis(e-caprolactone-4-yl): (**a**) *m/z* 150–2,000 and (**b**) *m/z* 50–500. Reprinted from [28] with permission. Copyright 2008 John Wiley & Sons

crucial for the safe use of the materials to establish these relationships. The addition of new components in most cases introduces new migrants, or at least influences the product pattern and release rate of degradation products [30]. Interestingly, ESI-MS revealed that even modification with similar chemical structures could introduce important changes in the product patterns. As an example, the hydrolysis of PLA stereocomplex formed by blending of poly(L-lactide) (PLLA) and poly(D-lactide) (PDLA) resulted in the formation of shorter and more acidic lactic acid oligomers as degradation products [31]. Figure 5 presents ESI-MS spectra of hydrolysis products from PLLA and PLA stereocomplex. The spectra clearly show the differences in the product patterns. Even though the stereocomplex material was more stable than the plain PLLA and demonstrated much smaller mass loss during aging, the higher acidity of the released hydrolysis products led to a larger pH

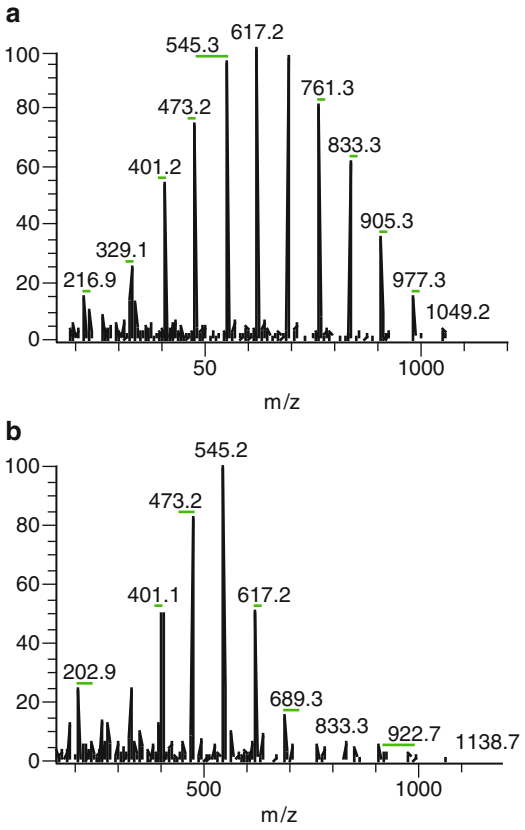

Fig. 5 Positive ESI-MS spectra showing the water-soluble degradation products of (**a**) PLLA and (**b**) PLLA/PDLA after hydrolysis in water for 13 weeks at 60 °C. Reprinted from [31] with permission. Copyright 2010 American Chemical Society

decrease for the stereocomplex material. Addition of plasticizers based on linear and cyclic lactic acids did not change the water-soluble product patterns, but ESI-MS showed significant differences in the release rate of these additives and the appearance of detectable water-soluble products [32]. The linear additives were water-soluble and started to migrate from the materials immediately after immersion in water. The cyclic structures on the other hand had first to be hydrolyzed before they could migrate into water.

In another study, a hydrophobic acetyl tributyl citrate (ATC) ester plasticizer was added to PLA [33]. The hydrophobic plasticizer partially prevented water-uptake by the materials and protected the PLA matrix against hydrolytic degradation. However, even though the water solubility of ATC is low, it was already detected in the aging solution by ESI-MS after 1 day of aging at 37 °C or 60 °C. On prolonged aging, hydrolysis of the plasticizer took place and various plasticizer degradation products were detected.

2.5 Effect of Substituents and Surface Modification on Hydrolytic Degradation

Hydrophilic material modification usually leads to faster hydrolysis rate, whereas hydrophobic modifications naturally decrease the degradation rate. ESI-MS analysis revealed that hydrophilic surface modification of PLA by acrylic acid accelerated the degradation rate and totally changed the water-soluble product patterns, which contained lactic acid and mixed acrylic acid grafted lactic acid oligomers [34]. Figure 6 illustrates the complex degradation product patterns after 28 days of hydrolytic degradation at 37 °C, which can be compared to the relatively simple pattern usually observed after hydrolysis of PLA (See Fig. 5a). For the surface-modified material, ESI-MS showed the appearance of water-soluble products already after 1 day at 60 °C or after 7 days at 37 °C. After hydrolysis of plain PLLA, the first water-soluble degradation products were detected after considerably longer aging times of 28 and 133 days at 60 °C and 37 °C, respectively. This effect can be partly due to the larger water uptake for the more hydrophilic material causing accelerated hydrolysis of the PLA matrix, but an even more important parameter is the high water solubility of the degradation products containing grafted acrylic acid. ESI-MS analysis also showed that hydrolytic degradation of hexyl-substituted PLAs led to the formation of oligoesters, and at later stages lactic acid and nontoxic 2-hydroxyoctanoic acid were formed [35].

2.6 Effect of Porosity on Hydrolytic Degradation

Acidic degradation products that are trapped into biomedical products can catalyze the hydrolysis process and lead to faster hydrolysis rates for thick specimens than for thin ones [36]. It could, thus, be expected that the hydrolysis of porous polyester scaffolds could proceed at lower rates compared to nonporous solid scaffolds [37]. Porosity and pore size were found to regulate the degradation rate and release rate of water-soluble degradation products from PLA scaffolds with over 90% porosity [38]. As expected, the solid PLA scaffolds had faster hydrolysis rates compared to the porous scaffolds and the hydrolysis rate decreased with decreasing pore size. This was also clearly reflected by the distribution of the oligomeric degradation product patterns determined by ESI-MS. However, somewhat unexpectedly, degradation products were detected earlier in the case of thicker solid PLA scaffolds, where the products could be trapped inside the films and their release into the aging solution could be delayed. Instead, the release of water-soluble products from the porous samples with very thin pore walls was delayed. This was attributed to the additional migration pathway within the porous structures and possible trapping of the hydrolysis products inside isolated pores.

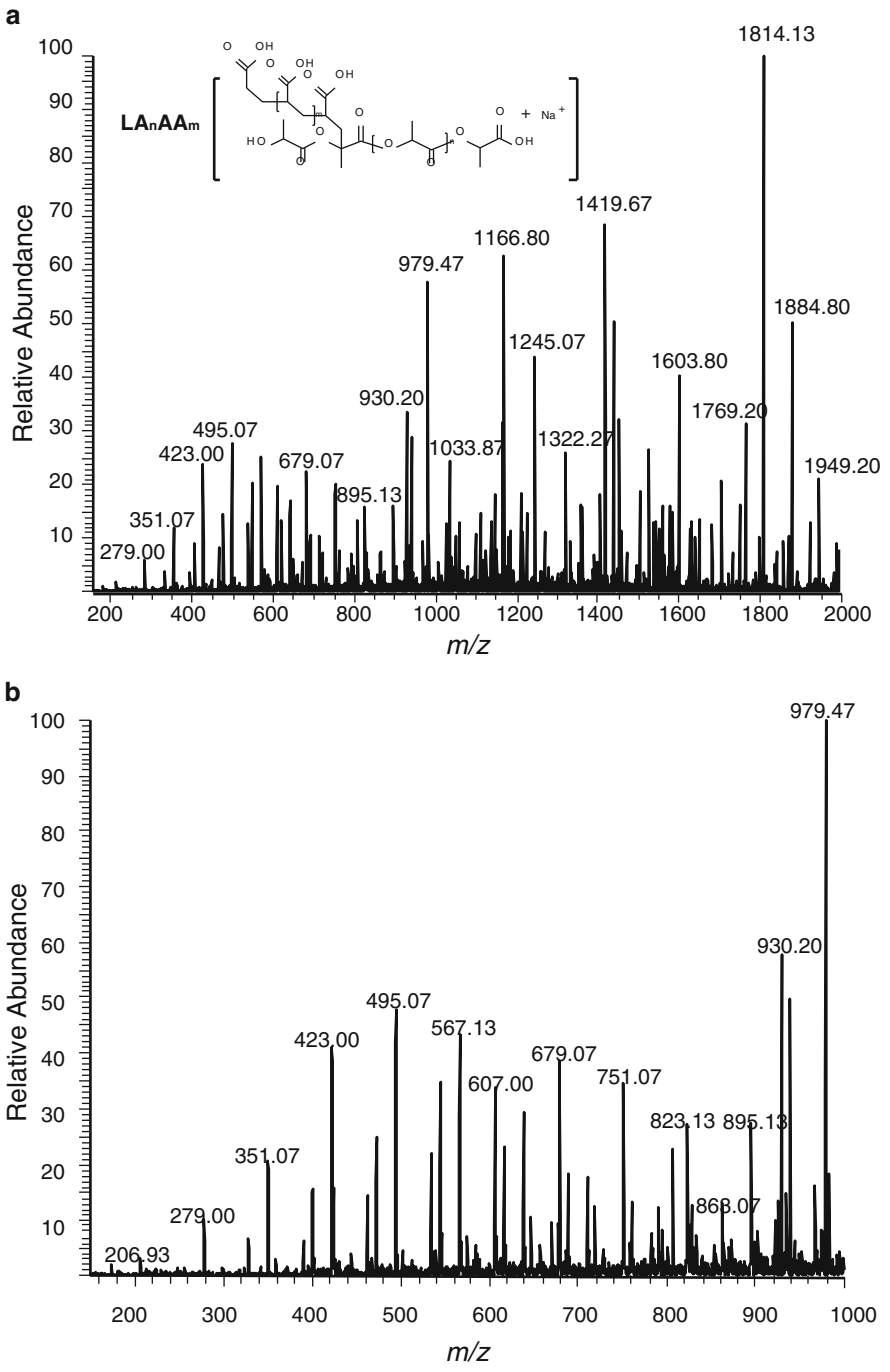

Fig. 6 ESI-MS spectra showing the complex water-soluble product pattern after hydrolysis of acrylic acid grafted polylactide for 28 days at 37 °C): (**a**) *m/z* 200–2,000 and (**b**) *m/z* 200–1,000. Reprinted from [34] with permission. Copyright 2010 American Chemical Society

2.7 Biodegradation

Only a few studies so far have utilized ESI-MS for establishing biodegradation mechanisms of aliphatic or aliphatic–aromatic polyesters. The great potential of the technique is, however, clearly demonstrated by these studies. Formation of oligomers with up to seven repeating units was shown by ESI-MS, and atmospheric pressure chemical ionization–mass spectrometry (APCI-MS) analysis of enzymatically hydrolyzed blends of poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV) and atactic poly(3-hydroxybutyrate) (a-PHB) [39]. The HPLC analysis of same samples only allowed identification of 3-hydroxybutyric acid and its dimer. Bioassimilation of water-soluble a-PHB oligomers ranging from dimer to dodecamer was also followed by ESI-MS [40]. These oligomers are analogous to PHB hydrolysis products. With the help of the ESI-MS analysis, utilization of these oligomers by two PHB degrading (*Alcaligenes faecalis* T1 and *Comamonas* sp) and one non-PHB degrading (*Ralstonia eutropha* H16) bacteria was shown, clearly indicating the total biodegradability of PHB in suitable natural environments. Poly(1,4-butylene terephthalate)-*co*-(1,4-butylene adipate) (PBTA) was aged in sandy soil for up to 22 months [41]. Even though PBTA is compostable under industrial composting processes, only limited degradability was shown in standardized sandy soil where disintegration and partial mineralization of PBTA was observed. The total mass loss after 22 months was only around 50%. After aging, the low molecular weight fraction was collected from size-exclusion chromatography analysis and further analyzed by ESI-MS. ESI-MS showed the retention of aromatic oligomers in the low molecular weight fractions, indicating preferential degradation of the aliphatic units. Phytotoxicity studies, however, indicated no visible damage or inhibitory effects on radish, cress and monocotyledonous oat.

HPLC-ESI-MS was utilized to study the enzymatic degradation process of poly (butylene succinate-*co*-butylene sebacate) and poly(butylene succinate-*co*-butylene adipate) with different compositions by lipase from *Mucor miehei* or *Rhizopus arrhizus* [42]. The hydrolysis resulted in a mixture of water-soluble oligomers. The sequence distribution of the oligomers with same molecular weight and monomer composition could be determined by HPLC-ESI-MS/MS analysis. The results clearly indicated preferential cleavage of ester bonds in the order sebacic, succinic and adipic ester bonds, starting from the most susceptible bond. The results gave indication that lipase catalysis was also active in aqueous solution, which was explained by the hydrophobic effect induced by the aliphatic units in the polyesters. In another study, enzymatic degradation of 2,2′-bis(2-oxazoline)-linked PCL by pancreatic enzymes was followed by HPLC-ESI-MS/MS [43]. With the help of HPLC-ESI-MS/MS the degradation was shown to proceed by surface erosion through hydrolysis of ester bonds, while amide bonds were mainly left intact. A large number of oligomers, altogether 80, were identified with m/z values up to 1,350. MS and MS^2 spectra of selected degradation products are shown in Fig. 7. HPLC-ESI-MS/MS was demonstrated to be a rapid and very useful technique for

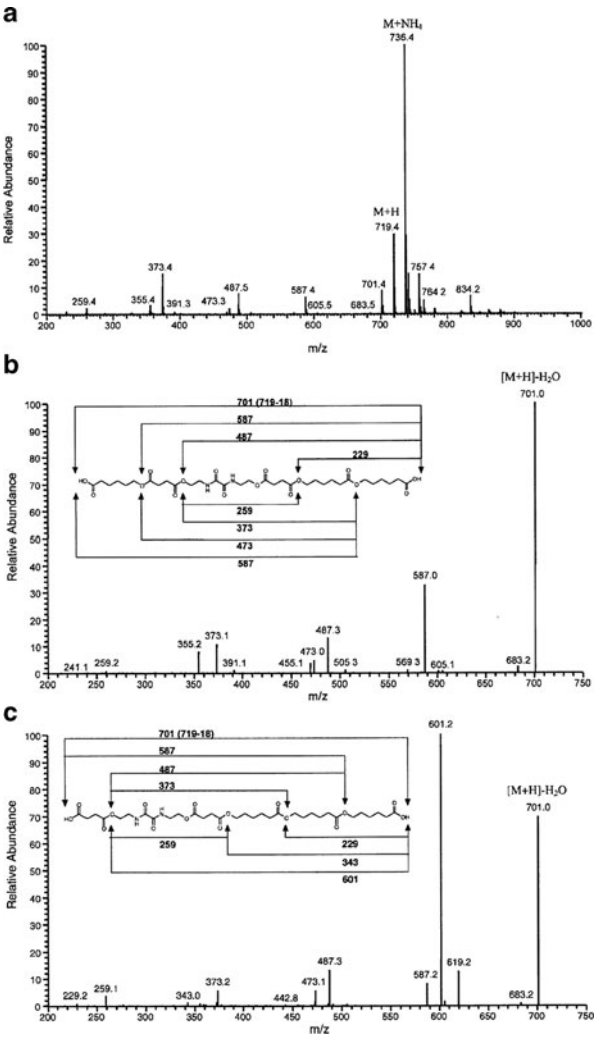

Fig. 7 Mass spectra of selected enzymatic degradation products from crosslinked PCL. (**a**) MS spectrum of the compounds eluting at retention time 19.78 min and having *m/z* 719, (**b**) MS^2 spectrum of the same compound, and (**c**) MS^2 spectrum of the compounds eluting at 21.56 min. Reprinted from [43] with permission. Copyright 2008 John Wiley & Sons

mapping the enzymatic degradation process at different stages, which is difficult to achieve by other techniques.

Enzymatic degradation of polyester amides based on natural amino acids, such as lysine and leucine, was performed by serine proteases (α-chymotrypsin) and proteinase K [44]. The water-soluble degradation products were analyzed by LC-ESI-TOF-MS. Tracking the release of degradation products showed that both α-chymotrypsin and proteinase K had esterase and amidase activity. The polymer was found to degrade at a steady rate in the presence of both enzymes, while the polymer was remarkably stable towards pure chemical hydrolysis. Aerobic biodegradation of PEG was evaluated in wastewater and seawater [45]. The molecular weight of the studied PEGs varied from 250 up to 60,000 g/mol. All the PEGs were

totally biodegraded during 65 days in freshwater media, while the degradation in seawater proceeded much more slowly. With the help of LC-ESI-MS and MALDI-TOF-MS analysis, significant differences in degradation mechanisms could be shown depending on the molecular weight of the materials.

3 Analysis of Medical Materials, Devices and Toys

Medical materials and toys are groups of materials where, for safety reasons, total control is needed over the type and content of low molecular weight compounds. These include compounds intentionally added to achieve certain properties as well as compounds formed due to degradation during synthesis, processing and, for example, sterilization of materials. The formation of ethylene glycol in ethylene oxide-sterilized medical devices is well known. A LC-MS/MS method was developed for detection of residual ethylene glycol in sterilized polymers [46]. In the method, an ammonium adduct of ethylene glycol was detected in the presence of ammonium acetate buffer and methanol. The method allowed quantification of ethylene glycol at levels down to 0.06 μg/mL. The potential of the method was demonstrated by analysis of ethylene glycol in sterilized polyethylene terephthalate fabrics for heart valve sewing rings. Dental composites are suspected of degradation during their lifetime in the oral environment. This degradation can lead to release of potentially toxic compounds such as bisphenol A (BPA). BPA diglycidyl methacrylate (BisGMA) was attached to a porous silicon oxide surface and this simplified model system was subjected to aging in an aqueous environment [47]. With the help of LC-ESI-MS, leaching of BisGMA and several other degradation products containing the BPA moiety were detected after aging of the materials for 2 weeks. No pure BPA was detected, but it could be formed later as a result of further degradation of the released degradation products.

N-Nitrosamines are a group of chemical compounds that can be formed during vulcanization of rubber in the presence of additives such as carbamate accelerators. The presence of *N*-nitrosamine in teats, soothers and child care articles is regulated by Commission Directive 93/11/EEC. LC-MS/MS was proposed and tested as a powerful technique for detection and identification of these compounds in rubber and elastomer teats and soothers [48]. The LC-MS/MS method was developed and validated for simultaneous determination of eight *N*-nitrosamines released into artificial saliva from rubber teats and soothers.

4 Degradation of Coatings and Paints

The application of polymer coatings on different substrate surfaces has great importance both for esthetic reasons and for corrosion protection. Understanding the microstructure of the coating and changes taking place when subjected to

environmental conditions is essential for development of improved coating materials. Polymethacrylates (PMMA), polyacrylates (PA), and polyesters are used in coating and paint formulations where the long-term properties and environmental stability are crucial parameters. In a series of studies, ESI-MS was utilized to fingerprint the degradation of PMMA under different environmental or accelerated conditions (95 °C and/or UV radiation) [49, 50]. ESI-MS analysis of degradation products of saturated and unsaturated poly(methyl methacrylate) model compounds revealed for the first time that PMMA degradation does not exclusively proceed via radical intermediates. The product analysis showed the formation of ethylene oxide-type end-groups after aging of unsaturated model compounds formed by the reaction of oxygen with the vinyl terminal groups. These end-groups were further rearranged under expulsion of formaldehyde and 2-oxo-propanoic acid. The corresponding saturated compounds were stable during the same time period up to 10 months. Combination with UV radiation accelerated the degradation process and resulted also in some degradation of the saturated compounds. Figure 8 shows the ESI-MS spectra and demonstrates the evolution of

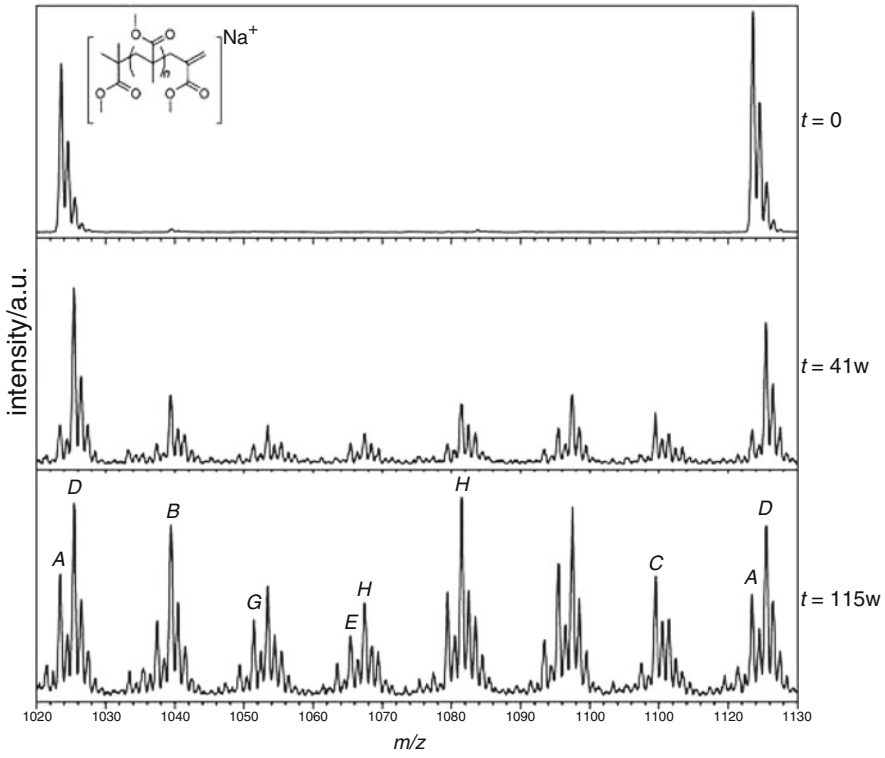

Fig. 8 ESI-MS spectra of vinyl terminated PMMA model compounds before ($t = 0$) and after 41 and 115 weeks of thermal aging at 95 °C. Reprinted from [50] with permission. Copyright 2010 John Wiley & Sons

degradation products as a function of thermal aging of unsaturated PMMA. It was further shown that butyl substituents were lost during the aging, leading to acid side groups [51]. The magnitude of this reaction was related to the side-chain structure as the reaction was more prominent for the compounds with *tert*-butyl groups compared to *n*-butyl groups. Acrylic polymers are also widely used in the artistic field as well as in conservation and restoration. Nano-ESI-MS was shown to be an excellent tool for identifying and characterizing additives such as PEG and poly (propylene glycol) in acrylic paints [52]. Degradation of an isopolyester based on isophthalic acid, glycols, maleic anhydride, cobalt dimethyl aniline and styrene as a crosslinking agent was studied in alkaline environment to simulate aggressive outdoor environments [53]. The LC-ESI-MS analysis showed leaching of low molecular weight compounds such as isophthalic acid from the material to the aging medium.

5 Migration from Food Packaging

Migration studies have an important role in ensuring the safety of polymer packaging in contact with different foodstuffs during storage and processing of food inside the polymer package. Gas chromatography and LC often coupled to a mass spectrometer have been applied in numerous studies for the identification of various migrants from polymer packaging, food simulants and/or real foods. ESI-MS has emerged as an attractive compliment to these analyses. It can be utilized alone for rapid direct analysis of liquid samples such as food simulants or it can be utilized as a detector for LC. A big advantage of ESI-MS compared to GC-MS or HPLC is that it can be applied for rapid screening of unknown compounds because it is less selective concerning the volatility and polarity of the compounds to be identified, which facilitates the detection of unknown non-intentionally added compounds in food packaging.

5.1 Direct Electrospray Ionization–Mass Spectrometry Analysis

Direct ESI-MS analysis of food simulants was recently demonstrated as a useful tool for studying migration from polymer packaging to food simulants [54]. The complexity of the resulting ESI-MS spectra clearly correlated with overall migration values. Compared to GC-MS analysis of the same samples, migrants with lower volatility could be detected. including polymer additives such as low molecular weight PEG. Figure 9 shows ESI-MS spectra of the compounds that migrated from random polypropylene copolymer (PP-R) to different food simulants during 1 h of microwave heating in contact with food simulants including water, 10% ethanol, 96% ethanol and 90/10 isooctane/ethanol. In addition, comparison of the ESI-MS spectra of the migrants from PP-R after 1 h of conventional heating and 1 h

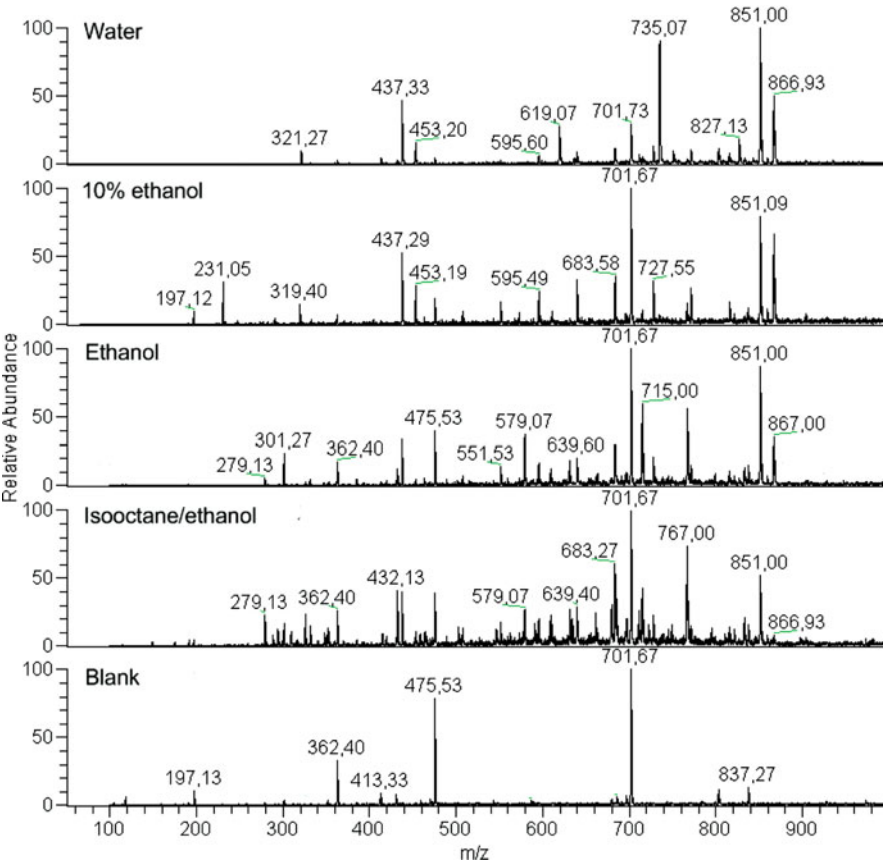

Fig. 9 ESI-MS spectra showing the compounds that migrated from PP-R into water, 10% ethanol, ethanol, and 90/10 isooctane food simulants during 1 h of microwave heating. The blank sample consisted of 90/10 isooctane/ethanol, which was microwave heated for 1 h at 80 °C. Reprinted from [54] with permission. Copyright 2011 American Chemical Society

of microwave heating clearly showed that significant antioxidant degradation took place during microwave heating in contact with fatty food simulants (Fig. 10). This degradation did not take place or was insignificant during heating at the same temperature without the microwaves. In another study, the large overall migration values during storage of PLA in contact with 96% ethanol food simulant could be explained because the ESI-MS showed migration of cyclic oligomers from PLA to ethanol. Due to solubility limitations, these compounds did not migrate to the other studied food simulants (water, 3% acetic acid, 10% ethanol and isooctane), which agreed with the considerably lower overall migration values (Bor, Alin, and Hakkarainen; unpublished results). The study also showed the higher stability of stereocomplex PLA in comparison with the regular PLLA during storage in contact with the food simulants.

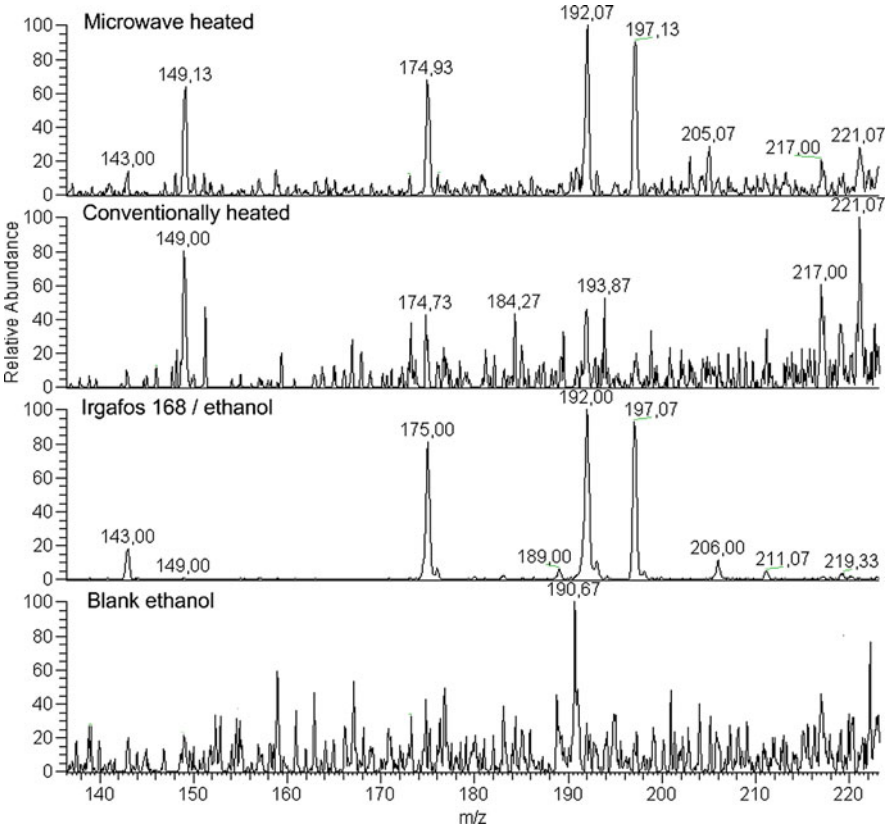

Fig. 10 ESI-MS spectra of (from *top* to *bottom*) 90/10 isooctane/ethanol extract of PP-R heated with microwaves, 90/10 isooctane/ethanol extract of PP-R heated conventionally, microwave-heated standard of Irgafos 168 (in ethanol), and conventionally heated ethanol blank sample. Samples and standard were heated for 1 h at 80 °C. The spectrum of microwave-heated PP-R have peaks corresponding to the degradation products from Irgafos 168. Reprinted from [54] with permission. Copyright 2011 American Chemical Society

5.2 Liquid Chromatography–Electrospray Ionization–Mass Spectrometry Analysis

Several studies utilized LC-ESI-MS for determination of various polymer additives or contaminants migrating from polymeric food packaging. The migration of the potential endocrine disrupter BPA from baby bottles into aqueous food simulants was studied by LC-ESI-MS [55]. The study showed that temperature was an important factor in controlling the migration of BPA from plastic bottles to water. However, the BPA released was decreased after repeated sterilization and use

cycles, indicating that the initial BPA release is due to residual BPA in the bottles and not caused by polymer degradation in hot water. LC coupled with negative ion ESI-MS/MS was also compared with positive ion ESI-MS for identification of bisphenolic migrants from can coatings [56]. LC-ESI-MS analysis in combination with elemental and NMR analysis allowed the identification of two compounds, which co-eluted with BPA and disturbed the LC analysis, as oxidized forms of epoxy can coating monomer.

Epoxidized soybean oil (ESBO) is a commonly used plasticizer/stabilizer in, e.g., polyvinyl chloride. It is used especially in food closure gaskets for metal lids and could migrate from them into the food in sealed glass jars. The main product of poly(vinyl chloride) (PVC) degradation, HCl, could react with ESBO to produce mono-and polychlorohydrins with unknown health effects. A method based on ultra-performance liquid chromatography (UPLC) coupled to ESI-MS was developed and allowed the detection of trace amounts of chlorohydrins in foodstuffs originating from ESBO [57]. Several potential mono-and dichlorohydrins were separated and identified, some of which were also detected in commercial foods at low concentrations. In another study, migration of polyadipates and their degradation products (also potential migrants from polyvinyl chloride used in lid gaskets of glass jars) into different food simulants was determined by LC-ESI-TOF-MS [58]. The direct determination of the polyadipate oligomers was complicated due to the large number of detected peaks. However, a rapid method for determination of adipic acid after alkaline hydrolysis was developed. In addition, a LC-ESI-MS/MS method was developed for the detection of different phthalates in milk and milk products including infant formulas [59]. Before analysis, the phthalates were extracted by organic solvent and separated from the milk fats.

Low level ink photo-initiator residues were determined by LC-ESI-MS/MS in milk packaged in carton or plastic [60]. The developed quantitative method allowed simultaneous quantification of several photo-initiator residues including, e.g., benzophenone, isopropylthioxanthone (ITX), 2-ethylhexyl-(4-dimethylamino)benzoate (EHA) and others. The method was applied to analysis of real samples of different fat contents and showed that benzophenone and ITX were the most important contaminants in these samples. GC-MS, LC-ESI-MS and LC-atmospheric pressure photoionization (APPI)-MS/MS were also utilized for identification of ink photo-initiators in packaged beverages [61]. Altogether, 40 packages and liquid foods were analyzed and benzophenone was found to be a common contaminant in most of the studied samples. UPLC-ESI-TOF-MS demonstrated strong potential as a screening tool for identification of adhesive compounds from polymer packaging [62]. Several acrylic adhesive formulations were extracted and analyzed by UPLC-TOF-MS. The possibility of obtaining full-mass spectra as well as fragmentation of each single-mass provides a powerful tool, even for analysis of a wide range of other unknown compounds in other complex sample matrixes.

6 Analysis of Antioxidants, Light Stabilizers, and Flame Retardants

In many applications, polymers need to be effectively stabilized against thermo-oxidative and/or photo-oxidative degradation. Considerable savings could be achieved through development of more effective antioxidants and light stabilizers. One step is a better understanding of the stabilization mechanisms. Hindered amine light stabilizers (HALS) are among the most effective antioxidants for polymeric systems. However, how they function in polymeric materials is still not totally understood. ESI-MS/MS was applied as a new tool for structural identification of standard HALS and its modifications formed through oxidation to better understand the mechanisms of stabilization [63]. In addition, the HALS species present in an extract from polyester-based coil coating were identified. With the help of MS/MS some degradation products were also identified. Figure 11 shows the ESI-MS/MS spectra conducted on $[M + H]^+$ ions of four different HALS. It was shown that all the studied piperidine-based HALS produced *m/z* 123 upon fragmentation. This ion could thus be utilized during analysis of extracts from polymers. ESI-MS was shown to be a very promising technique that could be more widely applied in the coatings industry to elucidate stabilization mechanisms and to develop improved formulations with optimized type and concentration of HALS.

ESI-MS was utilized for evaluating the mechanism of stabilization of chlorinated PVC by pentaerythritol/calcium-zinc stearate mixtures [64]. After aging at 185 °C under 40 rpm for 4 or 12 min, a significant number of reactions were detected and ESI-MS results indicated that oligomerization and chlorination of pentaerythritol had taken place. This indicates that pentaerythritol reacts with HCl, removing its harmful catalytic effect on PVC. It was also shown that addition of pentaerythritol considerably improved the stabilization effect of calcium and zinc stearates, but only exhibited a slight stabilizing effect if added alone. A LC-ESI-MS/MS method was developed and presented for the analysis organophosphorus flame retardants and plasticizers in wastewater samples [65]. This method allowed the determination of 11 different organophosphorus compounds with quantification limits after a solid-phase extraction concentration step of 3–80 ng/L. Direct LC-ESI-MS/MS analysis without a concentrations step allowed the detection of compounds in the low microgram per liter range, which in many cases is adequate. The method was successfully applied for the analysis of a municipal wastewater sample in which six phosphoric acid triesters were detected. LC-ESI-MS/MS was also shown suitable for the analysis of phthalates in house dust [66].

7 Radiation Effects on Polymers in the Nuclear Industry

PVC, polyurethanes and polyethers are frequently used in the nuclear industry where they are radiolyzed and as a result could undergo degradative processes. In a series of papers, the radiation effects on polyethers and polyether urethanes were evaluated.

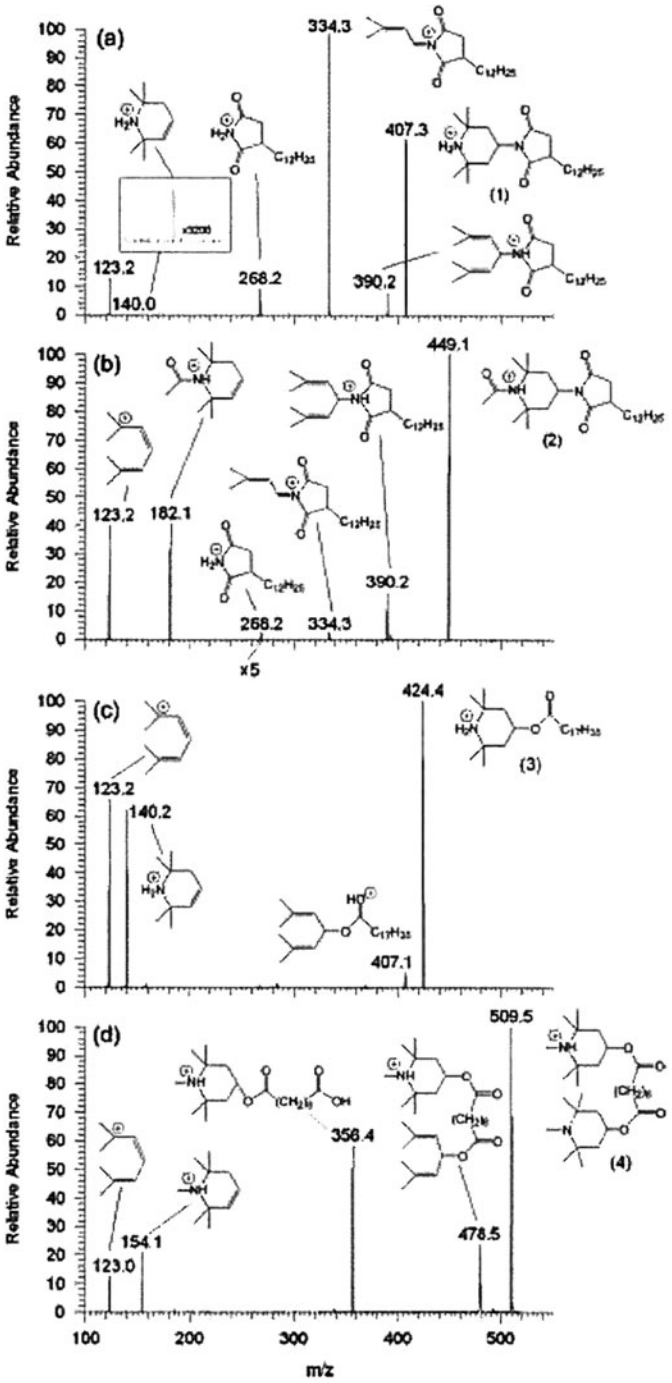

Fig. 11 ESI-MS/MS spectra conducted on $[M + H]^+$ ion of (**a**) HALS SANDUVOR 3055, (**b**) HALS SADUVOR 3058, (**c**) HALS CYASORB 3853, and (**d**) HALS TINUVIN 292 using a linear ion-trap mass spectrometer. Reprinted from [63] with permission. Copyright 2010 John Wiley & Sons

ESI-MS provided new insights into the degradation mechanisms of these materials. Aromatic polyether urethanes were subjected to high-energy radiation under oxygen atmosphere to predict the long-term behavior during a nuclear waste storage [67]. ESI-MS together with electron paramagnetic resonance (EPR) and Fourier transform infrared spectroscopy (FTIR) were utilized to propose an accurate degradation mechanism, which was then utilized to develop a predictive model of what would happen under long-term radio-oxidation. It was found that degradation mainly occurred at urethane bonds and in polyether soft segments, which resulted in the formation of formates, alcohols and carboxylic acids as stable degradation products. In addition to chain scission, crosslinking was a competing reaction during radiation.

Radiation effects were further evaluated with the help of low molecular weight model polyether–poly(tetramethylene glycol) (PTMG) and a degradation mechanism was proposed [68]. Figure 12 shows examples of ESI-MS mass spectra obtained after analysis of pristine and irradiated samples at different doses. For the pristine samples, the most intense peaks corresponded to the initial mass distribution of the oligomeric PTMG compounds. After irradiation, the mass spectra became more complex as many new peaks appeared, resulting in mass spectra with around 700 peaks representing both single and multiply charged ions. The most intense series of degradation products were identified with the help of ESI-MS and FTIR as formates and crosslinked species. Radiolysis of polyurethanes was further studied by ESI-MS and desorption electrospray ionization mass spectrometry (DESI-MS) [69]. The surface analysis of the irradiated polyurethane by DESI-MS revealed similar products as the analysis of methanol extracts by ESI-MS. The sensitivity of DESI-MS was lower, but nevertheless it allowed the analysis of irradiation products directly on the polymer surface without any sample preparation. The analysis also showed that similar degradation products are formed at the surface and in the bulk of the materials.

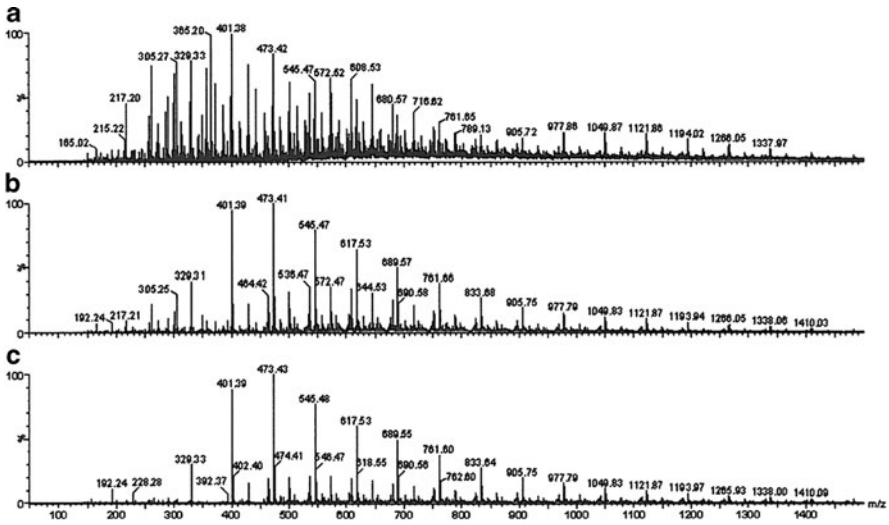

Fig. 12 ESI-MS analysis of PTMG after 380 kGy (**a**) and 94 kGy (**b**) doses of irradiation as well as the original spectra (**c**). Reprinted from [68] with permission. Copyright 2011 Elsevier

8 Degradation of Polymer Electrolyte Membranes

The polymer electrolyte membranes are susceptible to degradation caused by hydroxyl and peroxyl radicals formed by (electro)chemical side reactions. Understanding these processes and prevention of polymer electrolyte membrane degradation are crucial for the development of improved future membranes. In two interesting studies, LC-ESI-MS/MS and ESI-MS were applied for the analysis of degradation products from polymer electrolyte membrane fuel cells [70, 71]. The authors performed systematic method development for separation and identification of structurally similar compounds, such as 4-hydroxybenzoic acid, isophthalic acid, terephthalic acid, 4-hydrobenzaldehyde and 4-formylbenzoic acid. In addition, screening for unknown compounds in the product water of the fuel cell was performed by LC-MS. The developed ESI-MS method could be very valuable for real-time in situ membrane degradation product monitoring. This could allow the identification of relationships between fuel cell operating parameters and the resulting degradation products, giving insights into the membrane processes.

9 Structural Analysis and Recycling Through Controlled Degradation

A rapid method leading to complete hydrolytic degradation of polyester urethane acrylates was developed by utilizing a microwave instrument [72]. The method was applied in order to understand the structure and hydrolytic degradation of poly(2-hydroxylethyl methacrylate), poly(L-lactide-*co*-glycolide) diol and their copolymers. The degradation products were collected quantitatively and analyzed by NMR, size exclusion chromatography and HPLC-ESI-TOF-MS to elucidate the structure and hydrolysis process of these crosslinked materials. In another study, a recycling method for waste tires, causing considerable environmental pollution, was developed and evaluated. In a search for an effective recycling method, natural rubber was oxidized with the help of sodium tungstate, acetic acid, and hydrogen peroxide to prepare telechelic epoxidized liquid natural rubber (TELNR) [73]. With the help of ESI-MS analysis it was proposed that the catalysis proceeds via a tungstic anion, which is a mononuclear tungsten peroxo-species with a coordinated peracetyl/acetyl group.

10 Future Perspectives

ESI-MS has emerged as a relatively new tool for polymer degradation analysis. ESI-MS has already in many studies been utilized for structural characterization of polymers, including analysis of chemical structures and end-groups as well as copolymer microstructures, but its application to polymer degradation studies is

still scarce. The potential of the technique is, however, enormous as demonstrated by the examples summarized in this review. Wider utilization of ESI-MS, and mass spectrometric tools in general, for tracking the molecular level changes taking place in polymers during different stages of their lifecycle could significantly contribute to faster development of better functioning and more sustainable polymeric materials. Further development of instruments interfaced with ESI-MS will probably allow detection of broaden ranges of products, and utilization of mass analyzers such as Fourier transform ion cyclotron resonance will further enhance the possibilities. In numerous applications, ESI-MS can offer improved understanding of polymers and their long-term properties as well as the interactions between polymers and their environment. This will further promote the development of polymers for controlled optimum life times, whether we require materials with improved long-term properties and durability, or environmentally benign degradable polymers.

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