CHAPTER 1

OVERVIEW OF MS AND MALDI MS FOR POLYMER ANALYSIS

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POLYMER ANALYSIS involves many different activities ranging from average molecular mass determination to detailed characterization of chemical structures or compositions. It is a key step in understanding the relations of chemo-physical properties of a polymeric material and its functions. It is essential for quality control of polymeric products as well as in troubleshooting of a polymer manufacturing process. Currently, there is a high demand for developing specialty materials in many applications such as safe water treatment, recyclable materials in high-tech products, and drug delivery systems with improved therapeutic efficacies. Many of the new materials are based on synthetic polymers. One can expect that the field of polymer analysis will continue to become increasingly important in polymer industry and polymer science.

Polymer analysis is often a challenging task, particularly when a polymer is made from new polymer chemistry, catalysis, or formulation process. Fortunately, a great number of analytical techniques are now available for polymer analysis. They include separation techniques [1–7], spectroscopic methods [8–11], NMR [12–14], X-ray [15–17], microscopy [18–21] and other surface characterization tools [22–24], and mass spectrometry (MS) [25–35]. For a given polymeric system, these techniques each having advantages and limitations over the others are often combined to provide a detailed characterization of the system [33–41]. Among them, MS has become an indispensable tool for polymer analysis and has widely been used to study polymer structure, polymer composition, molecular mass and molecular mass distribution, bulk and surface properties, impurity contents, and so on.

MS offers several important attributes for polymer analysis [25–35]. MS, based on accurate mass measurement and/or tandem MS (MS/MS) analysis, can generate rich chemical information that is highly specific for polymer structural analysis. MS is also very sensitive, allowing the detection and identification of minor polymer components or impurities in a composed polymeric material and any by-

MALDI Mass Spectrometry for Synthetic Polymer Analysis, Edited by Liang Li

product of polymerization reaction of a desired polymer. Rapid MS analysis can be done for many polymer samples where no prior sample treatment or extensive separation is needed. MS can potentially provide quantitative information required for determination of the average molecular mass and molecular mass distribution of a polymer or characterization of relative amounts of different components of a polymer mixture. Some forms of MS such as secondary ion mass spectrometry (SIMS) can also be used to characterize polymer surfaces [35].

Almost all mass spectrometric techniques developed so far have been tried for polymer analysis, with varying degrees of success; some have been more widely used than the others. Traditional techniques such as electron impact ionization (EI), chemical ionization (CI), and gas chromatography/mass spectrometry (GC/MS) are still used for generating structural or compositional information on polymers, albeit applicable to only low-mass polymers or their precursors (monomers, dimers, etc.). Pyrolysis MS or GC/MS uses a pyrolysis process to thermally degrade polymers, including very high-molecular-mass polymers, to fragment products that are subjected to MS or GC/MS analysis [25]. This technique is still useful for generating chemical information on monomer structures, copolymer repeat units, end groups, and impurities or additives, particularly for those polymers not amendable to modern MS techniques [25]. In applying this technique, one needs to be cautious in interpreting the mass spectral results, as thermal degradation often alters the chemical structures of the polymeric materials. One interesting recent development in pyrolysis MS is to carry out a controlled degradation of polymer so that low-mass polymers or oligomers, instead of very low-mass products suitable for EI or CI, are generated. The low-mass polymers are analyzed using modern techniques such as matrix-assisted laser desorption ionization (MALDI) MS [42–44].

In the 1970s and earlier 1980s, active researches were being pursued to develop new ionization sources to overcome the limitations of EI and CI to handle thermally unstable and/or large molecules. Desorption techniques such as SIMS, fast atom bombardment (FAB), and laser desorption/ionization (LDI) were rapidly developed, and many researchers demonstrated that these techniques were useful for not only biopolymer characterization, but also synthetic polymer analysis. In the late 1980s, the introduction of MALDI and electrospray ionization (ESI) opened a new era in mass spectrometric analysis of biomolecules and synthetic polymers. Before MALDI and ESI, MS was limited to the analysis of relatively low-molecular-mass polymers of less than 3000 Da. Only in some favorable polymeric systems, such as poly(ethylene glycol) (PEG), MS analysis of up to 10,000 Da could be done [45]. Even for these polymers, the analysis was not routine, and was usually done by an experienced researcher.

ESI can be particularly useful for analyzing high-mass molecules that are easy to form multiply charged gas phase ions. PEG was one of the chemical samples used to illustrate the power of ESI for high-mass analysis in the early development of the ESI technique [46]. PEG can readily form multiply charged ions by attaching multiple sodium or potassium ions to a polymer chain and they are stable in the gas phase. However, a majority of synthetic polymers do not form multiply charged ions easily, and hence ESI has a limited applicability in synthetic polymer analysis, especially for high-mass polymers. Many polymers require the use of metal ions to form adduct ions. These adduct ions are not stable in the gas phase and do not survive during the translation from atmosphere to the mass analyzer via an ESI interface. Even if multiply charged ions are formed, to deduce molecular mass or molecular mass distribution information, oligomer ions must be resolved to determine the charge states. This is not trivial as many peaks from oligomers with different numbers of repeat units and different charge states may overlap. In addition, the oligomer distribution from the ESI ions is very sensitive to the experimental conditions such as the skimmer voltages, making accurate determination of the average mass and mass distribution difficult [47–50].

Despite these limitations, ESI can be a very powerful technique for characterizing ESI-able polymers such as low-mass PEGs or some water-soluble polymers with diverse end-group structures [29, 51–53]. This is because ESI offers several important attributes. First of all, ESI can be readily interfaced with solution-based separation techniques such as high-performance liquid chromatography (HPLC) for separating complex mixtures [54–56]. More recently, ion mobility separation in the gas phase can be used to further separate closely related polymeric ions [57–60]. Second, many different types of ESI tandem mass spectrometers, including those capable of carrying out multiple-stage dissociation of an ion, are available for generating structural and compositional information on a polymer sample [61]. Third, multiply charged ions produced by ESI are relatively easier to dissociate than a singly charged ion often found in MALDI [62–66]. Finally, high-performance ESI mass spectrometers such as high-resolution time-of-flight (TOF), Orbitrap, and high-field Fourier transform ion cyclotron resonance (FT-ICR) MS are now available, offering excellent mass resolving power and mass measurement accuracy. Overall, the combination of new separation tools with high-performance ESI MS will likely increase its popularity in polymer analysis, particularly for detailed characterization of chemical structures and compositions of a polymeric system. But, the major obstacle still remains: many polymers simply do not ionize well by ESI.

MALDI MS transforms the practice of polymer characterization. It has now become a widely used technique for analyzing a great variety of polymers. In this book, many aspects of the MALDI MS technique will be discussed in great detail. There are several unique attributes of MALDI MS, together making it a powerful technique for polymer characterization. In MALDI MS, molecular mass and molecular mass distribution information can be obtained for polymers of narrow polydispersity with high precision and speed. The accuracy, although difficult to determine due to the lack of well-characterized standards, appears to be good as well [67, 68]. The MALDI analysis of polymers does not require the use of polymer standards for mass calibration. Furthermore, this technique uses a minimum amount of solvents and other consumables, which translates into low operational costs. MALDI MS can also provide structural information, if the instrumental resolution is sufficient to resolve oligomers. In this case, monomer and end-group masses can be deduced from the accurate measurement of the mass of individual oligomers. This is particularly true when a high-resolution instrument such as FT-ICR MS is used for polymer analysis. With the use of MALDI MS/MS, structural characterization can be facilitated. Finally, impurities, by-products, and subtle changes in polymer distributions can often be detected even for relatively complex polymeric systems such as copolymers.

Because of these attributes, in many labs, MALDI MS has become a routine tool for polymer characterization. This is evident from an increasing number of publications in polymer science literature (e.g., *Macromolecules*), which indicate the use of MALDI MS as a tool for characterizing newly grafted or synthesized polymers. In the industry dealing with polymeric materials, MALDI MS is often combined with other analytical techniques to provide detailed analyses of a polymeric system. In some cases, MALDI MS is the only technique that can provide the information required to solve a practical problem. One example is in the area of product failure analysis involving four copolymer samples [69].

However, current MALDI techniques have several limitations for polymer analysis. Some narrow polydispersity polymers cannot be readily analyzed. There is a need to develop sample preparation protocols to analyze important polymers such as polyethylene, perfluoropolymer, and polycationic polymers. The analysis of polystyrenes with molecular mass up to 1.5 million has been demonstrated. But it remains to be seen how the technique can apply to other high-molecular-mass polymers (MW > 500,000). Searching for sensitive sample preparation methods and improving the overall detection sensitivity of the current MALDI instrument for high-mass analysis are required. The MALDI technique has not yet generated reliable results in direct analysis of broad polydispersity polymers. The instrumental and chemistry problems associated with the analysis of these broad polydispersity polymers have been studied by a number of groups, as discussed in several chapters in this book. We now have a better understanding of the issues involved, and we will see more development in this area in addressing these issues in the near future. Alternatively, gel permeation chromatography or size exclusion chromatography can be combined with MALDI MS for polymers of broad polydispersity. Finally, it is difficult, at present, to deduce quantitative information on polymer mixtures from the MALDI spectra. The overall detection sensitivity for different polymers is not the same. There is no direct correlation between the relative peak areas in the spectra and the relative amounts in the mixture. However, information on relative changes in polymer composition can be obtained, if several polymeric systems containing the same polymer mixture, but different relative amounts, are available for interrogation.

In conclusion, many different mass spectrometric techniques are currently available for detailed characterization of a synthetic polymer. Among them, MALDI MS has been widely used for analyzing a great variety of polymers. It offers some unique attributes while some limitations remain. However, future advances in fundamental studies of the MALDI process, sample preparation methods, ion detection techniques, and data processing issues will undoubtedly enhance its role in polymer science in general. Many of these topics will be the subject of discussion throughout this book.

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