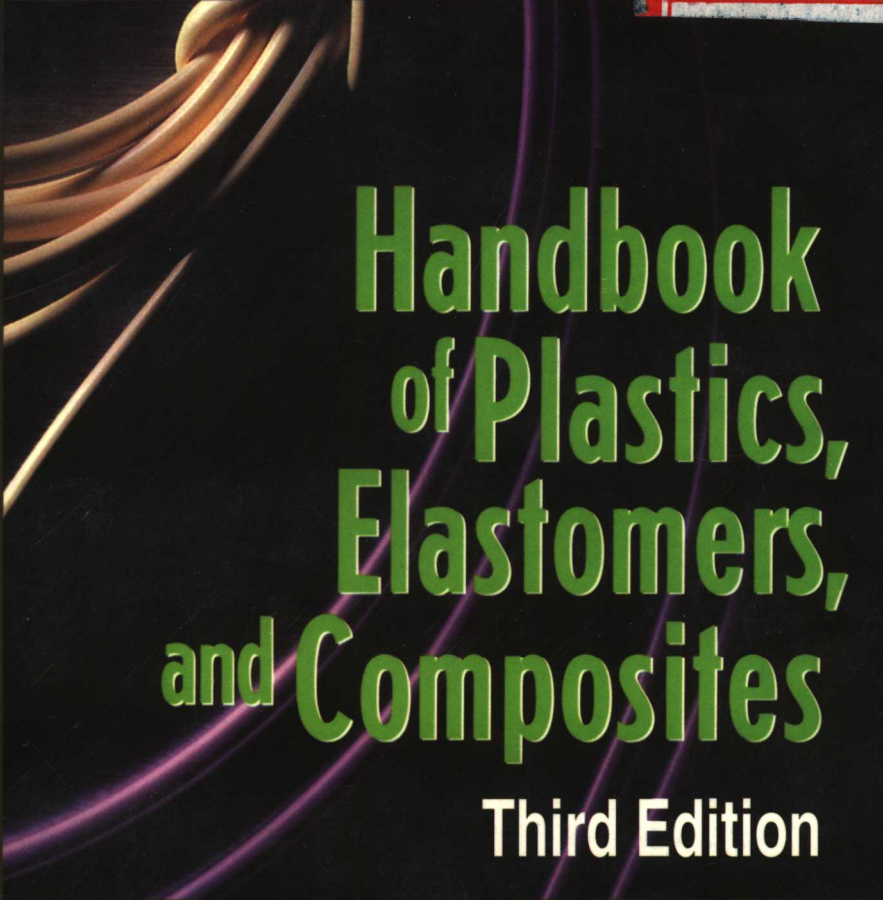


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Handbook of Plastics, Elastomers, and Composites

Third Edition

塑料、弹性体及 复合材料手册

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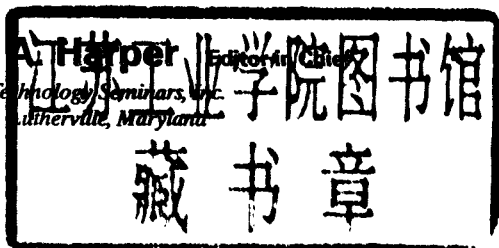
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HANDBOOK OF PLASTICS, ELASTOMERS, AND COMPOSITES

Charles A. Harper

*Technology Seminars, Inc.
Culterville, Maryland*

Editorial Chief



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CONTRIBUTORS

- Leonard S. Buchoff** *Elastomeric Technologies, Inc., Hatboro, Pennsylvania.* (CHAP. 4)
- Ruben Hernandez** *The School of Packaging, East Lansing, Michigan* (CHAP. 8)
- John L. Hull** *Hull Corporation, Hatboro, Pennsylvania.* (CHAP. 10)
- Carl P. Izzo** *Industry Consultant, Export, Pennsylvania.* (CHAP. 6)
- Joseph F. Meier** *Industry Consultant, Export, Pennsylvania.* (CHAP. 1)
- Stanley T. Peters** *Process Research, Mountain View, California* (CHAP. 3)
- Edward M. Petrie** *ABB Transmission Technology Institute, Raleigh, North Carolina.* (CHAP. 7)
- Charles P. Rader** *Advanced Elastomer Systems, L.P., Akron, Ohio* (CHAP. 5)
- Ronald N. Sampson** *Technology Seminars, Pittsburgh, Pennsylvania.* (CHAP. 2)
- Susan E. Selke** *The School of Packaging, East Lansing, Michigan* (CHAP. 11)
- Ronald Toth** *Chrysler Corporation, Dearborn, Michigan* (CHAP. 9)

ABOUT THE EDITOR IN CHIEF

Charles A. Harper is an industrial consultant and president of Technology Seminars, Inc., based in Lutherville, Maryland. Previously, he was Manager of Materials Engineering for Westinghouse Electric Corporation in Baltimore, Maryland. He is a member of the Society of Plastics Engineers, IEEE, and the Society for the Advancement of Materials and Process Engineers (SAMPE). He is widely recognized for his teaching and writing activities, and for his leadership roles in numerous major professional societies.

PREFACE

In recent years, the 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 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 of 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 plastic materials and forms.

This *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 and easy-to-use index, a comprehensive glossary, useful end-of-chapter reference lists, and several appendixes containing invaluable data and information for product engineers.

The chapter organization and coverage of the handbook is equally well suited for reader convenience. The opening chapter presents the fundamentals of plastics and elastomers and provides an overall foundation for the book, thus enabling readers to more fully understand the presentations in the following chapters.

The next six chapters deal with major plastic product forms that are so important in product design. One chapter each is devoted to laminates and conventional composites, advanced composites such as graphite-epoxy and others, liquid and low-pressure resin systems, thermoplastic elastomers, protective and decorative coatings,

and adhesives. Each of these subjects requires special treatment for product design, and designers will find that these chapters provide excellent guidelines.

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

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.

Charles A. Harper

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CHAPTER 1

FUNDAMENTALS OF PLASTICS AND ELASTOMERS

Joseph F. Meier
Industry Consultant
Export, Pennsylvania

1.1 INTRODUCTION

The *Handbook of Plastics, Elastomers, and Composites* will attempt to address important application and use data and guidelines for the entire field of plastics and elastomers. This initial chapter covers the nature of plastics and elastomers, including the chemical nature of polymers, an overview of testing and the significance of standard tests, primary characteristics of individual polymer classes, processing and processed forms of plastics, and related subjects that are basic to the field of plastics and elastomers.

Subsequent chapters will cover in detail many important individual applications of plastics and elastomers that have developed since the last edition of this handbook.¹ Thermoplastic elastomers (Chap. 5) and plastic and elastomer adhesives (Chap. 7) are just two examples.

Because of the tremendous volume of data available and the limited space, references at the end of each chapter will direct the interested reader to more in-depth information.

1.2 THE NATURE OF PLASTICS

Practically stated, a plastic is an organic polymer, available in some resin form or some form derived from the basic polymerized resin. These forms can be liquid or pastelike resins for embedding, coating, and adhesive bonding; or they can be molded, laminated, or formed shapes, including sheet, film, or larger mass bulk shapes.

The number of basic plastic materials is large, and the list is increasing. In addition, the number of variations and modifications to these basic plastic materials is also quite large. Taken together, the resultant quantity of materials available is just too large to

be completely understood and correctly applied by anyone other than those whose day-to-day work puts them in direct contact with a diverse selection of materials. The practice of mixing brand names, trade names, and chemical names of various plastics only makes the problem of understanding these materials more troublesome.

Another variable that makes it difficult for those not versed in plastics to understand and properly design with plastics is the large number of processes by which plastics can be fabricated. Fortunately, there is an organized pattern on which an orderly presentation of these variables can be based.

While there are numerous minor classifications for polymers, depending on how one wishes to categorize them, nearly all can be placed into one of two major classifications—thermosetting materials (or thermosets) and thermoplastic materials.² Likewise, foams, adhesives, embedding resins, elastomers, and so on, can be subdivided into the thermoplastic and thermosetting classifications.

1.2.1 Thermosetting Plastics

As the name implies, thermosetting plastics, or thermosets, are cured, set, or hardened into a permanent shape. Curing is an irreversible chemical reaction known as cross-linking, which usually occurs under heat. For some thermosetting materials, curing is initiated or completed at room temperature. Even here, however, it is often the heat of the reaction, or the exotherm, that actually cures the plastic material. Such is the case, for instance, with a room-temperature-curing epoxy or polyester compound.

The cross-linking that occurs in the curing reaction is brought about by the linking of atoms between or across two linear polymers, resulting in a three-dimensional rigidized chemical structure. One such reaction is shown in Fig. 1.1.³ Although the cured part can be softened by heat, it cannot be remelted or restored to the flowable state that existed before curing. Continued heating for long times leads to degradation or decomposition.

1.2.2 Thermoplastics

Thermoplastics differ from thermosets in that they do not cure or set under heat as do thermosets. Thermoplastics merely soften, or melt when heated, to a flowable state, and under pressure they can be forced or transferred from a heated cavity into a cool mold. Upon cooling in a mold, thermoplastics harden and take the shape of the mold. Since thermoplastics do not cure or set, they can be remelted and then rehardened by cooling. Thermal aging, brought about by repeated exposure to the high temperatures required for melting, causes eventual degradation of the material and so limits the number of reheat cycles. Most of the common thermoplastic materials are discussed in detail in a following section of this chapter.

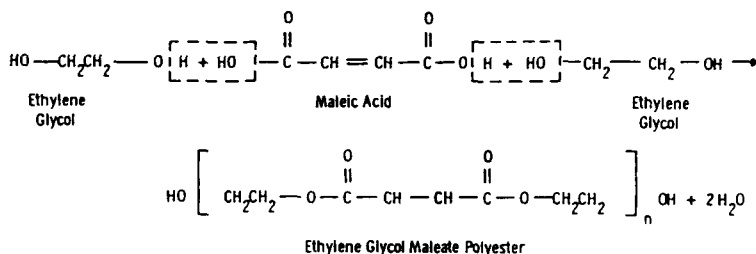
1.3 POLYMER STRUCTURES AND POLYMERIZATION REACTIONS

1.3.1 Polymer Structures

All polymers are formed by the creation of chemical linkages between relatively small molecules, or monomers, to form very large molecules, or polymers. As men-

Reaction A

One quantity of unsaturated acid reacts with two quantities of glycol to yield linear polyester (alkyd) polymer of n polymer units



Reaction B

Polyester polymer units react (copolymerize) with styrene monomer in presence of catalyst and/or heat to yield styrene-polyester copolymer resin or, more simply, a cured polyester. (Asterisk indicates points capable of further cross-linking.)

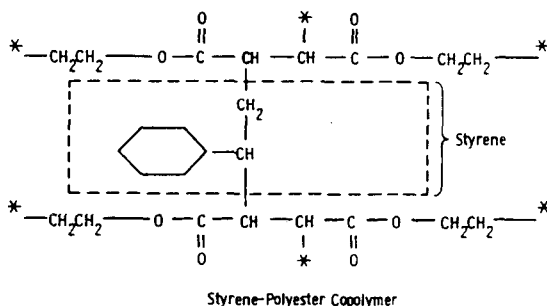


FIGURE 1.1 Simplified diagrams showing how cross-linking reactions produce polyester resin (styrene-polyester copolymer resin) from basic chemicals.

tioned, if the chemical linkages form a rigid, cross-linked molecular structure, a thermosetting plastic results. If a somewhat flexible molecular structure is formed, either linear or branched, a thermoplastic results. Illustrations of these molecular structures are presented in Fig. 1.2.¹

1.3.2 Polymerization Reactions

Polymerization reactions may occur in a number of ways; four common techniques are bulk, solution, suspension, and emulsion polymerization.^{1,2} Bulk polymerization involves the reaction of monomers or reactants among themselves, without placing them in some form of extraneous media as is done in the other types of polymerization.

Solution polymerization is similar to bulk polymerization, except that whereas the solvent for the forming polymer in bulk polymerization is the monomer, the sol-

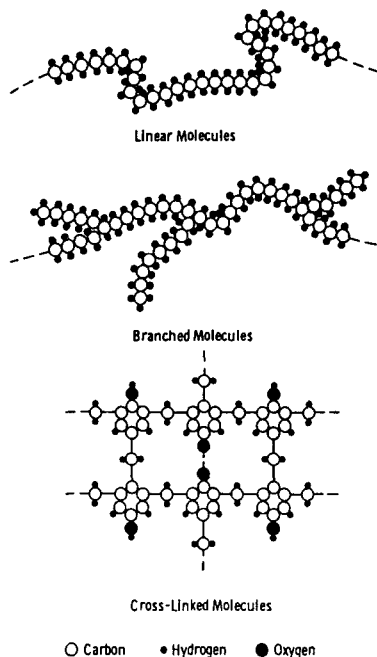


FIGURE 1.2 Some possible molecular structures in polymers.

vent in solution polymerization is usually a chemically inert medium. The solvents used may be complete, partial, or nonsolvents for the growing polymer chains.

Suspension polymerization normally is used only for catalyst-initiated or free-radical addition polymerizations. The monomer is dispersed mechanically in a liquid, usually water, which is a nonsolvent for the monomer as well as for all sizes of polymer molecules that form during the reaction. The catalyst initiator is dissolved in the monomer, and it is preferable that it does not dissolve in the water so that it remains with the monomer. The monomer and the polymer that is formed from it stay within the beads of organic material dispersed in the phase. Actually, suspension polymerization is essentially a finely divided form of bulk polymerization. The main advantage of suspension polymerization over bulk is that it allows cooling of the exothermic polymerization reaction and maintains closer control over the chain-building process. By controlling the degree of agitation, monomer-to-water ratios, and other variables, it is also possible to control the particle size of the finished polymer, thus eliminating the need to re-form the material into pellets from a melt, as is usually necessary with bulk polymerization.

Emulsion polymerization is a technique in which addition polymerizations are carried out in a water medium containing an emulsifier (a soap) and a water-soluble initiator. Emulsion polymerization is much more rapid than bulk or solu-

tion polymerization at the same temperatures and produces polymers with molecular weights much greater than those obtained at the same rate in bulk polymerizations.

In emulsion polymerization, the monomer diffuses into micelles, which are small spheres of soap film. Polymerization occurs within the micelles. Soap concentration, overall reaction-mass recipe, and reaction conditions can be varied to provide control of the reaction rate and yield.

1.3.3 Raw-Material Sources of Major Plastic Materials

The primary raw-material sources of the major plastic and elastomer materials are natural gas, coal, and crude oil.^{3,4}

1.4 PLASTIC-PROCESSING METHODS AND DESIGN GUIDELINES

Although most users of plastics buy parts from plastic processors, they should still have some knowledge of plastic processing, as such information can often be helpful in optimizing product design. Also, an increasing number of user companies are doing some in-house processing. For these reasons, some guideline information in plastic processing and some guidelines on the design of plastic parts are presented here. Further extensive and detailed guidelines are included in Chap. 9.

It should be mentioned that the information presented at this point applies broadly to all classes of plastics and types of processing. Most plastic suppliers will provide very specific data and guidelines for their individual products. This invaluable source of guidance is too often unused. It is strongly recommended that plastic suppliers be more fully utilized for product-design guidance. However, the information presented at this point will be valuable for making initial design and process decisions.

Table 1.1⁵ explains the major ways in which plastic materials can be formed into parts, and the advantages, limitations, and relative cost of each processing method. In general, a plastic part is produced by a combination of cooling, heating, flowing, deformation, and chemical reaction. As noted previously, the processes differ, depending on whether the material is a thermoplastic or a thermoset.

The usual sequence of processing a thermoplastic is to heat the material so that it softens and flows, force the material in the desired shape through a die or in a mold, and chill the melt into its final shape. By comparison, a thermoset is typically processed by starting out with partially polymerized material, which is softened and activated by heating (either in or out of the mold), forcing it into the desired shape by pressure, and holding it at the curing temperature until final polymerization reaches the point where the part hardens and stiffens sufficiently to keep its shape when demolded.

The cost of the finished part depends on the material and the process used. A very rough estimate of the finished cost of a part can be obtained by multiplying the material cost by a factor ranging from 1.5 to 10. The cost factors shown in Table 1.1 are based on general industry experience.

Table 1.2 gives guidelines on part design for the various plastic-processing methods listed in Table 1.1. The design of a part frequently depends on the processing

TABLE 1.1 Descriptions and Guidelines for Plastic-Processing Methods⁵

Process	Description	Key advantages	Notable limitations	Cost factor*
Blow molding	An extruded tube (parison) of heated thermoplastic is placed between two halves of an open split mold and expanded against the sides of the closed mold by air pressure. The mold is open, and the part is ejected	Low tool and die costs; rapid production rates; ability to mold relatively complex hollow shapes in one piece	Limited to hollow or tubular parts; wall thickness and tolerances often hard to control	1.5-5, 2-3
Calendering	Doughlike thermoplastic mass is worked into a sheet of uniform thickness by passing it through and over a series of heated or cooled rolls. Calenders also are used to apply plastic covering to the back of other materials	Low cost; sheet materials are virtually free of molded-in stresses, i.e., they are isotropic	Limited to sheet materials; very thin films not possible	1.5-3, 2-5.5
Casting	Liquid plastic (usually thermoset, except for acrylics) is poured into a mold (without pressure), cured, and removed from the mold. Cast thermoplastic films are made by depositing the material, either in solution or in hot-melt form, against a highly polished supporting surface	Low mold cost; ability to produce large parts with thick cross sections; good surface finish; suitable to low-volume production	Limited to relatively simple shapes; except for cast films, becomes uneconomical at high-volume production levels; most thermoplastics not suitable	1.5-3, 2-2.5
Compression molding	A thermoplastic or partially polymerized thermosetting resin compound, usually preformed, is placed in a heated mold cavity; the mold is closed, heat and pressure are applied, and the material flows and fills the mold cavity. Heat completes polymerization, and the mold is opened to remove the part. The process is sometimes used for thermoplastics, e.g., vinyl phonograph records	Little waste of material and low finishing costs; large, bulky parts are possible	Extremely intricate parts involving undercuts, side draws, small holes, delicate inserts, etc., not practical; very close tolerances difficult to produce	2-10, 1.5-3
Cold forming	Similar to compression molding in that material is charged into split mold; it differs in that it uses no heat—only pressure. Part is cured in an oven in a separate operation. Some thermoplastic sheet material and billets are cold-formed in process similar to drop hammer-die forming of metals. Shotgun shells are made in this manner from polyethylene billets	Ability to form heavy or tough-to-mold materials; simple; inexpensive; often has rapid production rate	Limited to relatively simple shapes; few materials can be processed in this manner	