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# HANDBOOK OF PLASTICS, ELASTOMERS, & COMPOSITES

## FOURTH EDITION

- Covers the fundamentals of plastics including electrical design properties
- New chapters focus on advanced uses of plastics
- Provides practical examples for day-to-day practice and reference for structural engineers

CHARLES A. HARPER

# Handbook of Plastics, Elastomers, and Composites

**Charles A. Harper** Editor-in-Chief

*Technology Seminars, Inc.*
*Lutherville, Maryland*

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# PREFACE

Welcome to this new, heavily revised and updated Fourth Edition of *Handbook of Plastics, Elastomers, and Composites.* The continued development of new and improved polymers, and their application in new and improved products, have led to almost unlimited product opportunities. In fact, there are probably few who would not rate this area of product growth as one of the most important in industry growth areas. The impact of polymers-plastics, elastomers, and composites—in all of their material forms—has been little short of phenomenal. New polymers and improvements in established polymer groups regularly extend the performance limits of plastics, elastomers, and composites. These achievements in polymer and plastic technology offer major benefits and opportunities for the myriad of products in which they can be used.

With all these achievements, however, a major impediment exists to the successful use of plastics, elastomers, and composites in products. This impediment is the lack of fundamental understanding of plastics, elastomers, and composites by product designers. Along with this lack of understanding is the absence of a useful consolidated source of information, data, and guidelines that can be practically used by product designers, most of whom do not "speak plastics." The usual practice is to use random supplier data sheets and data tables for guidance. It is, therefore, the object of this handbook to present, in a single source, all of the fundamental information required to understand the large number of materials and material forms, and to provide the necessary data and guidelines for optimal use of these materials and forms in the broad range of industry products. At the same time, this handbook will be invaluable to the plastics industry in acquainting its specialists with product requirements for which they must develop, manufacture, and fabricate plastics materials and forms.

This new Fourth Edition of *Handbook of Plastics, Elastomers, and Composites* has been prepared as a thorough sourcebook of practical data for all ranges of interests. It contains an extensive array of property and performance data, presented as a function of the most important product variables. Further, it presents all important aspects of application guidelines, fabrication-method trade-offs, design, finishing, performance limits, and other important application considerations. It also fully covers chemical, structural, and other basic polymer properties. The handbook's other major features include thorough lists of standards and specifications sources, a completely cross-referenced easy-to-use index, a comprehensive glossary, useful end-of-chapter reference lists, and several appendices containing individual data and information for product engineers.

The chapter organization and coverage of the handbook is equally well suited for reader convenience. The first three chapters present the fundamentals and the important information, data, and guidelines for the three basic material categories of thermoplastics, thermosets, and elastomers, thus enabling readers to more fully understand the presentation in the following chapters. The next four chapters are devoted to major plastic product forms that are so important to product design. The first two of these chapters cover composites, one chapter covering basic and structural composites and one chapter covering the increasingly growing area of composites in electronics. These two chapters are followed by one chapter each on plastics in coatings and finishes, and plastics in adhesives. After this, one chapter very thoroughly covers the critical and important subject of area of join-

ing of plastic parts. The understanding of this design area, almost always a major factor in the quality of plastic products, is most expertly covered in this chapter, which provides excellent guidelines for designers of plastic products.

Next, appropriately following the above listed chapters on basic plastics and plastic forms, a special chapter is devoted to a clearly illustrated presentation of all the important considerations for the design and fabrication of molded plastic products. The following two chapters thoroughly cover the use of plastics and elastomers in two of the largest application fields, namely, automotive and packaging.

The final chapter is an excellent presentation on a subject of increasingly vital importance to all of those in all areas of plastics and elastomers—the recycling of waste products.

The result of these presentations is an extremely comprehensive and complete single reference and text—a must for the desk of anyone involved in any aspect of product design, development, or application of plastics, elastomers, and composites. This handbook will be invaluable for every reference library.

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Chapter

# 1

# Thermoplastics

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## 1.1 Introduction

Plastics are an important part of everyday life; products made from plastics range from sophisticated articles, such as prosthetic hip and knee joints, to disposable food utensils. One of the reasons for the great popularity of plastics in a wide variety of industrial applications is the tremendous range of properties exhibited by plastics and their ease of processing. Plastic properties can be tailored to meet specific needs by varying the atomic composition of the repeat structure; and by varying molecular weight and molecular weight distribution. The flexibility can also be varied through the presence of side chain branching and according to the lengths and polarities of the side chains. The degree of crystallinity can be controlled through the amount of orientation imparted to the plastic during processing, through copolymerization, by blending with other plastics, and via the incorporation of an enormous range of additives (fillers, fibers, plasticizers, stabilizers). Given all of the avenues available to pursue in tailoring any given polymer, it is not surprising that the variety of choices available to us today exists.

Polymeric materials have been used since early times, even though their exact nature was unknown. In the 1400s, Christopher Columbus found natives of Haiti playing with balls made from material obtained from a tree. This was natural rubber, which became an important product after Charles Goodyear discovered that the addition of sulfur dramatically improved the properties; however, the use of polymeric materials was still limited to natural-based materials. The first true synthetic polymers were prepared in the early 1900s using phenol and formaldehyde to form resins—Baekeland's Bakelite. Even with the development of synthetic polymers, scientists were still unaware of the true nature of the materials they had prepared. For many years, scientists believed they were colloids—a substance that is an aggregate of molecules. It was not until the 1920s that Herman

Staudinger showed that polymers were giant molecules or *macromolecules*. In 1928, Carothers developed linear polyesters and then polyamides, now known as nylon. In the 1950s, Ziegler and Natta's work on anionic coordination catalysts led to the development of polypropylene; high-density, linear polyethylene; and other stereospecific polymers.

Materials are often classified as metals, ceramics, or polymers. Polymers differ from the other materials in a variety of ways but generally exhibit lower densities, thermal conductivities, and moduli. Table 1.1 compares the properties of polymers to some representative ceramic and metallic materials. The lower densities of polymeric materials offer an advantage in applications where lighter weight is desired. The addition of thermally and/or electrically conducting fillers allows the polymer compounder the opportunity to develop materials from insulating to conducting. As a result, polymers may find application in electromagnetic interference (EMI) shielding and antistatic protection.

**TABLE 1.1 Properties of Selected Materials[451]**

| Material | Specific gravity | Thermal conductivity, (Joule-cm/°C $cm^2$ s) | Electrical resistivity, μΩ-cm | Modulus MPa |
|---|---|---|---|---|
| Aluminum | 2.7 | 2.2 | 2.9 | 70,000 |
| Brass | 8.5 | 1.2 | 6.2 | 110,000 |
| Copper | 8.9 | 4.0 | 1.7 | 110,000 |
| Steel (1040) | 7.85 | 0.48 | 17.1 | 205,000 |
| $Al_2O_3$ | 3.8 | 0.29 | $>10^{14}$ | 350,000 |
| Concrete | 2.4 | 0.01 | – | 14,000 |
| Borosilicate glass | 2.4 | 0.01 | $>10^{17}$ | 70,000 |
| MgO | 3.6 | – | $10^5$ (2000°F) | 205,000 |
| Polyethylene (H.D.) | 0.96 | 0.0052 | $10^{14}$–$10^{18}$ | 350–1,250 |
| Polystyrene | 1.05 | 0.0008 | $10^{18}$ | 2,800 |
| Polymethyl methacrylate | 1.2 | 0.002 | $10^{16}$ | 3,500 |
| Nylon | 1.15 | 0.0025 | $10^{14}$ | 2,800 |

Polymeric materials are used in a vast array of products. In the automotive area, they are used for interior parts and in under-the-hood applications. Packaging applications are a large area for thermoplastics, from carbonated beverage bottles to plastic wrap. Application requirements vary widely, but, luckily, plastic materials can be synthesized to meet these varied service conditions. It remains the job of the part designer to select from the array of thermoplastic materials available to meet the required demands.

## 1.2 Polymer Structure and Synthesis

A polymer is prepared by stringing together a series of low-molecular-weight species (such as ethylene) into an extremely long chain (polyethylene), much as one would string together a series of bead to make a necklace (see Fig. 1.1). The chemical characteristics of

the starting low-molecular-weight species will determine the properties of the final polymer. When two different low-molecular-weight species are polymerized the resulting polymer is termed a copolymer such as ethylene vinylacetate. This is depicted in Fig. 1.2. Plastics can also be separated into thermoplastics and thermosets. A thermoplastic material is a high-molecular-weight polymer that is not cross-linked. It can exist in either a linear or a branched structure. Upon heating, thermoplastics soften and melt, which allows them to be shaped using plastics processing equipment. A thermoset has all of the chains tied together with covalent bonds in a three dimensional network (cross-linked). Thermoset materials will not flow once cross-linked, but a thermoplastic material can be reprocessed simply by heating it to the appropriate temperature. The different types of structures are shown in Fig. 1.3. The properties of different polymers can vary widely; for example, the modulus can vary from 1 MPa to 50 GPa. Properties can be varied for each individual plastic material as well, simply by varying the microstructure of the material.

There are two primary polymerization approaches: step-reaction polymerization and chain-reaction polymerization.[1] In step-reaction (also referred to as *condensation polymerization*), reaction occurs between two polyfunctional monomers, often liberating a small molecule such as water. As the reaction proceeds, higher-molecular-weight species

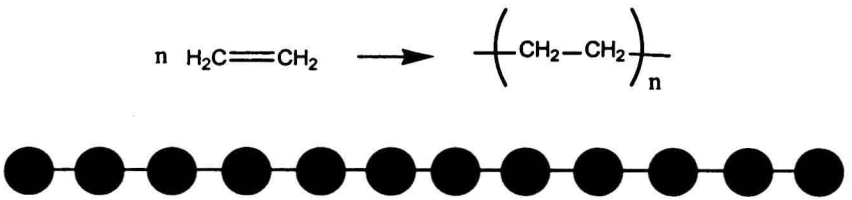


**Figure 1.1** Polymerization.

**Figure 1.2** Copolymer structure.

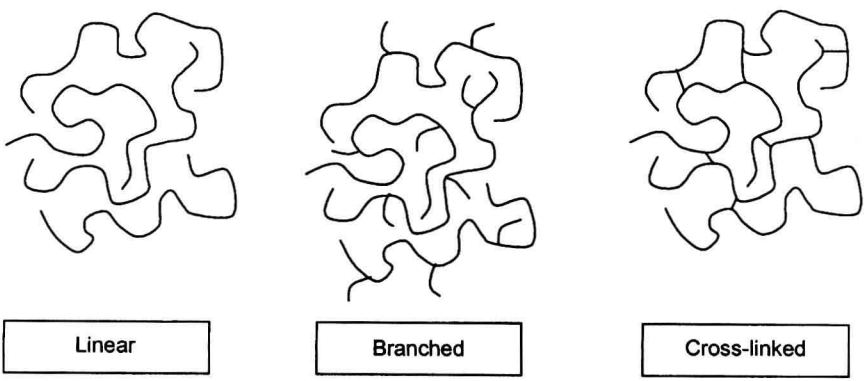


**Figure 1.3** Linear, branched, and cross-linked polymer structures.

are produced as longer and longer groups react together. For example, two monomers can react to form a dimer, then react with another monomer to form a trimer. The reaction can be described as $n$-mer + $m$-mer $\rightarrow$ ($n$ + $m$)mer, where $n$ and $m$ refer to the number of monomer units for each reactant. Molecular weight of the polymer builds up gradually with time, and high conversions are usually required to produce high-molecular-weight polymers. Polymers synthesized by this method typically have atoms other than carbon in the backbone. Examples include polyesters and polyamides.

Chain-reaction polymerizations (also referred to as *addition polymerizations*) require an initiator for polymerization to occur. Initiation can occur by a free radical or an anionic or cationic species, which opens the double bond of a vinyl monomer and the reaction proceeds as shown above in Fig. 1.1. Chain-reaction polymers typically contain only carbon in their backbone and include such polymers as polystyrene and polyvinyl chloride.

Unlike low-molecular-weight species, polymeric materials do not possess one unique molecular weight but rather a distribution of weights as depicted in Fig. 1.4. Molecular weights for polymers are usually described by two different average molecular weights, the number average molecular weight, $\overline{M}_n$, and the weight average molecular weight, $\overline{M}_w$. These averages are calculated using the equations below:

$$\overline{M}_n = \sum_{i=1}^{\infty} \frac{n_i M_i}{n_i}$$

$$\overline{M}_w = \sum_{i=1}^{\infty} \frac{n_i M_i^2}{n_i M_i}$$

where $n_i$ is the number of moles of species $i$, and $M_i$ is the molecular weight of species $i$. The processing and properties of polymeric materials are dependent on the molecular weights of the polymer.

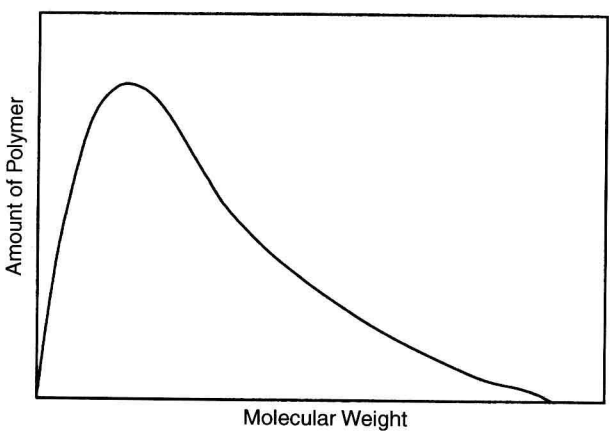


**Figure 1.4** Molecular weight distribution.

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