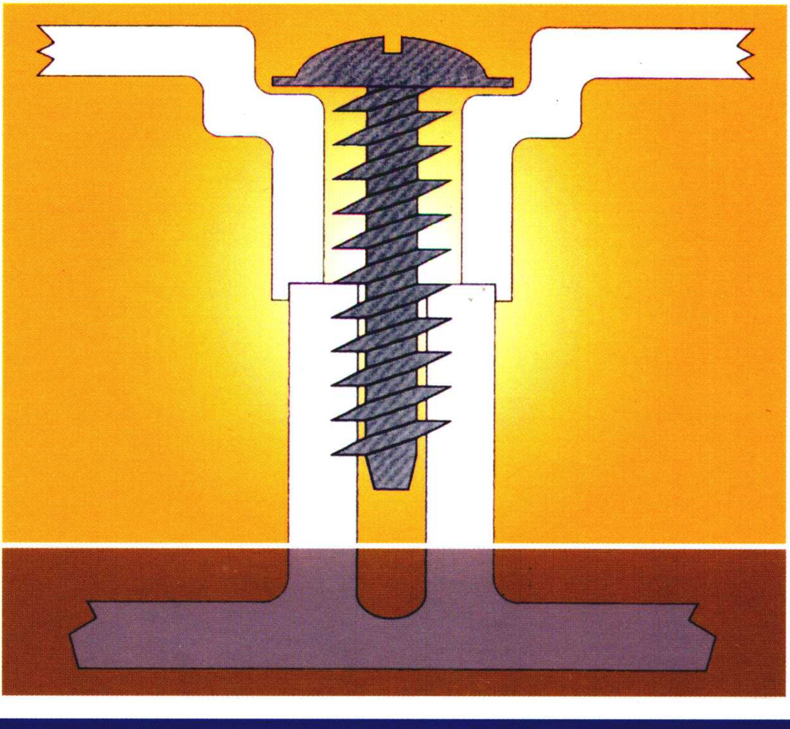
Robert A. Malloy

Plastic Part Design for Injection Molding

An Introduction



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Malloy

Plastic Part Design for Injection Molding

This book is dedicated to the memory of
S. J. Eileen, and Ahn-Ahn Chen

Preface

The injection molding process is the most widely used manufacturing process for the production of plastic parts. The process is so versatile, that it can be used for the production of small electronic and medical parts, or for the production of very large automotive or building construction components. The growth in the injection molding industry continues due in large part to advances in both plastic material and injection molding process technologies.

Unfortunately, designing injection molded plastic parts can be an extremely difficult task due to the complexities of both the part geometry and the molding process. It is also very difficult for even experienced designers to work with new plastic material grades that may process and perform in a different manner than those materials used previously. It is in fact very difficult to design a plastic part that is functional, manufacturable, and esthetically pleasing. The part design process involves a series of tradeoffs or compromises so that each of these important demands can be met. Ideally, injection molded plastic parts are developed using the *Concurrent Engineering* practices discussed in this book. This edition also includes a chapter on *Design for Enhanced Recyclability and Sustainability.*

The need for a book describing the various aspects of the plastic part design process was recognized by the author when searching for suitable design course texts. The author's integrated approach to plastic part design and plastic materials selection is described in the book, which includes hundreds of original figures that are used to illustrate specific points. The book goes into great detail on the subject of *Design for Manufacturability,* specifically how the various phases of the injection molding process can impact a part design. Common problems, such as weld lines, warpage, or ejection difficulties are discussed, as are potential solutions. In addition, the fundamentals of plastic material performance and structural design are covered, along with the subject of plastic part prototyping. The last section of the book reviews the various assembly methods that can be used for injection molded plastic parts.

The book should serve as a well illustrated reference and introductory design guide for the plastic part designer. It is hoped that the book provides an overview of the many different considerations that must be taken into account when designing a plastic part that will be manufactured by the injection molding process.

The author would like to thank the many friends, students, colleagues and companies whose names appear in the reference sections of this book. It is their work that has served as the basis for this text. Special thanks go to Garrett Gardener for all his valuable comments and corrections. The author would also like to thank the employees of Carl Hanser Verlag, especially Dr. C. Strohm for her continued encouragement and patience throughout the course of this project, and Steffen Jörg for his assistance in the production stages of the project. However, above all, the author would like to thank his family; his wife Ellen, and his children for the many sacrifices they made during the preparation of this manuscript.

Londonderry, New Hampshire
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1 Introduction

Undoubtedly, the single most important characteristic of plastic materials, as a general family, is their versatility. Most plastics are synthetic materials built up from monomeric building blocks to produce high molecular weight polymers. These high molecular weight polymers are classified as being either thermoplastic or thermosetting, depending on the specific material chemistry [1–6].

1.1 Thermoplastic Materials

Most of the plastic materials that are used in the injection molding process are described as thermoplastics. Thermoplastics are linear or branched polymeric materials that "soften" when heated, and "resolidify" when cooled. Thermoplastic materials are available in a variety of types and grades with properties that range from rigid to elastomeric. In theory, the processing of thermoplastic materials involves only physical changes (e. g., phase changes), therefore the materials can be readily recycled. Thermoplastic materials are recyclable; however, it is very likely that at least some small degree of chemical change (e. g., oxidation, thermal degradation) will take place during processing, and the second generation material properties may not be equivalent to those of the virgin polymer.

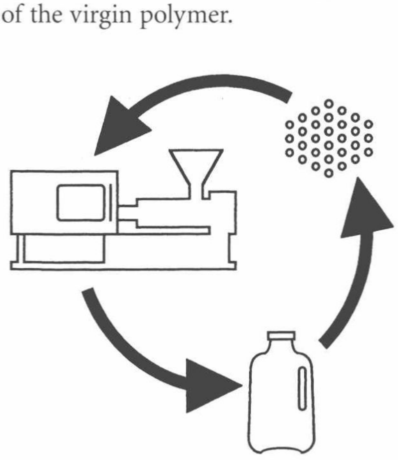

Figure 1.1 Concept of thermoplastic recycling

There are several different ways to classify thermoplastic materials. One classification is based on polymer chain conformation or morphology. Based on this concept, thermoplastic materials are described as being either amorphous, semi-crystalline, or liquid crystalline.

Amorphous Thermoplastics: Amorphous polymers consist of polymer molecules with no particular conformation as shown in Fig. 1.2 (i. e., random configuration). When amorphous polymers are heated (such as in the plasticating cylinder of a molding machine), the intertwined chains become more mobile/active, and disentanglement and chain slippage occur, resulting in a gradual softening and ultimately flow. As the level of molecular activity increases, the material becomes more fluid, because the attractive forces between the polymer molecules (i. e., intermolecular attractions) decrease as the average distance between the polymer chains increases. After the molten, amorphous polymer is shaped or formed (i. e., during mold filling), the polymer is cooled, and regains its rigidity as the molecular mobility is reduced. Polymers such as polystyrene, polycarbonate and polymethyl methacrylate are examples of amorphous thermoplastics.

Semi-Crystalline Thermoplastics: Some polymer molecules have enough regularity and flexibility built into their chemical structure that they can form ordered (rather than random) molecular arrangements. These ordered regions are crystals that form as the thermoplastic cools from the molten state. Upon reheating, the crystals remain intact until the polymer reaches its crystalline melting temperature (or temperature range) at which melting occurs. In the melt or molten state, these materials have an amorphous or random molecular configuration. It should be noted that crystalline thermoplastics are more appropriately described as "semi-crystalline", because these polymers contain both amorphous and crystalline regions, as shown in Fig. 1.2.

The "degree of crystallinity" (i. e., the relative percentage of crystalline vs. amorphous areas in the material) is influenced by both the chemical structure of the polymer and by the manufacturing/processing conditions; particularly by the rate at which the molten polymer cools. Processing variables that reduce the rate of cooling will generally increase the degree of crystallinity. Polymers such as polyethylene, polypropylene, and the polyamides (nylons) are examples of semi-crystalline polymers.

Liquid Crystalline Thermoplastics: Like semi-crystalline thermoplastics, liquid crystalline thermoplastics (LCPs) have ordered domain-type chain arrangements in the solid state. However, unlike conventional semi-crystalline polymers, liquid crystalline polymers also exhibit ordered (rather than random) molecular arrangements in the melt state. These unique materials are characterized by their stiff, rod-like molecules that form the parallel arrays or domains. LCPs offer a number of processing and performance advantages, including low melt viscosity, low mold shrinkage, chemical resistance, stiffness, creep resistance, and overall dimensional stability [2].

1.2 Thermosetting Plastic Materials

Thermosetting polymers (or thermosets) are polymers that chemically react during processing to form a cross-linked polymer chain network, as shown in Fig. 1.2. The chemical reaction is irreversible. Unlike thermoplastics, thermosets are not directly recyclable. Because there is a chemical reaction involved in thermoset molding, a number of additional reaction-related process variables enter into processing. Thermoset materials (as a group) can be difficult to work with and require special molding equipment/practices; however, the materials do offer

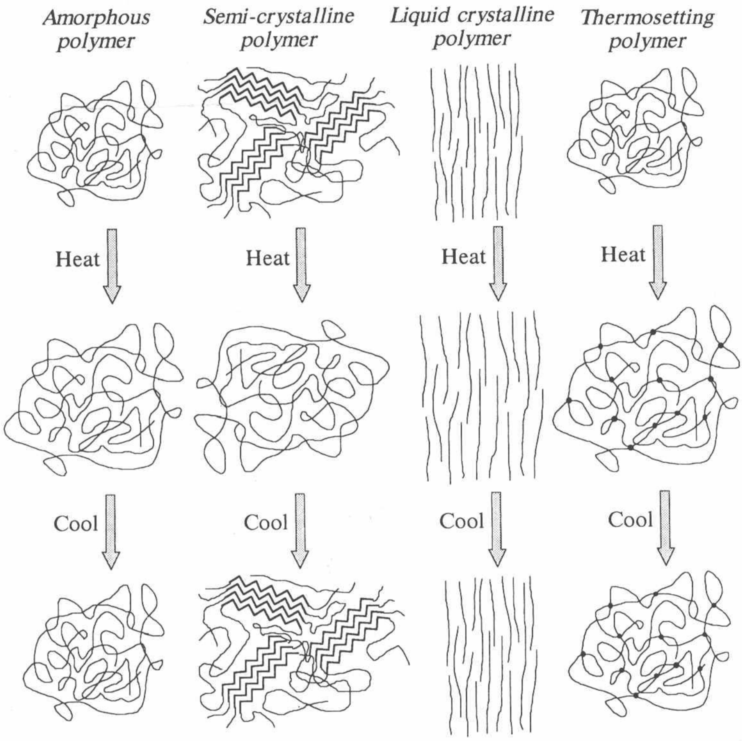

Figure 1.2 Plastic materials are categorized as either amorphous, semi-crystalline, liquid crystalline or thermosetting [2]

some outstanding properties. The cross-linked chain network characteristic of thermosetting polymers leads to properties such as excellent creep resistance, dimensional stability, and chemical resistance. However, the difficulties encountered when processing thermosetting polymers, along with their lack of recyclability, limit their use in most applications. Examples of thermosetting polymers include phenolics, epoxies, unsaturated polyesters, and a variety of elastomeric materials.

1.3 Structure-Property Relationships

The properties of a plastic material formulation can literally be "tailored" to meet the requirements of almost any specific end-use application. The properties of different plastic material formulations (or grades) will vary due to differences in its chemical composition and differences in the additives incorporated into the material formulation. The chemical compositions of the different plastic materials can vary in many ways, including:

- Structure of the repeat unit
- Homopolymer or copolymer
- Average molecular weight
- Molecular weight distribution
- Linear vs. branched vs. crosslinked

A change in any one of these chemical characteristics will have an influence on the plastic material's behavior and properties. Polycarbonate is a very different material than polystyrene because the repeat unit that makes up the chain is different. The repeat units that make up a polymer molecule are analogous to the "links" that make up a chain as shown in Fig. 1.3. The properties of polymers having different repeat units will be different, in much the same way the strength of a chain will differ when different types of links are used.

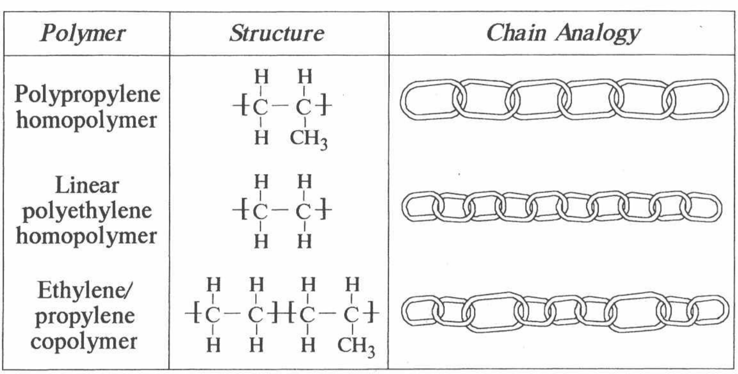

Figure 1.3 The repeat unit(s) that make up the polymer chain have a large influence on the properties and the processability of the material

Many plastic materials are described as copolymers because they have chain structures that are built from more than one type of monomer unit. A material such as poly(styrene-acrylonitrile), SAN, exhibits different properties than polystyrene because it is a copolymer. The properties of the SAN will vary according to its exact copolymeric composition and molecular weight characteristics. There are in fact an infinite number of possibilities with respect to chemical composition, and a wide variety of end-use properties can be achieved in this way.

Both the type of chain link(s) and the length of the polymer molecules will have an impact on the end-use performance and the processing related properties of a polymer (Fig. 1.4). Plastic material manufacturers can fine-tune the properties and processing behavior of a particular material type by altering the polymerization process to produce a polymer with a specific average molecular weight and a specific molecular weight distribution.

The average molecular weight of a polymer is typically expressed as either the number average molecular weight, M_n (the total weight of material divided by the number of molecules), or as

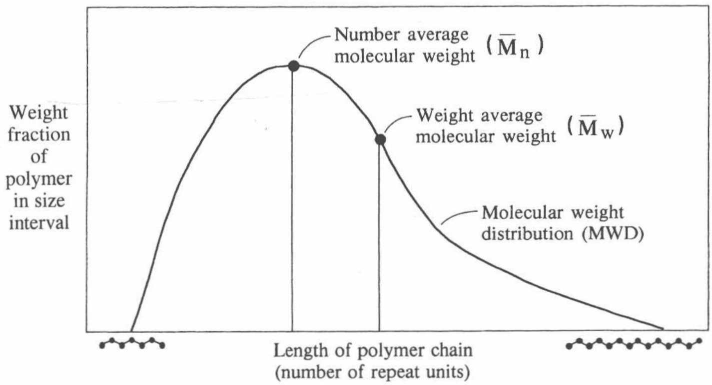

Figure 1.4 Both the average molecular weight and the molecular weight distribution will have an influence on the processability and the end use properties of a polymer

the weight average molecular weight, M_w, (places greater emphasis on the higher molecular weight fractions and therefore relates to properties that depend on the larger molecules) [1]. The number and weight average molecular weights of a polymer can be determined using Eqs. 1.1 and 1.2, respectively, where M_i is the molecular weight in each incremental fraction, and N_i is the number of molecules in each fraction.

The breadth of the molecular weight distribution curve for a particular polymer is typically characterized using the polydispersity index (PDI). The polydispersity index of a polymer is determined using Eq. 1.3.

$$M_n = \frac{\sum N_i \cdot M_i}{\sum N_i} \tag{1.1}$$

$$M_w = \frac{\sum N_i \cdot M_i^2}{\sum N_i \cdot M_i} \tag{1.2}$$

$$PDI = \frac{M_w}{M_n} \tag{1.3}$$

The average molecular size and size distribution will have a very significant influence on the processability and end-use properties of a polymer (e.g., mechanical properties, thermal properties, chemical resistance, etc.). Changes in the molecular weight for a particular polymer type will alter molecular entanglement, total intermolecular attraction, and end group effects. Consider the case of the series of polyethylenes (with the same repeat unit structure) listed in Table 1.1 [1]. The polyethylenes in Table 1.1 have different average molecular weights, and therefore different properties. Very low molecular weight polyethylenes are grease- or wax-like materials that are in theory injection moldable; however, they do not fulfill the property requirements for durable goods. Once the average molecular weight of the polyethylene reaches a certain point, the properties are useful enough that the material is categorized as a "plastic material". There is no well defined average molecular weight value