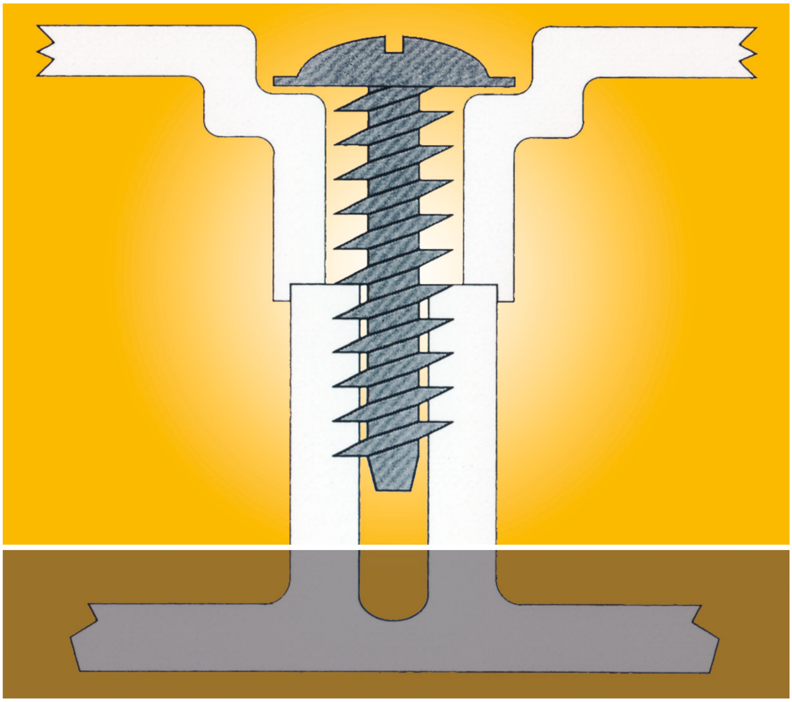
Robert A. Malloy

Plastic Part Design for Injection Molding

An Introduction



2nd Edition

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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 his continued encouragement and patience throughout the course of this project, and Steffen Jörg for her 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
Robert Malloy
Fall 2010

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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.

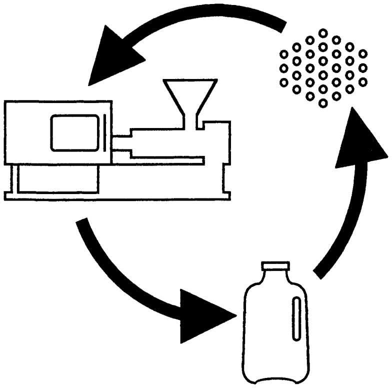

Figure 1.1 Concept of thermoplastic recycling

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

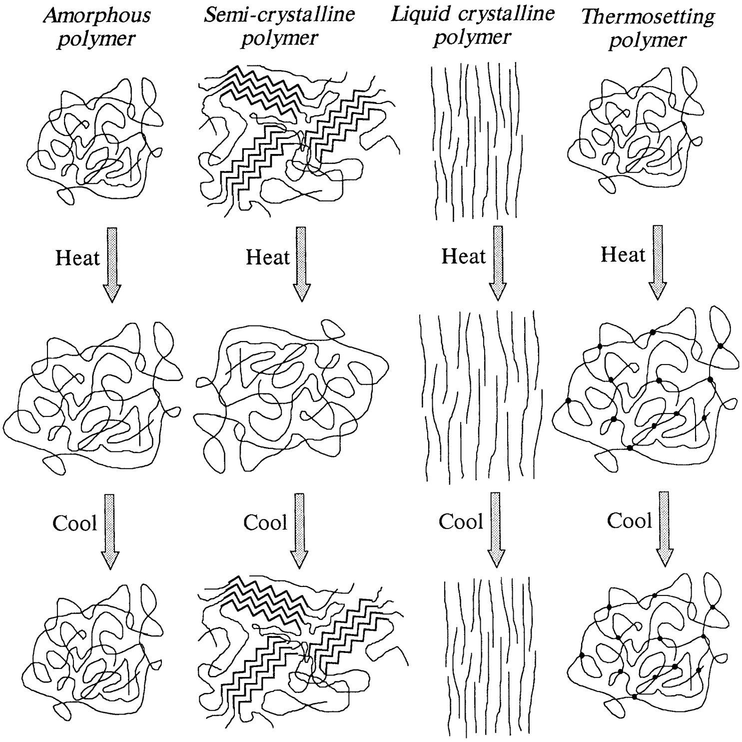

Figure 1.2 Plastic materials are categorized as either amorphous, semi-crystalline, liquid crystalline or thermosetting [2]

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.

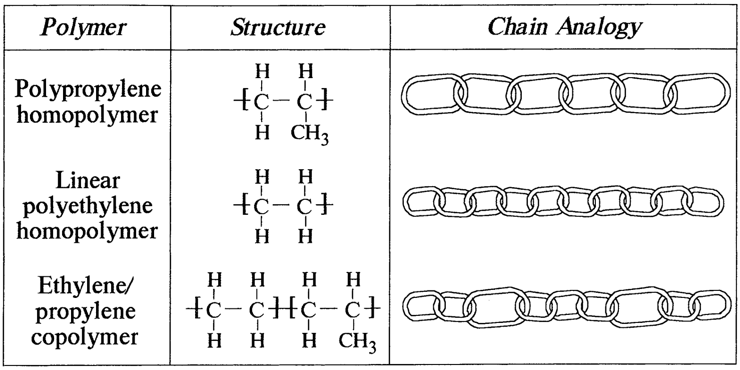

Figure 1.3 The repeat unit(s) that make up the polymer chain have a large influence on the properties and the processability of the material

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

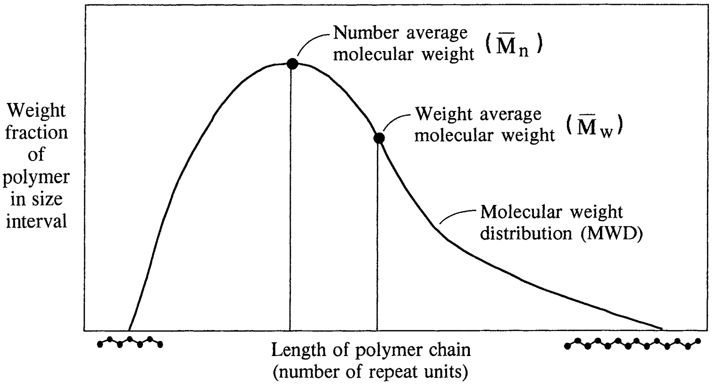

Figure 1.4 Both the average molecular weight and the molecular weight distribution will have an influence on the processability and the end use properties of a polymer

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

Table 1.1 Effect of molecular weight on the properties of polyethylene

Number of — (CH_2-CH_2) — units (links)	Molecular weight (g/mol)	Softening temparature (°C)	Characteristic of material at 25 °C		
1	30	−169 *	Gas		
6	170	−12 *	Liquid		Polymer
35	1000	37	Grease		
140	4000	93	Wax		
250	7000	98	Hard wax		
430	12 000	104	Hard resin	Plastic material	
750	21 000	110	Hard resin		
1350	38 000	112	Hard resin		

* melting point

where the material changes abruptly from a wax to a plastic material. There is simply a gradual increase in performance with an increase in average molecular weight. This concept can also be demonstrated using the graphical format given in Fig. 1.5.

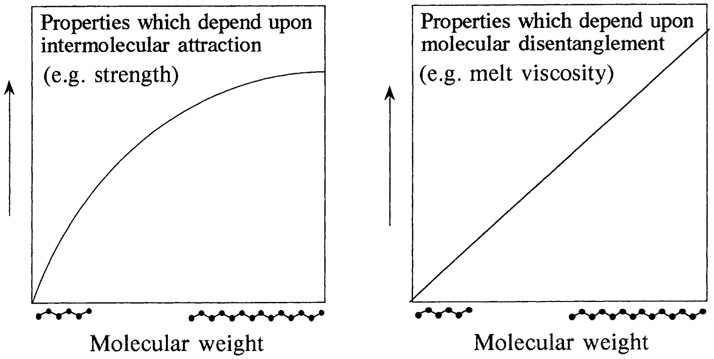

Figure 1.5 Both the end use properties and processability of a polymer depend on the material's molecular weight characteristics. Polymers having a high average molecular weight tend to offer improved performance, but are more difficult to process due to higher melt viscosity

Figure 1.5 shows that properties such as mechanical strength are dependent on average molecular weight up to a point, after which an increase in molecular weight will not lead to a significant increase in strength. One could use the analogy of the "weak link" in a chain. It is also extremely important to note that there is effectively a continuous increase in melt viscosity with increasing average molecular weight. The use of very high molecular weight polymers, which have improved mechanical or performance properties, can lead to very significant processing problems. As an example, consider ultra-high molecular weight polyethylene. The material has a number of outstanding properties, including chemical and abrasion resistance; however, it is nearly impossible to process via conventional melt processing techniques. Ther-

Table 1.2 Effect of molecular weight on the properties and flow behavior of polycarbonate

MFR (g/10 min)	σ_y (Mpa)	ε_y (%)	E_T (MPa)	Izod impact strength (J/m)	Spiral flow length (m)
4	61.4	6.7	2280	928	0.495
	− 2.3 %	− 3.0 %	− 0.0 %	− 11 %	+ 35 %
15	60.6	6.5	2280	827	0.668

Spiral flow equivalent conditions (T_m = 316°C, constant cavity thickness …)

σ_y = Tensile strength at yield E_T = Initial tensile modulus

ε_y = Tensile elongation at yield MFR = Melt flow rate

moplastics with higher average molecular weights tend to be more difficult to injection mold (process) because there melt viscosities are higher than lower molecular weight grades.

The importance of balancing "processability" and "properties" can be summarized using Table 1.2 [6]. Table 1.2 lists selected mechanical and flow properties of two grades of polycarbonate (i. e., two unfilled polycarbonates having different average molecular weights). The polycarbonate grade with a 4.0 g/10 min melt flow rate (see Section 3.8) has a higher average molecular weight value than the polycarbonate with the 15 g/10 min melt flow rate. The higher molecular weight polycarbonate does indeed have somewhat better mechanical properties. For example, the higher molecular weight material offers a 2.3 % improvement in tensile yield strength, a 3.0 % increase in tensile yield elongation, and an 11 % increase in Izod impact strength compared to the lower molecular weight polycarbonate. However, note that the maximum spiral flow length (a measure of processability described in Section 2.2.2) for the more viscous, higher molecular weight grade of polycarbonate is 35 % lower. The point here is that the property improvements associated with the higher molecular weight polymer *must* be balanced against the significant loss in processability (in terms of factors such as pressure losses, achievable surface finish, residual orientation, and reduced flow lengths).

1.4 Additives for Plastic Materials

There are few instances where a designer will have the leverage or lead time to work with materials suppliers on the development of an entirely new polymer (having a "new" chemical composition or molecular weight) for a particular product application. In most cases, designers must select a material to meet his/her needs from one of the thousands of material grades that are commercially available. Almost all of these commercially available plastic material grades are modified to some degree using additives. In effect, a designer selects a polymeric system rather than a simple homogeneous polymeric material.

Additives are commonly used to enhance certain specific properties (e. g., UV stability, stiffness, color, etc.) that the base polymer is lacking. Additives include processing stabilizers, antioxidants, UV stabilizers, internal or external lubricants, colorants/pigments, plasticizers, fillers or reinforcements, flame retardants, other polymers, or any number of other organic/inorganic additives used alone or in combination. However, it should be noted that, like medication, additives do have side effects which are sometimes important, particularly when the additives are used at high concentrations. For example, the addition of glass fibers to a material will typically improve properties such as modulus, strength, and thermal conductivity; however, the reinforced materials are typically more difficult to process when considering issues such as equipment/mold abrasion, achievable part surface finish, weld (knit) line quality, and fiber orientation. The side effects of additives such as antioxidants or anti-aging additives that are used at very low concentrations (typically parts per million) are generally less of a concern; however, even a small concentration of these additives can affect properties such as color or taste.

In any case, it is important for designers to recognize the fact that commercial plastic material grades do contain additives, and the effect of these additives on all aspects of performance (including processability) should be considered. While it is unlikely that designers will work with material suppliers on the creation of an entirely new chemical composition, it is not uncommon for designers to work with material suppliers (especially compounding houses) on the development of new material formulations using a new additive package. This is commonly done in situations where there is no commercial grade of material available for a particular end-use application (or no material available at the right price). An example of a new material being developed using additives could simply be a custom-colored thermoplastic grade. These material lots are commonly supplied as pre-compounded custom color lots, or as custom compounded color master batches that are blended with "standard" (natural) resin grades during production.

1.5 General Characteristics of Plastic Materials

Product designers have the option to choose from a variety of different materials when selecting the material(s) of construction for a particular product. Depending on the application, plastics compete with materials such as woods, sheet metals, cast or forged metals, ceramics, or glass. In many cases, plastics offer distinct advantages over the other materials in terms of performance, cost, or performance/cost ratio. However, in most cases, each of the competing materials offers inherent benefits, and of course some limitations. The designer must attempt to correlate the end-use performance requirements of the product with the property profiles of the individual materials in an attempt to obtain the best material for the application. While there are literally thousands of commercial grades of plastic materials to choose from, there are certain generalities that can be stated with respect to the relative advantages and limitations of plastics in comparison with other more conventional materials [7–11].

Versatility: As stated earlier, the single most important characteristic of plastic materials, as a general family, is their versatility. Plastics are generally synthetic materials built up from monomeric building blocks that are joined together to produce high molecular weight polymers. The properties of a plastic material can literally be "tailored" to meet the requirements of a specific end-use application. These tailor made properties can be obtained by either altering the basic chemical composition (using different monomers, co-monomers, polymerization conditions, etc) or by using different additives that are melt-blended with the polymer to enhance specific properties that are lacking in the base polymer.

Relatively Easy to Mold into Complex Shapes: The injection molding process can be used to produce thermoplastic or thermosetting plastic parts of very complex geometries. These parts can be mass-produced and require little or no secondary finishing. For example, it is common practice to incorporate assembly features such as holes, bosses, snap beams, etc. directly into the molded part. These integral design features greatly simplify, or possibly eliminate, the need for secondary assembly operations. The part geometries that are achievable using the injection molding process are becoming even more complex as advanced injection molding technologies, such as fusible core molding, continue to evolve.

Low Specific Gravity: Neat plastic materials have specific gravities that range from approximately 0.8 to 1.8. These values are much lower than those for steel, which has a specific gravity of more than 7. Plastic materials also have good strength/weight or stiffness/weight ratios. This is an advantage in terms of performance, since it is possible to make lightweight, easy to handle products that are durable and long lasting. The low specific gravity is a distinct advantage in the automotive industry, where product weight savings are essential. Plastic foams, such as injection molded structural foams, have even lower specific gravities (typically 15–25 % density reduction); however, thicker part walls are often required for these foamed polymers. Reinforced plastic material grades, most commonly filled with inorganic fillers or reinforcements having specific gravities greater than 2.0, have specific gravities that are influenced by the filler concentration and specific gravity (i. e., the composite material specific gravity will essentially follow the rule of mixtures).

Ironically, the low specific gravity has limited the use of plastic materials in many applications, because many consumers associate "strength" or "toughness" with weight. Material manufacturers have actually developed grades that are loaded with high specific gravity fillers. The fillers are purposely added to the polymer in order to increase the specific gravity of the formulation, thereby allowing the production of "heavy" molded parts that have the look and feel of a ceramic material.

Sometimes Transparent: Some amorphous thermoplastics, such as polystyrene, polymethyl methacrylate, or polycarbonate, are available as transparent material grades. Materials such as polycarbonate offer light transmission that is similar to glass, along with toughness, low specific gravity, and good manufacturability. However, unlike glass, transparent plastic grades tend to "yellow" or "cloud" over time, particularly when the plastic material is exposed to ultraviolet radiation for extended periods of time. In addition, the scratch resistance of plastics is often limited. Transparent plastic parts slated for outdoor applications are sometimes coated with a combination UV screener/hard coating to extend their service life.

Most semi-crystalline materials are translucent or opaque. Translucent semi-crystalline polymers, such as polypropylene, offer a relatively high degree of light transmission, particularly in thinner wall moldings. Clarified or nucleated grades of polypropylene (that reduce the physical light scattering effects of the crystals) offer improved light transmission capabilities.

Semi-crystalline materials are commonly used for products, such as medical syringes, where a limited degree of light transmission is required.

Coloring Throughout: Coloring additives, such as pigments or dyes, are commonly melt-blended directly into the polymer formulation. The colored materials can be purchased from the supplier or compounder as pre-colored pellets, or colorants can be added to a natural resin at the molding machine (as liquids, powders, or most commonly in the form of a masterbatch additive). Internal coloring offers a number of distinct advantages over the alternative, painting. The use of colorants obviously eliminates the cost of secondary operations associated with painting and potential cleaner or solvent hazards. Problems, such as paint chipping, are also eliminated because the color is integral. In addition, damage due to abrasion or scratching is much less obvious when the color is distributed throughout the thickness of the part.

However, it can be difficult, if not impossible (depending on the standards) to obtain a class-A finish on the molded part using internal colorants. Color matching can also be a problem, because factors such as residence time, shear history, and heat history (and thus regrind level), can cause color shifts due to the effects on the color of both the colorant and the base plastic material (for an overall net color change). Fading can also be a problem over the long term, depending on the conditions of ultraviolet exposure and the thermal or ultraviolet stability of both colorant and polymer. Painting is a secondary operation that is sometimes required (i. e., in cases where very high gloss, defect free, precisely color matched surfaces are required). Many plastic materials can also be plated or metallized.

Relatively Low Energy Requirements for Processing: The process of thermoplastic injection molding begins with the injection of molten polymer into a relatively cool mold cavity. Once in the cavity, the polymer cools by conduction, and eventually becomes rigid enough that it can be ejected from the tool. After ejection, the part cools to room temperature. The energy requirements for processing are determined by the molding machinery efficiencies (e. g., electric machines are more energy efficient than hydraulic machines), and by the plastic material's processing requirements. Processing conditions such as drying temperature, "melt" temperature, and mold temperature contribute to the overall energy requirements. For example, the energy, Q, required to bring a polymer from room temperature, T_0, the processing (melt) temperature, T_m, is given by:

$$Q = m \cdot Cp \cdot [T_\mathrm{m} - T_0] \tag{1.4}$$

where m is the mass of the polymer, and Cp is the specific heat of the polymer at constant pressure. The energy required to bring the polymer to its processing temperature is the result of both electrical conduction (from the heated barrel), and viscous dissipation/internal friction (associated with plastication and injection). Compared to other materials (such as metals), polymers generally have significantly lower processing temperature values (i. e., lower T_m) and lower specific gravities/part weights (i. e., low m). The specific heat values for polymers are generally higher than for other competitive materials; however, the overall energy requirements for polymer processing (considering all three terms in Eq. 1.4) are significantly lower than for metals, glasses, or ceramics. While low processing temperatures are beneficial from an energy consumption viewpoint, it should be noted here that the high temperature capabilities of most polymers are of course limited for the same reason.

Chemical Resistance: Most plastic materials offer good resistance to corrosion caused by the presence of moisture, salts, weak acids, and bases. However, most thermoplastics are soluble or will swell in the presence of specific organic solvents (i.e., those with a similar solubility parameter), especially at elevated temperatures. In general, thermosetting, liquid crystalline, and semi-crystalline polymers offer improved chemical resistance over amorphous polymers. The chemical resistance of a polymer must be carefully matched with the application for which it is intended. For example, in automotive applications, resistance to organic chemicals, such as fuels and a variety of other automotive fluids, must be given careful consideration.

Different chemicals will affect a plastic material in different ways. For example, the chemicals can react with the polymer. An example of a chemical reaction would be the hydrolysis that can occur when a polyester is heated in the presence of water. Water can also have a plasticizing effect (a physical softening effect) for hygroscopic polymers, such as polyamides. In other cases, organic chemicals can solvate the polymer. This problem is commonly encountered when amorphous thermoplastics are exposed to an organic chemical, such as a hydrocarbon solvent. Chemicals, particularly organic chemicals, can also cause environmental stress cracking and crazing (ESCC). The phenomenon of environmental stress cracking and crazing can be summarized as follows. In an unstressed state, a plastic material may appear to be unaffected by the presence of a certain chemical. However, when the same polymer is subject to a stress (even a low stress) *and* the same chemical, crazing or cracking (and eventual catastrophic failure) can occur. The stresses can be due to external loads, or can be residual (locked-in) molding stresses. It is therefore critical that injection molded products are designed and molded properly, minimizing their internal stress level and the potential for environmental stress cracking and crazing in applications where chemical contact is anticipated.

Mechanical Performance: Plastic materials are available with mechanical properties that range from elastomeric to rigid and stiff. However, even very rigid materials have modulus values that are an order of magnitude lower than steel. When stiffness is a product requirement, designers rely on geometric features such as ribs and edge stiffeners to obtain the required stiffness. Plastic materials can also be very impact resistant or tough and are useful in a variety of high abuse/high impact applications. The mechanical properties of plastics are commonly modified using additives that range from toughening agents to reinforcing fibers. In some cases, particularly for fiber reinforced polymer grades, the mechanical performance can be anisotropic due to molecular or fiber orientation effects.

Unlike metals, a plastic's mechanical properties can be very sensitive to even small changes in temperature, rate of loading, and in some cases, relative humidity (an important factor for hygroscopic polymers). Designers must consider the mechanical performance of a plastic material over the range of temperatures, times, and relative humidities associated with the application. For example, plastic materials can become very brittle at low temperatures. At higher temperatures, plastic materials can exhibit excessive creep deformation. However, if a designer does consider the extremes of temperature, a suitable material for the application can usually be identified, and a part designed accordingly.

Good Electrical Insulation: Many plastic materials offer outstanding electrical insulating properties, and as a result, find widespread use in electrical insulating applications such as switches and electronic enclosures. This is an advantage in these applications; however, in other applications some degree of conductivity is required. For example, computer enclosures must provide a level of electromagnetic interference (EMI) shielding. In these applications, additives such as conductive stainless steel or nickel coated fibers, can be compounded into the polymer matrix to enhance electrical conductivity, or alternatively the part can be painted, plated, or metallized to provide the required conductivity.

Good Thermal Insulation: Plastic materials also offer good thermal insulation. This is important in a variety of energy conservation applications. The reduced heat transfer rates give plastic products a warm feel, even when the temperature of the plastic object is cool. On the other hand, the low thermal conductivity can be a problem in dynamic applications, such as gearing (where frictional heat is generated), or in applications such as computer enclosures (where electrical sources generate heat). Forced ventilation systems (e.g., fans) are often required for applications where natural conduction and convective heat transfer to the environment cannot keep pace with heat generation. When heat dissipation is a problem, designers must pay strict attention to both the surface area to volume ratio for the part and the material's thermal properties. Filled or reinforced thermoplastic material grades (composite materials) can offer significantly improved heat transfer capabilities.

Flammable: Almost all plastic materials will burn to some degree or decompose when subject to combustion conditions. A polymer, such as polyethylene, will ignite and burn readily, while a thermosetting phenolic will simply char. The flammability resistance of most plastic materials can be improved using flame retardant additive packages. Designers must be concerned with a number of issues with respect to flammability, including combustibility, dripping, and combustion byproducts, including the byproducts of the additives.

Poor Weather Resistance: Many plastic materials exhibit poor long-term weather resistance. While most materials are unaffected by the presence of moisture at low temperature (with the exception of the plasticizing effect for hygroscopic polymers), the combined effects of ultraviolet energy (from sunlight) and oxidation can lead to a deterioration in color, transparency, and other properties over time. This is a concern for the many long-term outdoor applications, such as automotive, toys, sporting goods, or building construction products. Some plastic materials, such as acrylics, have excellent inherent weather resistance, while others, such as polypropylene, require additional stabilization. The long-term weather resistance of any polymer can be improved significantly using ultraviolet stabilizers and antioxidants as additives. In some cases, coatings are used to overcome the problems associated with long-term aging.

Relatively High Coefficient of Thermal Expansion: In general, plastic materials have relatively high coefficients of thermal expansion (CTE). This becomes a concern when plastics are used as a component of a larger product assembly containing metals, glass, ceramics, or even another plastic material (having a different CTE value) due to the thermal expansion mismatch. The thermal expansion coefficients for plastic materials vary greatly from material to material. Materials, such as filled or reinforced liquid crystal polymers, have very low coefficients of linear thermal expansion, while a material, such as an unfilled polyethylene, has a coefficient of linear thermal expansion that is an order of magnitude greater than that of steel. Designers must incorporate provisions to compensate for this thermal expansion mismatch into their product designs. The coefficient of linear thermal expansion for a polymer can be reduced significantly by adding inorganic fillers and reinforcements, such as glass fiber (glass has a very low CTE). However, when fiber reinforced materials are used, anisotropic thermal expansion behavior can be observed due to fiber and molecular orientation effects. It should also be noted here that hygroscopic polymers, such as acetals or nylons, can also exhibit dimensional changes with changes in relative humidity due to its effect on the level of absorbed moisture within the polymer. A hygroscopic thermoplastic will tend to swell as the level of absorbed moisture increases.

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2 Manufacturing Considerations for Injection Molded Parts

2.1 Introduction

The injection molding process is a high speed, automated process that can be used to produce plastic parts with very complex geometries. The process can produce either very small or very large parts using virtually any plastic material. It is important, however, for part designers to recognize that the design of the product will ultimately determine the "ease of molding" or the "manufacturability" of the part, as well as the tooling requirements and cost. It is also important for the part designer to recognize that the overall shape of a product and specific feature details may need to be altered in order to improve the moldability of the plastic part. In addition, the part designer must recognize that the properties of the molded plastic part will be greatly influenced by factors such as the tool design and processing conditions. In order to develop a quality part, the plastic part designer, the mold designer, the material supplier, and the process engineer must all work together in an effort to develop a part that is both moldable and fully functional. Plastic part designs are more likely to be successful if such concurrent engineering practices are followed.

The injection molding process is a complex process that involves a series of sequential process steps. The different phases of the injection molding process include the mold filling phase, the packing phase, the holding phase, the cooling phase, and part ejection.

Mold Filling After the mold closes, the melt flows from the injection unit of the molding machine into the relatively cool mold through the sprue, the runners, the gates, and then into the cavity.

Packing The melt is pressurized and compressed to ensure complete filling and detailed surface replication.

Holding The melt is held in the mold under pressure to compensate for shrinkage as the part cools. Holding pressure is usually applied until the gate solidifies. Once gate solidification occurs, melt can no longer flow into (or out of) the cavity.

Cooling The melt continues to cool and shrink without shrinkage compensation.

Part Ejection The mold opens and the cooled part is then stripped from the core or cavity, in most cases using a mechanical ejector system.

Each phase of the injection molding process has an influence on the design of a plastic part. In order for a plastic part to be considered moldable, it must satisfy the moldability requirements for each of these five processing phases. While there is a great deal of interaction between the various phases of the injection molding process, the discussion given below highlights the important design considerations associated with each phase of the process.