

closing mechanism to prevent closing of the mold until the wiper is retracted.

**Mold witness line** A line on a molded part due to poor alignment or fit of mating metal components such as sliding cores.

**Multicavity** Having two or more cavities to mold two or more parts at once.

**Nonplastication** This condition produces uneven stress distribution with consequent undesirable melt lumpiness. The product may appear ugly or have a fine matte surface. With a wide molecular-weight distribution there can be a lack of gloss.

**Nozzle** A device attached to the end of the plasticating barrel that directs the melt into the mold's sprue opening.

**Nozzle and locating ring** The ring is used to align the mold to the platen. It is commonly affixed to the stationary platen. This alignment is essential for the mold to operate properly—e.g., for the knockout system to operate without damage.

**Part coring** Removal of excess plastic from the cross section of a molded part to obtain a more uniform wall thickness.

**Part cosmetics** The Molders Division of SPI publishes and updates its bulletin entitled Cosmetic Specifications of Injection Molded Parts. Its purpose is to provide quantitative definitions and recommended methods of inspection and measurement of cosmetic attributes in the absence of customer-provided specifications. The guidelines include black specks, flow lines, etc.

**Pillar support** The general construction of a mold base usually incorporates an ejection housing. If the span in the housing is long, the forces during molding can cause a sizable deflection in the plates that are supported by the ejector housing, causing flashing, etc. To overcome this problem, pillar supports are included so that deflection does not occur.

**Pin** Pins used in IMMs include dowel pin, ejector pin, leader pin, return pin, side draw pin, and sprue draw pin.

**Platen bolting pattern** See *Bolting pattern, mold to platen*.

**Pressure transducer** An instrument mounted in different parts of a mold (cavity, knockout pin, etc.) to measure melt pressure.

**Processing defect** Also called processing flaw. A structural or other defect in material or part induced inadvertently during manufacture of the material and/or during processing. At fault could be factors such as the wrong additives or other ingredients, tooling, processing conditions, part design, etc. Usually what has happened was preventable.

**Product downgrade** Reduction in performance or other characteristics.

**Production bill of material** A listing of the quantity of all materials, subassemblies, and other products required to produce one assembled product.

**Production budget base** The number of hours, machine and/or labor, that is required to meet an anticipated volume level.

**Production capacity overhead rate** The manufacturing overhead hourly rate based on practical capacity volume of an operation.

**Production capacity plan** A procedure to determine the production hours required to produce an order, and then to consider the total capacity required to produce all parts.

**Production capacity utilization** The degree to which facilities are used. Usually measured in terms of a percentage of total capacity.

**Production data acquisition** PDA is the basic building block for computer-aided production or computer-integrated manufacture. It assumes a central role as the link

between logistic information flow [production planning and control (PPC)] and technical information flow. The objective of PDA is to make it possible for all operating areas to achieve optimal performance of their tasks on the basis of solid current data. It is provided by a cost-effective, fault-free capture of complete operating data and its detailed presentation in real time as required for conducting a logical product sales analysis.

**Production order point** Also called reorder point. An inventory quantity. When the available quantity falls to or below this level, the need to issue a replenishment order is indicated.

**Production order quantity** Also called lot size. The quantity of a material or product to be ordered or produced.

**Production overrun analysis** A technique for determining economical production-run quantities for products that are shipped infrequently.

**Production pegging** Identification of the source of a need for materials or parts, such as the customer name, order number, assembly production order, etc.

**Production prioritizing** The act of determining which production order should be run first, second, etc., based on factors such as customer delivery schedule and available sources such as equipment, materials, and people. Prioritizing orders results in a production sequence.

**Production schedule** A document that communicates the orders to be produced in a given time (daily, weekly, monthly, etc.).

**Product life cycle** A document for each product where time periods are estimated from facts and/or by logical evaluation.

**Product scale-up** A limited amount of development has been conducted investigating scale-up of products and fabricating equipment. Experience continues to be the main

approach, since no direct relationships exist; many variables have to be considered. As an example, scale-up techniques have been used where shear rate is kept constant, Newtonian flow characteristics are used, and so on.

**Product, semifinished** Plastic stock material, such as extruded rods and profiles and compression-molded blocks, requiring secondary operations such as machining and drilling to produce the finished product.

**Project checklist** The following are factors to be prioritized by the manufacturer/fabricator according to the company's project and/or expansion requirements: market potential, labor climate, infrastructure, quality of life, business environment, taxes and incentives, sites, financial stability, and regulatory framework.

**Quench aging** Aging induced by rapid cooling after annealing or heat treatment.

**Quench bath** The cooling medium, usually water, used to quench molten thermoplastics to the solid state.

**Set** To cause a specific condition, such as solidifying a plastic melt. For plastics, *set 1* is the conversion of a liquid plastic a solid or semisolid state. *Set 2* is the strain remaining after complete release of the force producing a deformation. *Set 3* is the conversion of a plastic into a fixed (hardened) state by chemical or physical action, such as condensation, polymerization, vulcanization, or gelatin.

**Shear edge** The cut-off edge of the mold.

**Side action** Operation of a mold at an angle to the normal open-closed action, permitting the removal of a part that would not clear a cavity or core. There may be a pin to core a hole that has to be withdrawn prior to opening the mold.

**Single-impression mold** A mold with only one cavity.

**Spacer block** Also called parallel spacer. (1) Parallel support spacers can be placed between a short-height mold and its press platen. Such blocks take up space to allow a mold that is not wide enough to meet the IMM's minimum daylight opening. (2) A mold of small (cross-sectional area is supported by a large spacer to prevent the platen's middle section from bending under pressure.

**Spacer, insulating** A spacer located between the mold and platen to restrict heat transfer from the mold to the platen. It can provide better control of the mold temperature, eliminate the uneven heating and tiebars, expansion of conserve energy, etc.

**Spew groove** The groove in a mold that permits the escape of excess plastic.

**Stripper plate** A plate that strips a molded part(s) from a cavity with or without air support.

**Taper, back** A reverse draft or undercut in a mold, which prevents molded parts from being removed freely from the mold.

**Undercut** Reverse or negative draft, such as a protuberance or indentation in a mold molding a rigid plastic, necessitating inserts or a split mold for removal of the part; if a flexible mold can be used, it will provide for the ejection of a rigid part. A flexible plastic with a slight undercut usually can be ejected intact, but may require sliding cores or split molds. External undercuts can be placed at the parting line to obviate the need for core pins. Shallow undercuts often may be stripped from the mold without need for core pulls. If the undercut is strippable, the other half of the mold must be removed first. Then the mold ejector pins can act to strip the part.

**Unit** A mold designed for quick changing of interchangeable cavities.

**Vacuum mold** A mold that includes a vacuum chamber or system for removal of air and/or gasses.

**Volatiles** Many plastics contain small quantities of material that boil at processing temperatures, and/or they may be contaminated by water absorbed from the atmosphere. These volatiles may cause bubbles, a scarred surface, or other defects. Different methods are used to remove volatiles (See Chap. 3, Section on Vented Barrels; Chap. 10, Section on Drying Plastics).

**Water conditioning, magnetic** Magnetic water-conditioning systems are designed to improve the efficiency of existing water softeners in chillers and other equipment by reducing scale formation. Improved heat transfer in equipment such as molds that come in contact with water is a major benefit. This technology has been used in other industries since the 1940s. Nothing is taken out of the water; nothing changes except that crystal formation is prevented. Magnetic fields align molecular particles of calcium carbonate in water so they can not form hard scale that adheres to hot surfaces. The molecules are retained in solution and pass harmlessly through the water system.

**Water, hard** Water containing certain salts, such as those of calcium and magnesium, which form insoluble deposits in water cooling of molds.

**Water softening** Removal of scale-forming calcium and magnesium ions from hard water, or replacing them by the more soluble sodium ions; can be done by chemicals or ion exchange.

**Weld line** The result of two melt flow paths in the mold cavity(s) meeting head-on. It can be very visible and has a weak bond strength. Different methods are used to eliminate or mitigate the weld line by changing the product design, mold design, and/or melt flow-processing conditions. See *Meld line*.

**Weld-line overflow tab** A small, localized extension of a part at a weld-line junction to

allow a longer melt flow path for the purpose of obtaining a better fusion bond of the meeting melt fronts.

**Wiper** See *Mold wiper*.

**Yoke** In a large single-cavity mold, the

entire cavity and core plates usually form the mold cavity. In a smaller and multicavity mold, core and cavity blocks (inserts) are mounted on or in the various plates of the mold base. When various components are mounted in the plates, the plates are called yokes.

# Fundamentals of Designing Products

## Overview

The term “design” has many connotations. Essentially it is the process of devising a product that fulfills as completely as possible the total requirements of the user, while satisfying the needs of the fabricator in terms of cost effectiveness (return on investment). Basically design is the mechanism whereby a requirement is converted to a meaningful plan such as summarized in Fig. 5-1.

Designing, like engineering (or life itself), is the science of compromise. The goal is to meet factors such as product performance and cost requirements (Chap. 14), reliability, industry codes, legal matters (Chap. 17), and serviceability (1, 7, 10, 18, 386). Although some design features support all these factors, usually compromises are required. Often competing factors are involved (18, 176).

The efficient use of the best available material and production process should be the goal of every molding design effort, including the mold and other tool designs. One must recognize that product design is as much an art as a science. Design guidelines for plastics have existed and most have been repeated for over a century. These have enabled production of many thousands of parts meeting various service requirements, including long life.

There is a practical, simple approach to designing with plastics that differs little from designing with other materials such as different steels, aluminum, titanium, copper, wood, and so forth. Each material has its respective advantages that require certain different design approaches. With over 17,000 plastics available worldwide, one has to comprehend factors such as the range of their different properties, structural responses, product-performance characteristics, part shapes, and available fabricating processes, as well as their influence on product performances and how economics influence design approaches (Chaps. 6 and 14).

Design criteria for fabricated products range from meeting tight weight tolerances from grams to many tons to size tolerances from microns to many feet, for objects having simple to very complex shapes. There are products that take low or extremely high loads and operate in widely different environments.

Plastics provide an opportunity to optimize design by focusing on a material's composition and orientation as well as its structural-member geometry. There are important interrelationships among shape, material selection (including elastomers, foams, and various degrees of reinforcement),

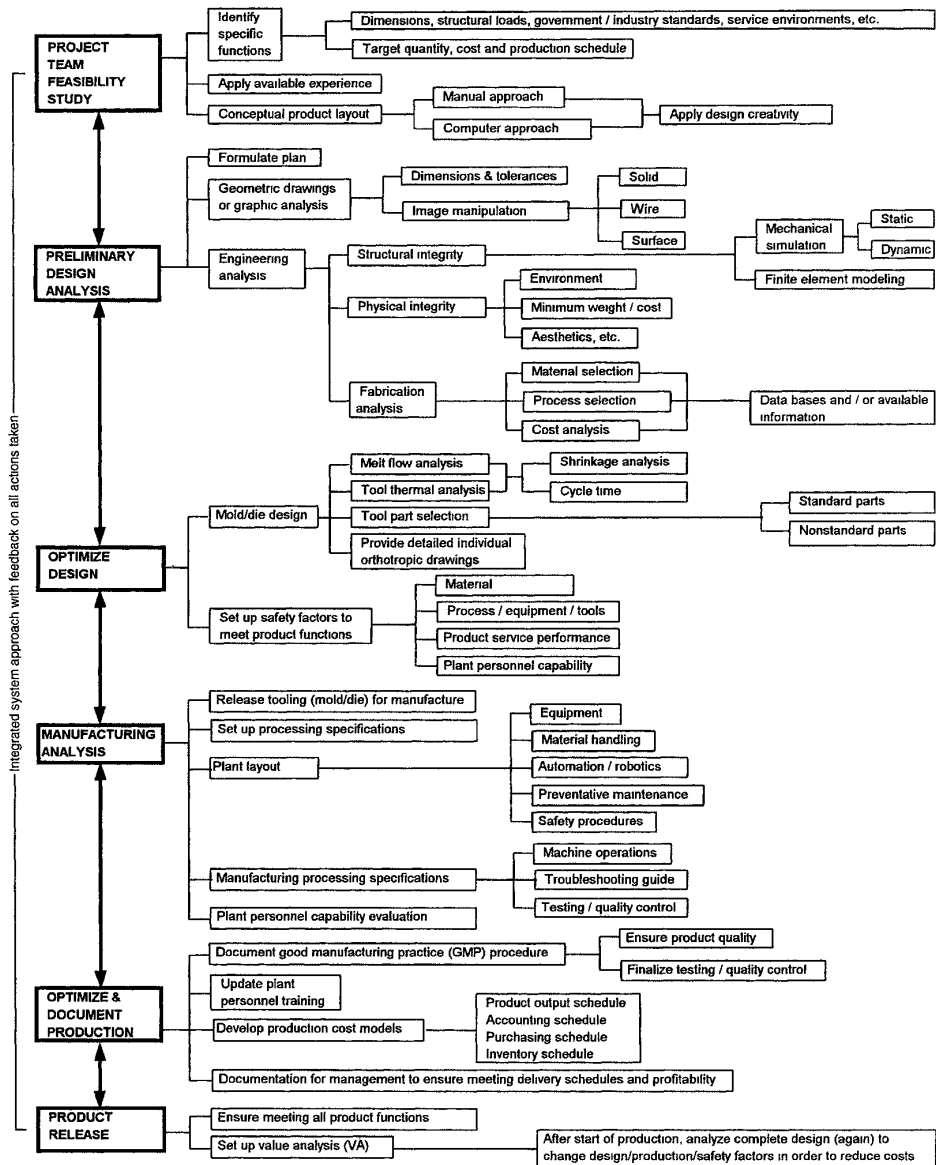


Fig. 5-1 Product design diagram incorporating process selection.

and consolidation of parts, manufacturing selection, and other factors that provide low cost-to-high performance products. For the many applications that require only minimal mechanical performance, shaping through processing techniques can provide

significant performance and cost advantages when using the usual lower cost commodity plastic (18, 191).

The charts shown in Figs. 5-2 to 5-8 summarize a simplified flow pattern guide to product design.

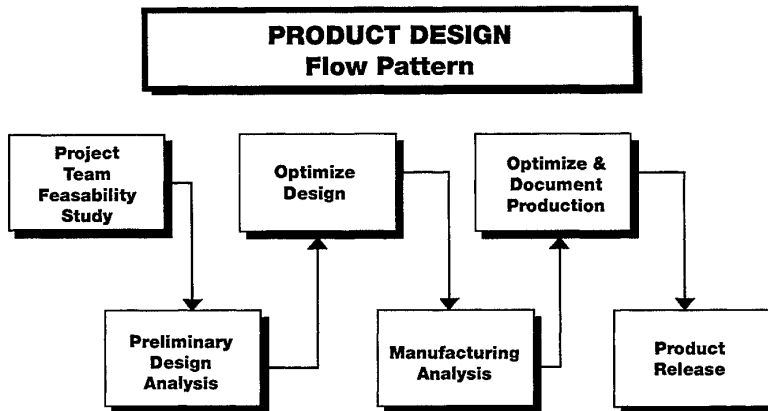


Fig. 5-2 Product design flow pattern.

### Molding Influences Product Performance

In designing a totally new product or re-designing an existing one to improve the product, bring about cost savings, or some combination of these or other reasons, consideration should be given to the key advantages of injection molding. These advantages include the ability to produce finished, mul-

tifunctional, or complex molded parts accurately and repeatedly in a single, highly automated operation. While keeping this in mind during the initial planning stage, one should also be aware of the general design considerations presented in this section.

Many parts of an injection mold will influence the final product's performance, dimensions, and other characteristics. These mold

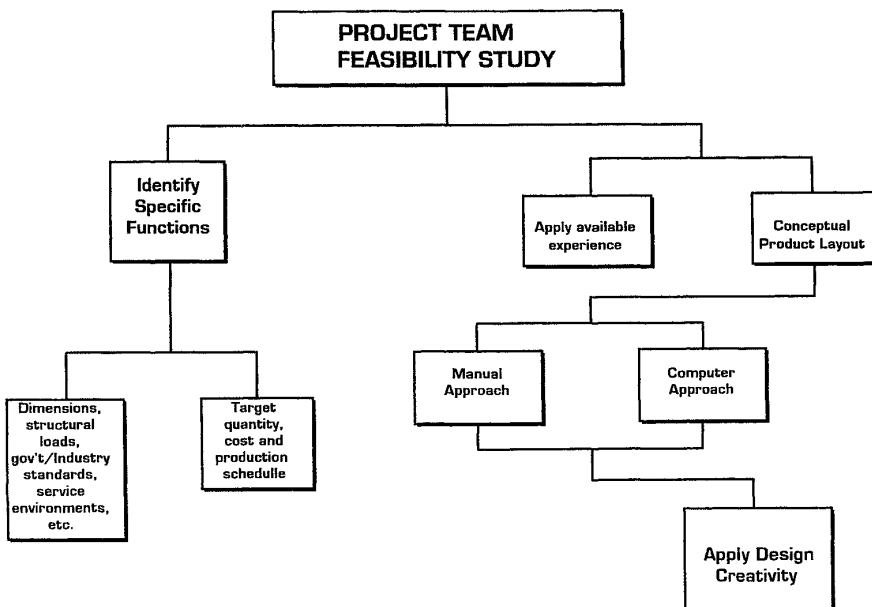


Fig. 5-3 Project team feasibility study.

**Table 5-1** Examples of errors in mold and part design

| Faults                                                       | Possible Problems                                                                                                                                             |
|--------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wrong location of gate                                       | Cold weld lines, flow lines, jetting, air entrapment, venting problems, warping, stress concentrations, voids, and/or sink marks                              |
| Gates and/or runners too narrow                              | Short shots, plastics overheated, premature freezing of runners, sink marks, and/or voids and other marks                                                     |
| Runners too large                                            | Longer molding cycle, waste of plastics, and pressure losses                                                                                                  |
| Unbalanced cavity layout in multiple-cavity molds            | Unbalanced pressure buildup in mold, mold distortion, dimensional variation between products (shrinkage control poor), poor mold release, flash, and stresses |
| Nonuniform mold cooling                                      | Longer molding cycle, high after-shrinkage, stresses (warping), poor mold release, irregular surface finish, and distortion of part during ejection           |
| Poor or no venting                                           | Need for higher injection pressure, burned plastic (brown streaks), poor mold release, short shots, and flow lines                                            |
| Poor or no air injection                                     | Poor mold release for large parts, part distortion, and higher ejection force                                                                                 |
| Poor ejector system or bad location of ejectors              | Poor mold release, distortion or damage in molding, and upsets in molding cycles                                                                              |
| Sprue insufficiently tapered                                 | Poor mold release, higher injection pressure, and mold wear                                                                                                   |
| Sprue too long                                               | Poor mold release, pressure losses, longer molding cycle, and premature freezing of sprue                                                                     |
| No round edge at end of sprue                                | Notch sensitivity (cracks, bubbles, etc.) and stress concentrations                                                                                           |
| Bad alignment and locking of cores and other mold components | Distortion of components, air entrapment, dimensional variation, uneven stresses, and poor mold release                                                       |
| Mold movement due to insufficient mold support               | Part flashes, dimensional variations, poor mold release, and pressure losses                                                                                  |
| Radius of sprue bushing too small                            | Plastic leakage, poor mold release, and pressure losses                                                                                                       |
| Mold and injection cylinder out of alignment                 | Poor mold release, plastic leakage, cylinder pushed back, and pressure losses                                                                                 |
| Draft of molded part too small                               | Poor mold release, distortion of molded part, and dimensional variations                                                                                      |
| Sharp transitions in part wall thickness and sharp corners   | Parts unevenly stressed, dimensional variations, air entrapment, notch sensitivity, and mold wear                                                             |

parts include the cavity shape, gating, parting line, vents, undercuts, ribs, hinges, etc. (see Table 5-1). The mold designer must take all these factors into account. At times, to provide the best design, the product designer, processor, and mold designer may want to jointly review where compromises can be made to simplify meeting product requirements. With all this interaction, it should be clear why it takes a significant amount of time to ready a mold for production.

Thus, in the design of any injection molding part, there are certain desirable goals that the designer should use. In meeting them, prob-

lems can unfortunately develop. For example, the most common mold design errors of a sort that can be eliminated usually occur in the following areas:

- Thick or thin sections, transitions, warp, and stress
- Multiple gates and weld lines
- Wrong gate locations
- Inadequate provision for cavity air venting
- Parts too thin to mold properly (such as diaphragms)
- Parts too thick to mold properly

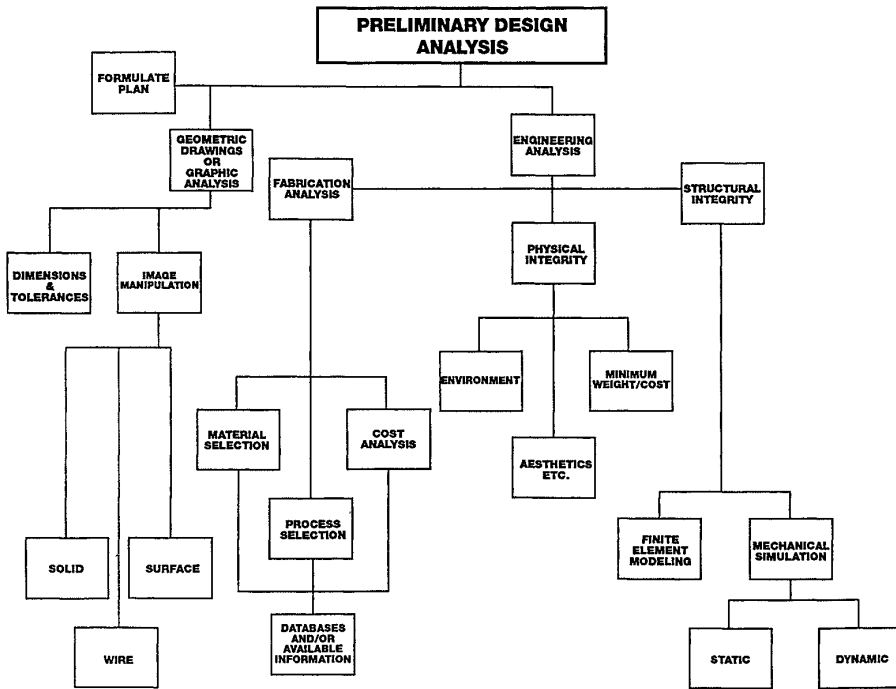


Fig. 5-4 Preliminary design analysis.

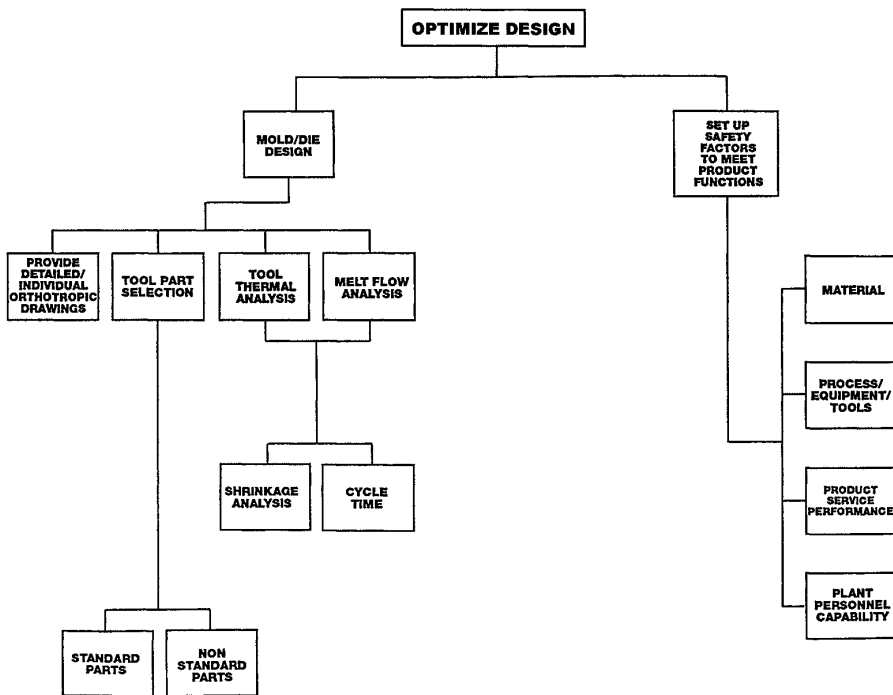


Fig. 5-5 Optimize design.

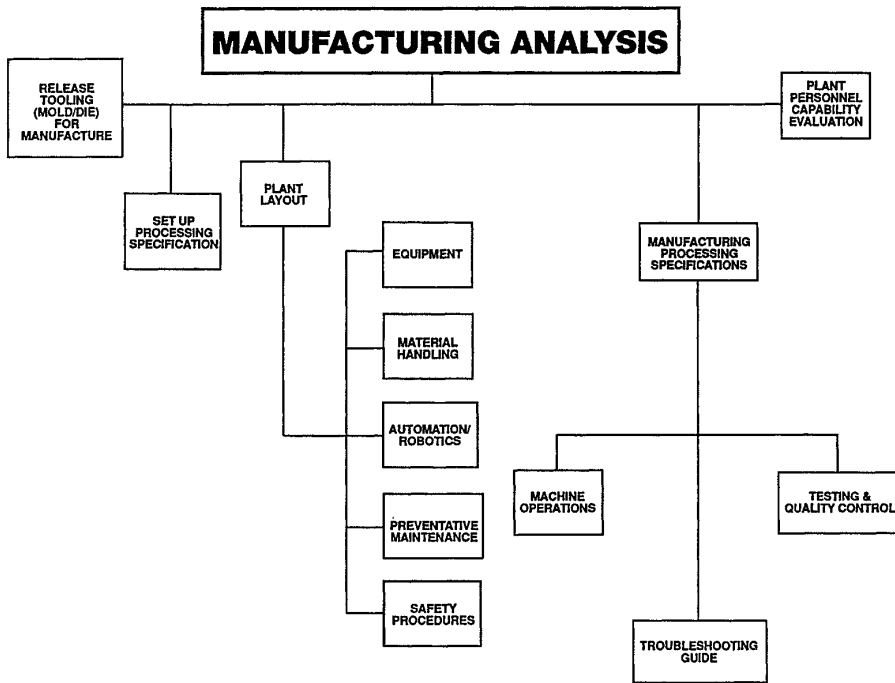


Fig. 5-6 Manufacturing analysis.

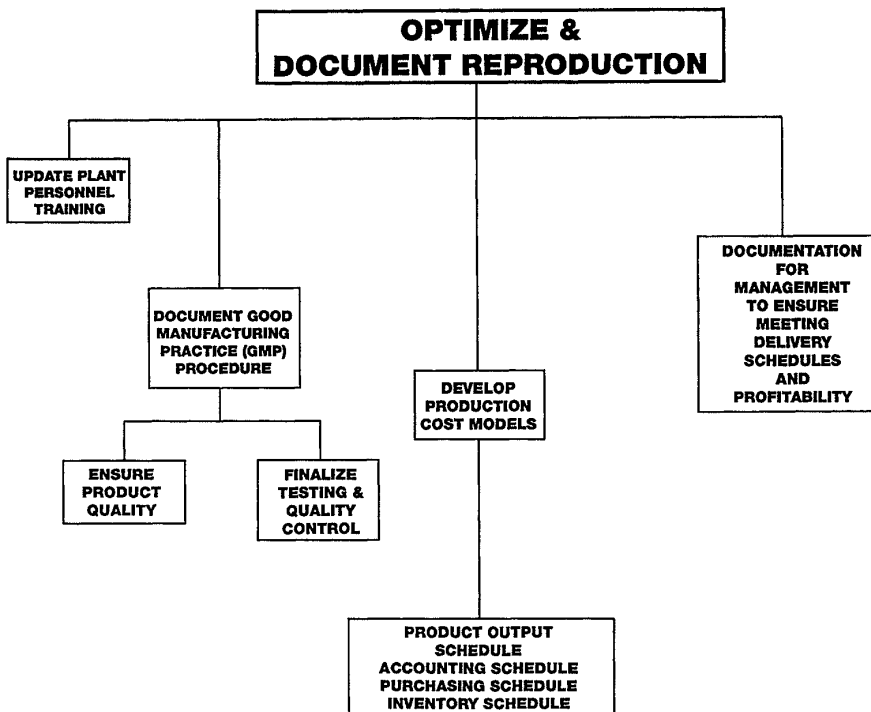


Fig. 5-7 Optimize and document reproduction.

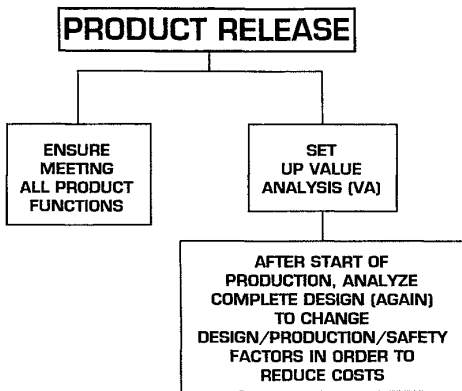


Fig. 5-8 Product release.

Plastic flow path too long and tortuous  
 Runners too small  
 Gates too small  
 Poor temperature control  
 Runner too long  
 Part symmetry and gate symmetry  
 Orientation of polymer melt in flow direction  
 Hiding gate stubs  
 Stress relief for interference fits  
 Living hinges  
 Slender handles and bails  
 Thread inserts  
 Creep or fatigue over long-time stress (extremely important)

As seen in other chapters, different plastics have different melt and flow characteristics. What is used in a mold design for a specific material may thus require a completely different type of mold for another material. These two materials might, for instance, have the same polymer but use different proportions of additives and reinforcements. This situation is no different from that of other materials such as steel, wood, ceramics, and aluminum.

It is important to recognize that the drawing of a plastic product will not specifically spell out the way many of its details will be carried out in the mold design. Some fea-

tures adversely affect the strength and quality of the molded product. In most cases, these problem details can be modified by the designer to minimize their adverse effects on the properties of the part.

### Design Optimization

To a greater extent than with other materials, plastics lend themselves to design optimization. The injection molding process offers simple to complex shaped molded products that can replace complex and/or less costly complex assemblies. However, certain molded products can fail in service, distort, or exhibit surface defects. Factors such as the anticipated lead time or desired production rate may also impose certain restrictions. The causes of these shortcomings in many case can be traced back to the design approach and are usually the result of the "knowledge gap" that exists between the various people involved in the design process.

Many of the injection moldings produced will become component parts of products that also include metal pressings, turned metal parts, springs, electrical parts, and electronic circuitry. These products may have been designed by engineers who are skilled in the use of traditional materials, but who have a limited knowledge of plastics (18).

Engineering drawings of plastic parts frequently carry statements such as no sink marks, weld lines, gate marks, or ejector pin marks permitted. These drawings have been produced by designers with insufficient or inappropriate training, who believe that it is the function of the mold designer, moldmaker, or molding process technician to meet these unrealistic requirements and still produce the parts at economic production rates.

Recognition of this problem and the need to develop more efficient design procedures have led to the introduction of simultaneous engineering via computer-aided techniques (Chap. 9) to replace the traditional linear design approach. Ensuring that the various individuals are brought together early in the

design cycle enables them to all have input based on their various skills and experience.

In the traditional linear sequential design process, the product designer has created a part design to meet functional requirements. As part of the design process, he or she may have been advised on material selection by a raw material supplier or will use physical property data derived from the material supplier's specification sheets. What is not readily apparent to the designer accustomed to traditional materials is that data generated from a simple test bar, molded under optimum conditions, may not be replicated in a complex part that may have been molded under less than ideal conditions. As an example, tensile strengths in the area of the weld lines in glass-fiber-reinforced plastics may be as low as 20% of the quoted values used by the designer (Chaps. 6, 8, and 12).

Once the design has been finalized, the mold designer will design a mold to make the part (Chap. 4). It is a commonly accepted principle that the mold designer will use great skill to create a mold that will enable the part to be produced to the required geometry. Some of the mechanical solutions adopted, with inwardly collapsing cores, multiple side actions, and complex split lines, are most ingenious and very functional. Unfortunately, they often mask the poorly chosen gate positions, feed system dimensions, and inefficient cooling circuits that result from the mechanical complexity (Chap. 8). In attempting to create the desired geometry, the mold designer may have created a mold that will produce parts with unacceptable surface defects or variations in shrinkage that cause dimensional problems or that can only be produced with extended cycle times. Often, relatively small modifications to the part design would overcome these problems.

Although some discussions may take place about design changes, the linear nature of the process makes the part designer reluctant to change his or her design. Such discussions often digress into justifications of the design prejudices of the parties involved and as such are less objective.

Once the mold has been made, it is passed to a processing technician who attempts to

select processing conditions to produce parts to the desired specification. Despite sophisticated controls on modern injection molding machines (Chap. 7), the technician can only basically change three variables that fundamentally affect the part filling: mold temperature, melt temperature, and injection time. If we add packing time and pressure, we then have the limited range of basic tools available to produce good parts from the mold.

In attempting to optimize the process, it is normal to carry out a number of mold trials. This action takes up production capacity, extends the lead time of the project, and may involve modifications of the mold to enable it to produce acceptable parts. Thus, at the end of the linear design line, the errors of the part designer relate to the production personnel who will have to live with them for the life of the project. Using multidisciplinary teams to design better parts faster has been one means of overcoming these problems.

### *Computer Analysis*

The logical consequence of using a computer-guided approach in part design is to use the computer to simulate processing to detect possible problems before going to the manufacturing floor. It also optimizes the processing conditions to get the most out of a plastic and to process according to optimum economical conditions (Chap. 9). Software programs are available for:

1. Calculating the melt front advance, which gives information about weld lines, air entrapments, and the pressure distribution during the mold-filling phase
2. Calculating the shear rates, shear stresses, and melt temperatures along freely selected flow paths
3. Analyzing the holding pressure phase and estimating shrinkage
4. Determining the most favorable machine-operating point and its dependence on operating parameters—for example, to find better processing conditions
5. Predicting orientation patterns

All this generated information is very important for designing the mold in a way that minimizes injection molding processing problems. In injection molding, such programs for the rheological, thermal, and proper mechanical mold design are already quite frequently and successfully used. Models for reactive processing have also been developed.

The computer-controlled injection molding operation of the future will also involve more computer-aided selection of the best machine for a given production order. What is required here is a suitable means of allocating a mold to the machine from a process engineering and business economics approach. This also means that the process control data, which specify the optimum process sequence, have to be included in machine selection. Thus, a mold and machine database is developed for defining the optimum combination of mold and machine. Information obtained in the course of computer-aided molding design now can provide data on parameters relevant to production, such as the maximum clamping force required.

Measuring and controlling strategies are definitely very important with respect to quality molding. Therefore, a process model can be used for describing such factors as the pressure buildup in the mold for plastics under the influence of dilation, thermal compression, and reaction shrinkage.

### Material Optimization

Designers can turn to materials as a means of dramatically improving their products, in terms of both performance and cost. However, many of the design automation CAD/CAE tools focus directly or indirectly on the use of geometry as the only or main means of optimizing product design. Over 70% of product designs are nongeometric. With over 80,000 materials (including over 17,000 plastics) to choose from, material-selection software tools have become an asset to designers and engineers, including those familiar with material types (Chap. 9 and Appendix 4).

Some software provides information on specific performance requirements so that only one or a few will be listed as the best material for the product. These tools let designers consider materials as a variable in design to meet their specific product requirements. A simplified example of selecting a plastic for a product design is shown in Tables 5-2 to 5-4.

### Material Characteristics

There is a practical and easy approach in designing with plastics; it is essentially no different from designing with other materials: steel, aluminum, wood, concrete, etc. This chapter presents design information based on properties of plastics, structural responses, performance characteristics, part shape, process variables, and economics.

Plastics have been designed into many different products for over a century. They have been used successfully and provided exceptional cost advantages compared to other materials. Unfortunately, some people think plastics are new because the industry has an endless capability of producing new plastics to meet new performance or processing requirements. This does not mean that they will replace other materials (metals, wood, glass, concrete, etc.); each material will be used when it offers cost-to-performance advantages.

The job of designing is becoming more difficult as more materials become available—with plastics constituting the major portion of those materials. There are over 17,000 different plastics, only a few hundred of which are used in large quantities. Plastics are not a single type of material, but a family of materials, each having its special advantages (Figs. 5-9 to 5-16 and Tables 5-5 to 5-7). Details on plastic materials used in molding are given in Chaps. 6, 8, 11, and 12.

Many different products can be designed using plastics. They can be made to take low to extremely high loads and to operate in widely differing environments, ranging from highly corrosive to electrical-insulation conditions. They provide the designer with a

Table 5-2 Glass reinforced thermoplastic compound selector (LNP Engineering Plastics Inc.)

| G/R Resin Groups         | Design Criteria | Strength & Stiffness | Toughness | Short Term Heat Resistance | Long Term Heat Resistance | Environmental Resistance | Dimensional Accuracy In Molding | Dimensional Stability | Wear & Frictional Properties | Cost |
|--------------------------|-----------------|----------------------|-----------|----------------------------|---------------------------|--------------------------|---------------------------------|-----------------------|------------------------------|------|
| Styrenics                |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| ABS                      |                 | 2 3                  | 1 6       | 1 6                        | 1 6                       | 1 6                      | 3 1                             | 2 5                   | 3 6                          | 3 2  |
| SAN                      |                 | 1 1                  | 2 2       | 2 2                        | 2 2                       | 2 2                      | 1 1                             | 1 1                   | 1 1                          | 2 2  |
| Polystyrene              |                 | 3 3                  | 3 3       | 3 3                        | 3 3                       | 3 3                      | 2 2                             | 3 3                   | 2 2                          | 1 1  |
| Olefins                  |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| Polyethylene             |                 | 2 5                  | 2 4       | 2 4                        | 2 5                       | 2 3                      | 1 5                             | 1 5                   | 2 3                          | 1 1  |
| Polypropylene            |                 | 1 1                  | 1 1       | 1 1                        | 1 1                       | 1 1                      | 1 1                             | 1 1                   | 1 1                          | 2 2  |
| Other Crystalline Resins |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| Nylons                   |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| 6                        |                 | 2 1                  | 2 3       | 2 3                        | 2 1                       | 5 4                      | 1 2                             | 4 3                   | 3 2                          | 1 2  |
| 6/6                      |                 | 1 1                  | 3 1       | 3 1                        | 1 1                       | 4 3                      | 2 2                             | 3 2                   | 2 3                          | 2 3  |
| 6/10, 6/12               |                 | 3 3                  | 1 1       | 1 1                        | 3 3                       | 3 3                      | 2 2                             | 2 2                   | 3 3                          | 4 4  |
| Polyester                |                 | 4 4                  | 4 4       | 2 2                        | 1 1                       | 2 2                      | 2 2                             | 1 1                   | 4 4                          | 1 1  |
| Polyacetal               |                 | 5 5                  | 5 5       | 5 5                        | 2 2                       | 1 1                      | 3 3                             | 2 2                   | 1 1                          | 1 1  |
| Arylates                 |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| Modified PPO             |                 | 4 2                  | 3 1       | 4 3                        | 4 3                       | 3 4                      | 4 1                             | 4 3                   | 4 4                          | 1 2  |
| Polycarbonate            |                 | 2 2                  | 2 2       | 2 2                        | 2 2                       | 2 2                      | 2 2                             | 2 2                   | 3 3                          | 3 3  |
| Polysulfone              |                 | 1 1                  | 3 3       | 1 1                        | 1 1                       | 1 1                      | 3 3                             | 1 1                   | 2 2                          | 4 4  |
| Polyethersulfone         |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| High Temp. Resins        |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| PPS                      |                 | 1 2                  | 2 4       | 2 1                        | 2 1                       | 1 2                      | 1 4                             | 2 1                   | 2 4                          | 1 5  |
| Polyamide-imide          |                 | 2 2                  | 1 1       | 1 1                        | 1 1                       | 2 2                      | 2 2                             | 1 1                   | 1 1                          | 2 2  |
| Fluorocarbons            |                 |                      |           |                            |                           |                          |                                 |                       |                              |      |
| FEP                      |                 | 2 6                  | 1 2       | 2 2                        | 1 1                       | 1 1                      | 2 6                             | 2 6                   | 1 1                          | 2 6  |
| ETFE                     |                 | 1 1                  | 2 2       | 1 1                        | 2 2                       | 2 2                      | 1 1                             | 1 1                   | 2 2                          | 1 1  |

Ratings: 1—most desirable, 6—least desirable. Large numbers indicate group classification; small numbers are for the specific resins within that group.

**Strength & stiffness:** The ability to resist instantaneous applications of load while exhibiting a low level of strain. Materials that demonstrate a proportionality between stress and strain have been assigned better relative ratings.

**Toughness:** The ability to withstand impacting at high strain rates.

**Short-term heat resistance:** The ability to withstand exposure to elevated temperatures for a limited period of time without distortion.

**Long-term heat resistance:** The ability to retain a high level of room-temperature mechanical properties after exposure to elevated temperature for a sustained period.

**Environmental resistance:** The ability to withstand exposure to solvents and chemicals

**Dimensional accuracy in molding:** The ability to produce warp-free, high tolerance molded parts.

**Dimensional stability:** The ability to maintain the molded dimensions after exposure to a broad range of temperatures and environments

**Wear and frictional properties:** The ability of the plastic to resist removal of material when run against a mating metal surface. The lower the frictional values, the better the relative rating.

**Cost:** The relative cost per cubic inch.

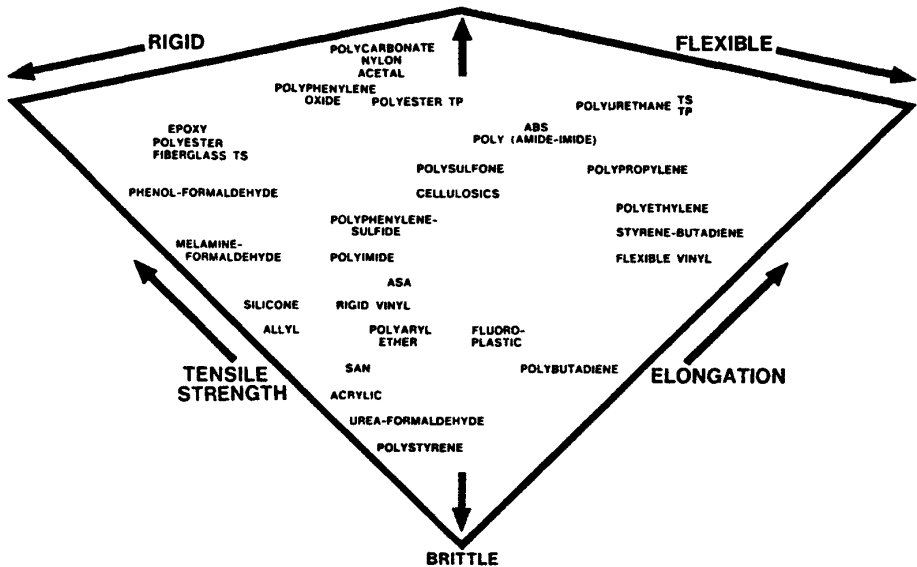


Fig. 5-9 Example of range of mechanical properties for plastics.

**Table 5-3** Impellor for chemical handling pump. Design criteria: Strength and stiffness, toughness, short term and long term heat resistance and environmental resistance

| Material Characteristics                                                                | Strength & Stiffness             | Toughness | Short Term Heat Resistance       | Long Term Heat Resistance        | Environmental Resistance         | Dimensional Accuracy In Molding | Dimensional Stability | Wear & Frictional Properties | Point Sub Total | Cost                             | Point Total                       |
|-----------------------------------------------------------------------------------------|----------------------------------|-----------|----------------------------------|----------------------------------|----------------------------------|---------------------------------|-----------------------|------------------------------|-----------------|----------------------------------|-----------------------------------|
| <b>Design Criteria</b>                                                                  |                                  |           |                                  |                                  |                                  |                                 |                       |                              |                 |                                  |                                   |
| G/R Resin Groups                                                                        | X                                |           | X                                | X                                | X                                |                                 |                       |                              |                 |                                  |                                   |
| Styrenics<br>ABS<br>SAN<br>Polystyrene                                                  | 3                                |           | 6                                | 6                                | 6                                |                                 |                       |                              | 21              | 2                                | 23                                |
| Olefins<br>Polyethylene<br>Polypropylene                                                | 5                                |           | 4                                | 5                                | 3                                |                                 |                       |                              | 17              | 1                                | 18                                |
| Other Crystalline Resins<br>Nylons<br>6<br>6/6<br>6/10, 6/12<br>Polyester<br>Polyacetal | 1                                |           | 2                                | 4                                | 4                                |                                 |                       |                              | 11              | 3                                | 14                                |
| Arylates<br>Modified PPO<br>Polycarbonate<br>Polysulfone<br>Polyethersulfone            | 3                                |           | 3                                | 3                                | 5                                |                                 |                       |                              | 14              | 4                                | 18                                |
| High Temp. Resins<br>PPS<br>Polyamide-imide                                             | 2 <sub>1</sub><br>2 <sub>2</sub> |           | 1 <sub>2</sub><br>1 <sub>1</sub> | 1 <sub>2</sub><br>1 <sub>1</sub> | 2 <sub>1</sub><br>2 <sub>2</sub> |                                 |                       |                              | 6 <sub>6</sub>  | 5 <sub>1</sub><br>2 <sub>2</sub> | 11 <sub>7</sub><br>8 <sub>8</sub> |
| Fluorocarbons<br>FEP<br>ETFE                                                            | 6                                | 2         | 2                                | 1                                | 1                                |                                 |                       |                              | 10              | 6                                | 16                                |

Comments: "High Temp. Resins" clear choice throughout. Final selection would be PPS based on price advantages. If heat resistance had not been a factor, olefins would have been the choice.

Table 5-4 Compound selector worksheet

| Material Characteristics        | Strength & Stiffness | Toughness | Short Term Heat Resistance | Long Term Heat Resistance | Environmental Resistance | Dimensional Accuracy In Molding | Dimensional Stability | Wear & Frictional Properties | Point Sub Total | Cost | Point Total |
|---------------------------------|----------------------|-----------|----------------------------|---------------------------|--------------------------|---------------------------------|-----------------------|------------------------------|-----------------|------|-------------|
| <b>Design Criteria</b>          |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>G/R Resin Groups</b>         |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>Styrenics</b>                |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| ABS                             |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| SAN                             |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polystyrene                     |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>Olefins</b>                  |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polyethylene                    |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polypropylene                   |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>Other Crystalline Resins</b> |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Nylons                          |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| 6                               |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| 6/6                             |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| 6/10, 6/12                      |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polyester                       |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polyacetal                      |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>Arylates</b>                 |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Modified PPO                    |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polycarbonate                   |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polysulfone                     |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polyethersulfone                |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>High Temp. Resins</b>        |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| PPS                             |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| Polyamide-imide                 |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| <b>Fluorocarbons</b>            |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| FEP                             |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |
| ETFE                            |                      |           |                            |                           |                          |                                 |                       |                              |                 |      |             |

**Ratings:** 1—most desirable, 6—least desirable. Large numbers indicate group classification, small numbers are for the specific resins within that group  
**Strength & stiffness:** The ability to resist instantaneous applications of load while exhibiting a low level of strain. Materials that demonstrate a proportionality between stress and strain have been assigned better relative ratings

**Toughness:** The ability to withstand impacting at high strain rates.

**Short-term heat resistance:** The ability to withstand exposure to elevated temperatures for a limited period of time without distortion

**Long-term heat resistance:** The ability to retain a high level of room-temperature mechanical properties after exposure to elevated temperature for a sustained period

**Environmental resistance:** The ability to withstand exposure to solvents and chemicals

**Dimensional accuracy in molding:** The ability to produce wrap-free, high tolerance molded parts.

**Dimensional stability:** The ability to maintain the molded dimensions after exposure to a broad range of temperatures and environments

**Wear and frictional properties:** The ability of the plastic to resist removal of material when run against a mating metal surface. The lower the frictional values, the better the relative rating

**Cost:** The relative cost per cubic inch

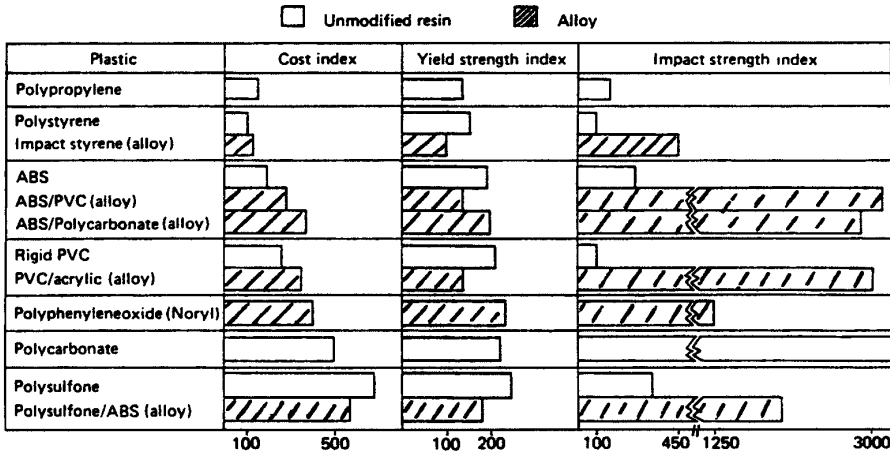


Fig. 5-10 Different plastics can be combined (alloyed) to provide cost-performance improvements.

combination of often unfamiliar and unique advantages and limitations that can challenge his or her ability. By understanding their many different structures, properties, design freedoms, and fabrication techniques, the designer can meet this challenge.

There is no scarcity of materials for the designer, who has plastics, metals, and other materials available. In the area of steels alone, one can select from any number of plain steels, as well as many alloy steels, the superalloys, etc. Among plastics, there are reinforced or composite plastics incorporating fibers or filaments of glass, as well as those with carbon-graphite, aramid/organic, boron, single crystal/whisker, and flake-type reinforcement (Figs. 5-14 and 5-15 Table 5-7). The major consideration for a designer is to analyze properly what is available and de-

velop a logical selection process to meet performance requirements, which generally are related to cost factors. The range of plastic properties is indicated in most of the accompanying figures, particularly Figs. 5-9 and 5-14. Figure 5-9 follows the “pie” approach, identifying broad mechanical properties for all plastics; however, the pie can be used for individual plastics such as polyvinyl chlorides and polyurethanes. The pie approach for selecting plastics can also be used to devise separate pies for physical properties, chemical resistance, electrical resistance, static or dynamic loads, creep (to no creep) behavior, heat resistance, directional properties, etc.

The range of properties literally encompasses all types of environmental conditions, each with its own individual broad range of properties for the different plastics.

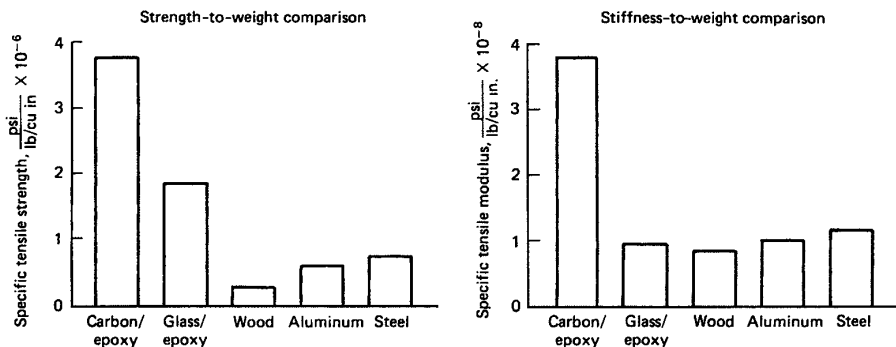


Fig. 5-11 Comparing reinforced plastics with other materials.

These properties can include wear resistance, integral color, impact resistance, transparency, energy absorption, ductility, thermal or sound insulation, and weight. Unfortunately, no one plastic can meet all property requirements, but the designer has the option of combining different plastics (keeping them separate materials by processes such as

coinjection). Plastics are also combined with other materials such as steel. Any combination requires that certain aspects of compatibility exist, such as having the same thermal coefficient of expansion or contraction, etc. Combining or mixing plastics to produce what are generally referred to as “alloys” creates plastic compounds with properties

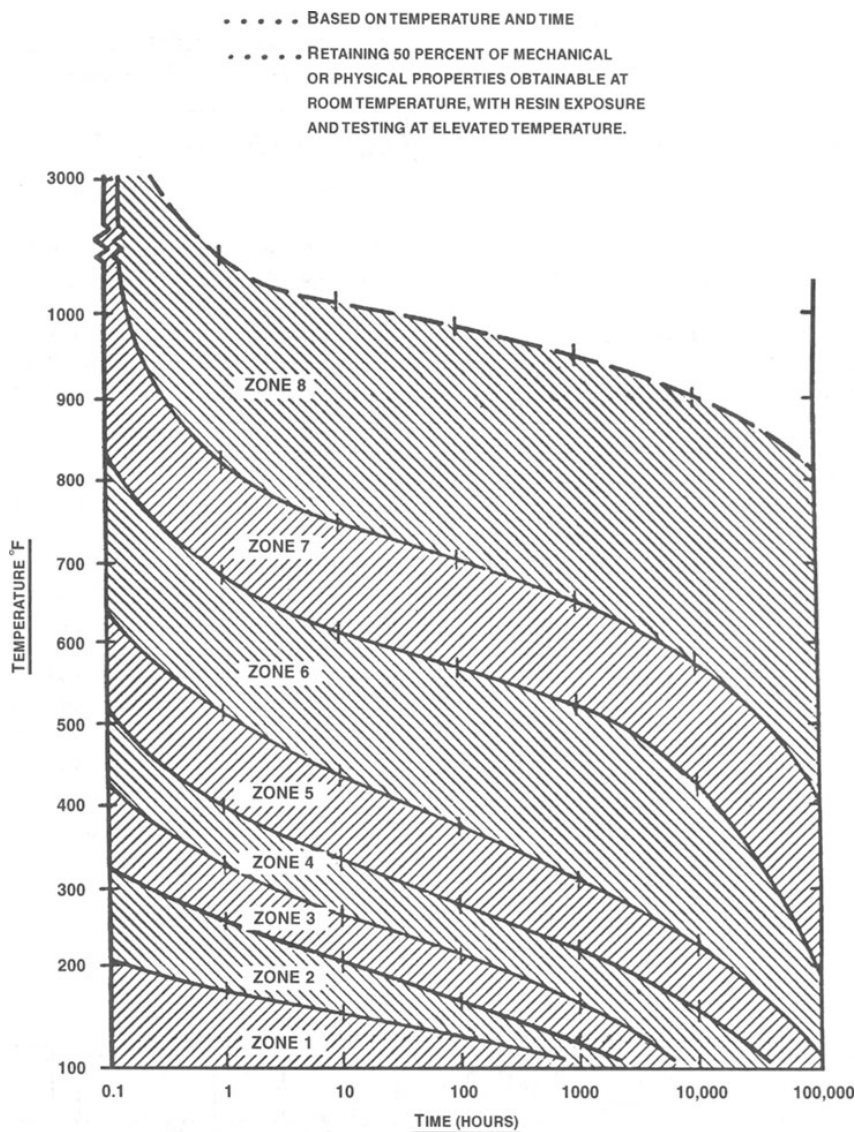


Fig. 5-12 Heat-resistant properties of plastics.

| Examples                               |                                   |
|----------------------------------------|-----------------------------------|
| <b>ZONE 1</b>                          | <b>ZONE 4</b>                     |
| Acrylic                                | Alkyd                             |
| Cellulose Acetate (CA)                 | Fluorinated Ethylene              |
| Cellulose Acetate-Butyrate (CAB)       | Propylene (FEP)                   |
| Cellulose Acetate Propionate (CAP)     | Melamine-Formaldehyde             |
| Cellulose Nitrate (CN)                 | Phenol-Furfural                   |
| Cellulose Propionate                   | Polyphenylene oxide (PPO)         |
| Polyallomer                            | Polysulfone                       |
| Polyethylene, Low-Density (LDPE)       |                                   |
| Polystyrene (PS)                       |                                   |
| Polyvinyl Acetate (PVAC)               |                                   |
| Polyvinyl Alcohol (PVAL)               |                                   |
| Polyvinyl Butyral (PVB)                |                                   |
|                                        | <b>ZONE 5</b>                     |
| Polyvinyl Chloride (PVC)               | Acrylic (Thermoset)               |
| Styrene-Acrylonitrile (SAN)            | Diallyl Phthalate (DAP)           |
| Styrene-Butadiene (SBR)                | Epoxy                             |
| Urea-Formaldehyde                      | Phenol-Formaldehyde               |
|                                        | Polyester                         |
|                                        | Polytetrafluoroethylene (TFE)     |
| <b>ZONE 2</b>                          |                                   |
| Acetal                                 |                                   |
| Acrylonitrile-Butadiene-Styrene (ABS)  |                                   |
| Chlorinated Polyether                  | <b>ZONE 6</b>                     |
| Ethyl Cellulose (EC)                   | Parylene                          |
| Ethylene Vinyl Acetate Copolymer (EVA) | Polybenzimidazole (PBI)           |
| Furan                                  | Polyphenylene                     |
| Ionomer                                | Silicone                          |
| Phenoxy                                |                                   |
| Polyamides                             |                                   |
| Polycarbonate (PC)                     |                                   |
| Polyethylene, High-Density (HDPE)      |                                   |
| Polyethylene, Cross-Linked             |                                   |
| Polyethylene Terephthalate (PETP)      | <b>ZONE 7</b>                     |
| Polypropylene (PP)                     | Polyamide-imide                   |
| Polyvinylidene Chloride                | Polyimide                         |
| Urethane                               |                                   |
| <b>ZONE 3</b>                          | <b>ZONE 8</b>                     |
| Polymonochlorotrifluoroethylene (CTFE) | Plastics now being developed      |
| Vinylidene Fluoride                    | using intrinsically rigid linear  |
|                                        | macro-molecules' principle        |
|                                        | rather than usual crystallization |
|                                        | and cross-linking principles.     |

Fig. 5-12 (Continued)

that differ from those of the components (Fig. 5-10). Compounding certain plastics can produce synergistic results, enhancing properties (Fig. 5-16). With the right knowledge, designers can create their own alloys.

With metals you may have to vary a structure to do a job and get strength where you want it; with plastics you can produce a composite to meet performance requirements.

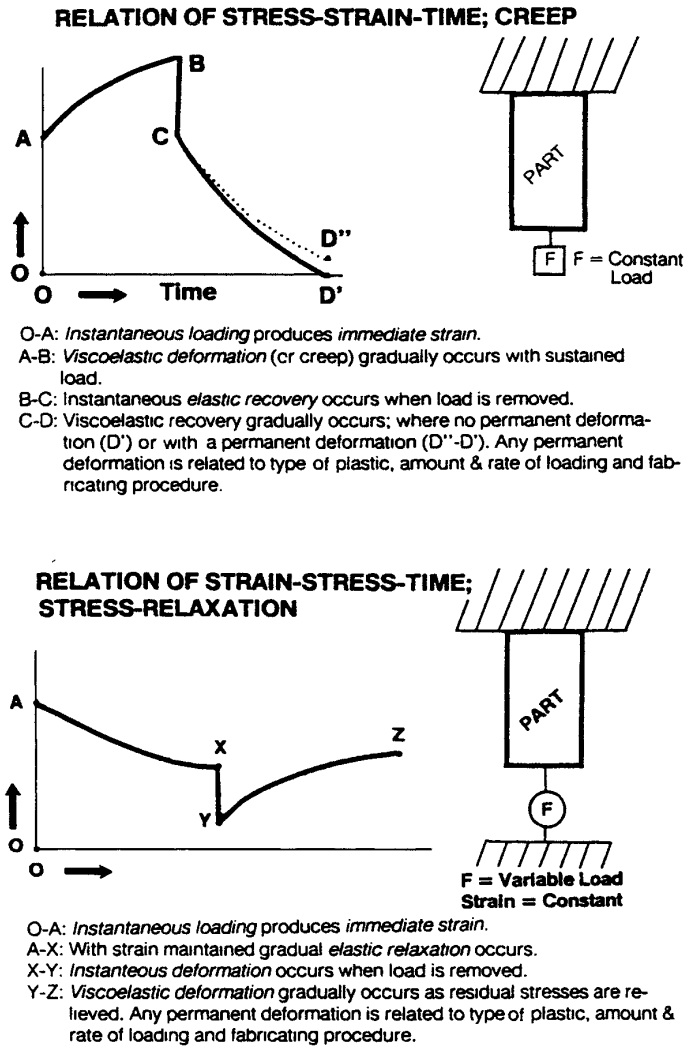


**Fig. 5-13** Viscoelastic behavior. The viscoelastic nature of plastics has made them extremely useful for the past century.

Although the designer can use conventional plastics that are available in sheet form, I-beams, etc., as is done with steel and most other materials, this approach is rarely used with plastics, since their real advantage lies in their processability. Thus, the designer must be familiar with the techniques used in processing plastics. Another important advantage, then, is the ability to design complex shapes with plastic. Unlike the case of most

other materials, it is possible to combine two or more individual plastic parts into one integrated processed part. Parts can include mechanical connections, living hinges, color, etc.

All plastics, like other materials, can be destroyed by hot enough fires. Some burn readily, others slowly, others with difficulty, whereas still others do not support combustion upon removal of the flame. Certain plastics are used to resist the reentry [2,500°F

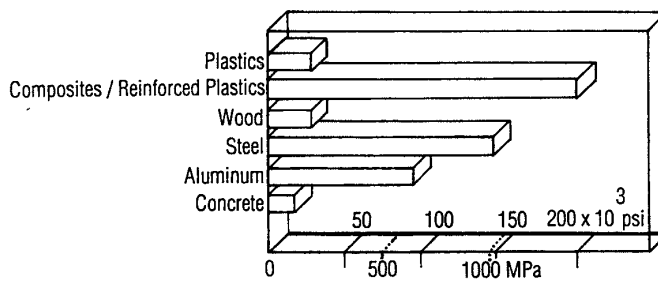
(1,371°C)] heat that occurs when outer space vehicles return into the earth's atmosphere. Different industry standard codes can be used to rate plastics at various degrees of combustibility. Behavior in fire depends on the nature and scale of the fire, as well as the surrounding conditions. Fire is a highly complex, variable phenomenon; designing for this environment requires an understanding of all variables, so that the proper plastic is used.

### Behavior of Plastics

A representative cross section of the myriad of plastics available to designers is described in Chap. 6. This section is intended to acquaint the designer with the structural behavior of plastics. It provides concepts as background for estimating and anticipating behavior in actual design situations. Obviously, there are no universal methods to describe the behavior of all plastics, just as there

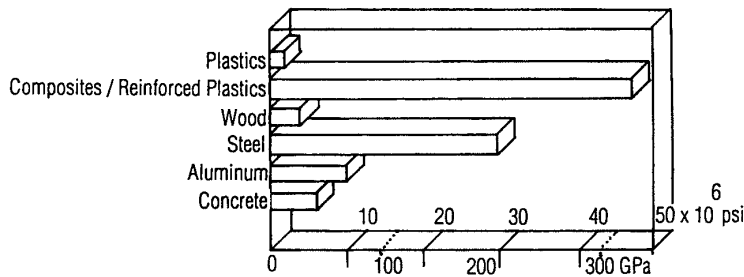
(a)

### Strength



(b)

### Modulus of Elasticity



(c)

### Specific Gravity

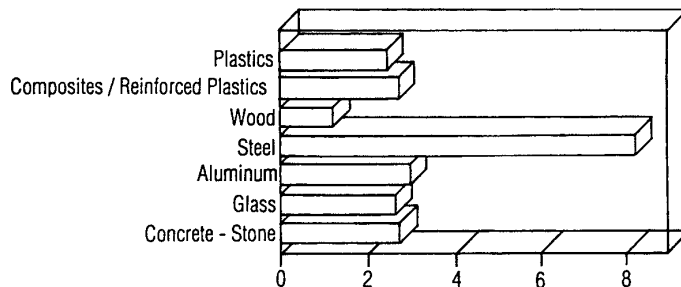
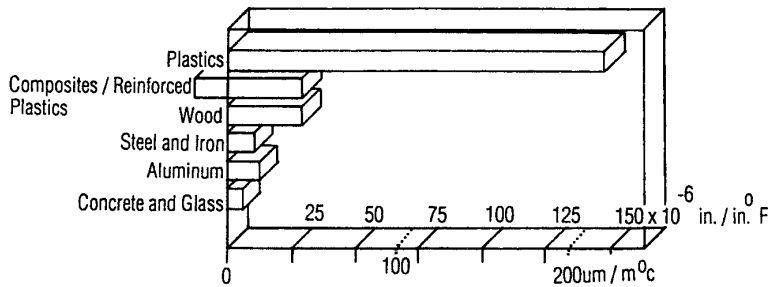
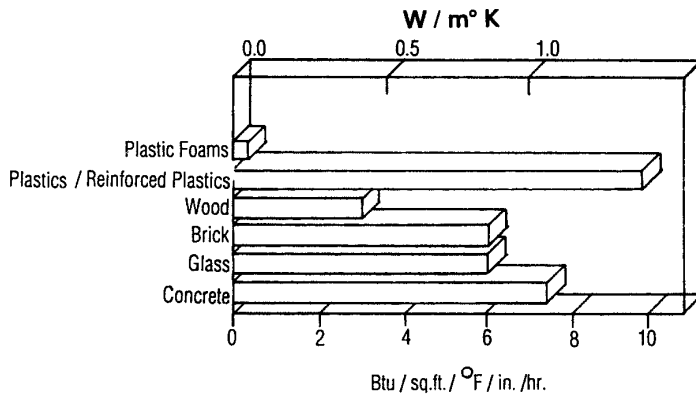


**Fig. 5-14** General comparison of different materials.

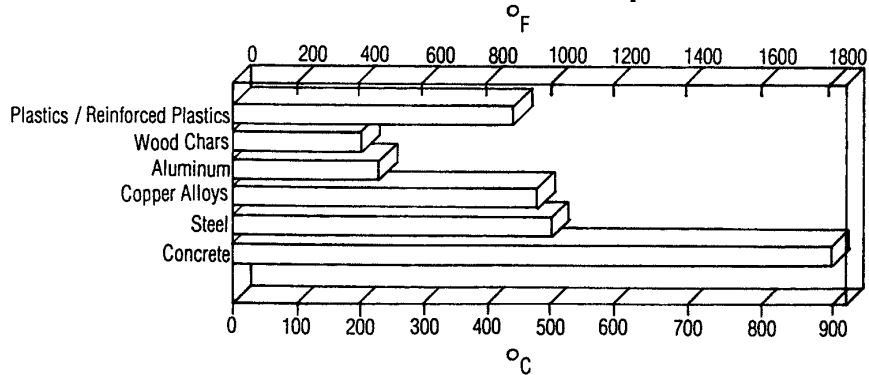
(d)

**Thermal Expansion**

(e)

**Thermal Conductivity**

(f)

**Maximum Continuous Service Temperature****Fig. 5-14 (Continued)**

is no single reference that covers completely the behavior of all metals and their alloys. Nonetheless, all plastics show many similarities in behavior. The differences are frequently in terms of magnitude, not of kind (18).

The stress-strain and strength behavior of plastics varies widely, depending on the generic type, or family, of plastic and the specific composition of compounds within that family. Many factors interact to alter the behavior of a given compound over a very wide

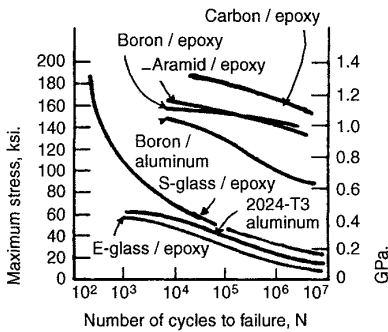


**Fig. 5-15** Fatigue behavior of different unidirectional reinforced plastics and aluminum.

range. Key parameters that must be considered in the structural design of plastics are:

1. *Magnitude and duration of stress, strain, and temperature.* At a given temperature, both the magnitude and duration of stress or strain affect structural response and strength behavior. Conversely, at a given magnitude and duration of stress or strain, a shift in temperature can produce marked changes in structural response and strength behavior.

2. *Environment.* The environment interacts with the magnitude and duration of stress, strain, and temperature to further alter material response and strength of plastics. The chemical environments' permeability, ultraviolet (UV) radiation, sustained elevated

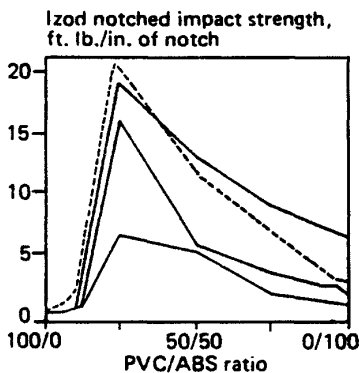


**Fig. 5-16** Synergistic gains can occur when alloying certain plastics.

**Table 5-5** Examples of materials for the designer

*Metals: Basic*

Aluminum, magnesium, beryllium, titanium, copper, nickel, gold, iron, etc.

*Metals: Alloys*

Steel, brass, and all metals that are not basic metals.

*Nonmetals: Ceramics*

Aluminas, beryllias, carbides, cordierites, nitrides, titanias, steatites, zirconias, etc.

*Nonmetals: Glasses*

Silicas, soda limes, leads, borosilicates, aluminosilicates, etc.

*Nonmetals: Others*

Fluids, greases, lubricants, oils, papers, etc.

*Nonmetals: Plastics*

*Thermoplastics<sup>a</sup>:* ABS, acetates, acrylics, cellulose, chlorinated polyethers, fluorocarbons, nylons (polyamides), polycarbonates, polyethylenes (low density, high density, etc.), polypropylenes, polyimides, polyphenylene oxides, polystyrenes, polysulfones, polyurethanes, polyvinyl chlorids, etc.

*Thermosets:* Alkyds, diallyl phthalates, epoxies, melamines, phenolics, polyesters, polyurethanes, silicones, etc.

<sup>a</sup> In addition to the many different types of plastics (or polymers) that are made up of only a single plastic (or homopolymer), there are many different combinations of plastics that provide many different cost-to-performance advantages. A major example is ABS (acrylonitrile-butadiene-styrene).

temperature, and even water, for example, can have a profound influence on performance and hence may dominate the design problem. Environmental effects, or the failure to properly design for them as they interact with sustained stress or strain, have been a chief cause of failure of plastics products.

3. *Additives and modifiers.* Fillers and plasticizers alter the basic response and strength of plastic materials. Particulate fillers (e.g., wood flour, flake, clay, limestone, etc.) are introduced to reduce resin shrinkage, increase stiffness, improve processing characteristics, or to lower cost. Most fillers also lower impact resistance. Plasticizers increase flexibility and toughness; impact modifiers such as rubber blends are more permanent





**Table 5-7** Properties of high performance fibers in reinforced plastics

| Fiber    | Density<br>(lb/in. <sup>3</sup> ) | Tensile<br>Strength<br>(10 <sup>3</sup> psi) | Strength<br>Specific<br>(10 <sup>6</sup> in.) | Tensile<br>Modulus<br>(10 <sup>6</sup> psi) | Specific<br>Modulus<br>(10 <sup>6</sup> in.) |
|----------|-----------------------------------|----------------------------------------------|-----------------------------------------------|---------------------------------------------|----------------------------------------------|
| Glass    | 0.092                             | 500                                          | 5.43                                          | 10.5                                        | 1.14                                         |
|          | 0.090                             | 665                                          | 7.39                                          | 12.4                                        | 1.38                                         |
| Boron    | 0.095                             | 450                                          | 4.74                                          | 58                                          | 6.11                                         |
|          | 0.065                             | 400                                          | 6.15                                          | 38                                          | 5.85                                         |
| Graphite | 0.070                             | 300                                          | 4.29                                          | 55                                          | 7.86                                         |
|          | 0.063                             | 360                                          | 5.71                                          | 27                                          | 4.29                                         |
| Aramid   | 0.052                             | 400                                          | 7.69                                          | 18                                          | 3.46                                         |

and improve toughness without significantly sacrificing stiffness. Thus, the properties of a basic generic plastic, such as PVC, can be varied to provide either rigid sewer pipe or flexible rubberlike water stops and liners.

4. *Reinforcement.* Stiff strong fibers and flakes incorporated into plastics improve stiffness, strength, and dimensional stability. An increase in their proportion relative to the resin matrix results in a corresponding improvement in these properties.

5. *Process.* The mold process used to convert plastic materials into structures may dictate the structural performance of the finished product, as illustrated by the following:

(a) Orientation of the molecular structure of thermoplastics may strengthen the product in the direction of orientation. Such preferential orientation can be used to advantage. The designer, however, must be on guard to ensure that orientation does not prove to be the cause of failure. For example, flow patterns and knit and weld lines developed during molding can cause orientation that creates zones of weakness.

(b) Oxidation and crystallization induced during processing can embrittle an otherwise ductile material. Polyethylene, for example, held too long at high temperatures may either oxidize in the air or develop excessive crystallization.

6. *Similarities with conventional materials.* The plastics behavior introduced here is not necessarily any more complicated than that of conventional structural materials. Overall, the engineer must design both plastics and conventional materials to meet the criteria

of time, temperature, and environment. The similarities are as follows:

(a) *Time.* In designing with conventional materials (steel, aluminum, glass, wood, and concrete), the effects of load duration are recognized in terms of creep and ultimate strength. Time effects are frequently more prominent in plastics, particularly in terms of strength.

(b) *Temperature.* In designing with steel and glass, brittleness at low temperatures and loss of yield strength at high temperatures must be considered. Similarly, in designing with plastics, both stress-strain behavior and strength can vary with temperature, and the low and high temperature limits of certain plastics are frequently in the range of the normal outdoor environmental limits.

(c) *Environment.* The strength, stiffness, dimensional stability, and useful life of wood are a strong function of moisture content. Steel rusts, glass cracks, aluminum corrodes, etc. The problem is similar for plastics, but because composition can vary widely, each plastic compound must be considered for its strengths and weaknesses on exposure to various environments.

Although the above similarities exist, there are significant differences between designing with plastics and with conventional materials. Stringent specifications define the characteristics, and formal detailed rules define design procedures for a limited number of aluminum, steel, and glass compounds and a broad range of timber species. Concrete and steel quality are checked by fairly simple tests; wood quality is assessed visually in

accordance with long established “grading” rules. Working rules of thumb, which may be highly empirical, have evolved from both experience in the field and research using these materials of construction.

Design criteria for plastics are generally not established in standard specifications. Myriad different materials and variations are available. Only a relatively few compounds drawn from several generic classes of plastics have been characterized structurally for sustained loads (7).

### Thermal Stresses

If a plastic part is free to expand and contract, its thermal-expansion property will

usually be of little significance. However, if it is attached to another material, one having a lower coefficient of linear thermal expansion (CLTE), then the movement of the part will be restricted. A temperature change will then result in developing thermal stresses in the part. The magnitude of these stresses will depend on the temperature change, method of attachment and relative expansion, and modulus characteristics of the two materials at the point of the exposed heat.

For instance, a 304.8-cm (120-in.)-long extruded TP with a high CLTE is securely fastened to a heavy steel member. It is subjected to a 43.33°C (78.11°F) temperature change, from 21.11°C (70°F) to -22.22°C (-48°F).

|       | CLTE<br>(cm/cm/°C)    |   | Temperature<br>Change (°C) |   | Length<br>(cm) |   | Contraction<br>(cm) |
|-------|-----------------------|---|----------------------------|---|----------------|---|---------------------|
| Steel | $1.6 \times 10^{-5}$  | × | 43.33                      | × | 304.8          | = | 0.21131             |
| TP    | $15.2 \times 10^{-5}$ | × | 43.33                      | × | 304.8          | = | 2.00746             |

Comparing the contraction for the two materials shows that the TP part will contract about ten times as much as the steel. Because of the higher-modulus steel, the contraction of the TP will be restrained

and thermal stresses will occur. The level of stress developed in the TP will be determined basically by its coefficient of expansion and the modulus of elasticity as follows:

| CLTE<br>TP Steel                           |   | Temperature<br>Change (°C) |   | Modulus<br>at -40°F<br>for TP (kPa) |   | Stress Developed      |
|--------------------------------------------|---|----------------------------|---|-------------------------------------|---|-----------------------|
| $15.2 \times 10^{-5} - 1.6 \times 10^{-5}$ | × | 43.33                      | × | $19.3 \times 10^5$                  | = | 11.38 MPa (1.653 psi) |

In this example, although the level of stress produced is below the yield stress of the TP, the presence of stress increasers can lead to failure of the product. Stress raisers can magnify the effect of thermally induced stress at the point at which the TP’s tensile strength will be exceeded, which will be followed by part failure. Stress raisers may exist in the form of sharply reduced section thicknesses, notches from poor trimming operations, or fastener holes.

### Viscoelastic Behavior

The relationship between stress and strain, or structural response, of plastics varies from viscous to elastic (Fig. 5-13). Most plastics display a structural response that is intermediate between the viscous and elastic states. They are viscoelastic materials. The type of plastic compound, stress, strain, time, temperature, and environment all play a significant role in determining whether the response is mostly viscous, elastic, or viscoelastic.

Viscoelasticity is a complex subject that is covered in Chap. 6. Rigorous approaches are not usually needed in practical structural design; hence, simple models and analogies are used below to demonstrate viscoelastic behavior. The terminology used here to characterize the viscoelastic behavior of plastics, including the idealized components of viscoelastic models, is given below:

1. *Elastic response.* Represented by a Hookean solid, as modeled by a linear spring. Stress is proportional to strain and independent of time; the response to stress is instantaneous; there is no permanent or irrecoverable deformation; all energy used to deform the spring is stored and fully recoverable.

2. *Viscous response.* Represented by a Newtonian fluid, as modeled by a dashpot. Stress is proportional to strain rate, making behavior time dependent. Recovery is nil when stress is removed. Energy to deform the dashpot is dissipated completely during the deformation process.

3. *Creep.* The time-dependent increase in the strain of a viscous or viscoelastic material under sustained stress. Some of the time-dependent deformation is recoverable with time after the release of stress. Creep experiments are usually performed under constant load conditions, and when stresses are high, the sample may “neck” and the cross section supporting the load may be reduced significantly at some point during the test. Unless otherwise indicated, the creep stress based on original cross-sectional area (“engineering” stress) will be used rather than the “true” creep stress, based on the reduced cross-sectional area, that occurs on necking. This reflects typical practice, which is to report engineering rather than true creep stress in creep experiments, but this practice is not universal, particularly in scientific behavioral investigations.

4. *Relaxation.* The time-dependent decay in the stress of a viscoelastic material under sustained strain. Some of the deformation is recoverable with time after release of the sustained strain. Unless the imposed initial strain is above the yield point, the cross section remains fairly close to the original throughout

the test. This differs from creep behavior as noted above.

5. *Recovery.* The extent to which an element returns to its original configuration after the release of stress or strain.

6. *Linear viscoelastic response.* The viscoelastic response in which stress and strain are related by a single modulus that depends only on the duration of the applied stress and strain for a given temperature. This differs from a nonlinear viscoelastic response in which the modulus depends on the magnitude and duration of stress or strain.

Viscoelastic stiffness response traditionally has been expressed in terms that relate to the manner of loading. That is, the time-dependent apparent modulus, or ratio of the (decaying) *stress* to the (constant) *strain* imposed during relaxation experiments, is termed the “relaxation modulus”  $E(t)$ . If the test is performed in creep, the “creep compliance,” or ratio of (increasing) *strain* to applied *stress*  $D(t)$ , is used to define response. This notation is extremely useful in the study of nonlinear viscoelastic behavior that occurs at the stresses and temperatures above the range of interest in structural engineering.

It can be shown that for small strains at temperatures in the useful range,  $E(t) \approx i/D(t)$ . Thus, providing the range over which this assumption can be made is known, a single modulus can be used to describe the time-dependent stiffness response under both creep and relaxation loading conditions.

A term “viscoelastic modulus”  $E_v$  defines the ratio between stress and strain after any duration of stress or strain. This ratio is frequently referred to as the “apparent modulus.” The viscoelastic modulus terminology, however, appears to be a more descriptive and appropriate companion to the term “elastic modulus,” which is well known to the structural designer. The approach taken by some designers is to establish conditions over which  $E_v \approx E(t) \approx 1/D(t)$ , for practical purposes; in essence, this establishes the linear viscoelastic range.

Whether or not behavior is in the linear or nonlinear viscoelastic range decides whether or not behavior can be modeled by simple adaptations of conventional, readily

available analysis methods based on elastic theory.

Linear viscoelasticity means that deformation is a function of time, and time only, under a given magnitude of sustained stress (creep). Alternately, stress is uniquely a function of time under sustained strain (relaxation). In both instances, the temperature is assumed to be constant. In essence, the assumptions of linear viscoelasticity are similar to those of Hooke's law (stress is proportional to strain, or vice versa) except that time dependence is also involved.

By contrast, in nonlinear viscoelastic behavior the relation between stress and strain (modulus) at a given time depends on the magnitude of the applied stress or strain. The complications introduced by such non-linear stress-strain behavior should be obvious.

Viscoelastic behavior for real plastics becomes increasingly nonlinear under high stress or strain level. Stresses or strains approaching yield or failure levels produce nonlinear viscoelastic response. Most plastics display nonlinear viscoelastic behavior even at low stress levels, but viscoelastic behavior may be assumed to be linear within certain limits.

### Molding Tolerances

Molding tolerance is a specified allowance on the deviation in parameters such as dimensions, weights, shapes or angles, compounding mixtures, etc. at standard or stated environmental conditions. To maximize control in setting tolerances, there is usually a minimum and maximum limit on thickness, based on the process to be used. Each resin has its own range that depends on its chemical structure and melt-processing characteristics (Fig. 5-17). Outside these ranges, melts are usually uncontrollable. Any dimensions and tolerances are theoretically possible, but they could result in requiring special processing equipment, which usually becomes expensive. There are, of course, products that require and use special equipment.

One factor in tolerances is shrinkage. Generally, shrinkage is the difference between the

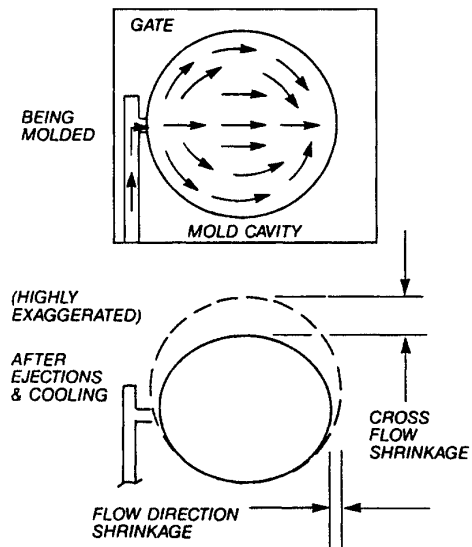


**Fig. 5-17** Example of directional shrinkage in an injection molding that can be related to the isotropic performance of plastics during processing.

dimensions of a fabricated part at room temperature and the cooled part, checked usually 12 to 24 h after fabrication. Having an elapsed time is necessary for many plastics, particularly the commodity TPs, to allow parts to complete their inherent shrinkage behavior. The extent of this postshrinkage can be near zero for certain plastics or may vary considerably. Shrinkage can also be dependent on such climatic conditions as temperature and humidity, under which the part will exist in service, as well as its conditions of storage (Fig. 5-18).

The cycle time for injection molded articles varies, depending on the part thickness, size, plastic material, configuration, and operation of the mold. Although cycle times have varied from as short as a few seconds to as long as 5 min for extremely thick parts, the average cycle generally will fall between 20 and 60 sec for a well-designed injection mold with the proper temperature control system. (See Fig. 5-19.)

Plastic suppliers can provide the initial information on shrinkage that has to be added to the design shape and will influence its processing. The shrinkage and post-shrinkage will depend on the types of plastic and fillers.

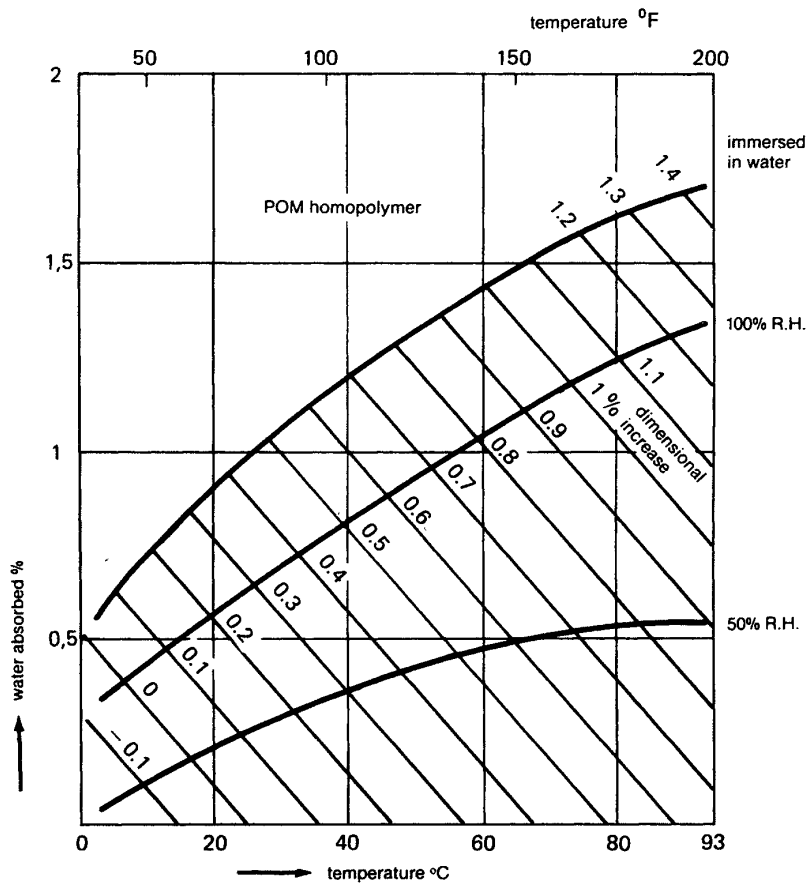


Fig. 5-18 Dimensional change of acetal plastic as a function of temperature and moisture absorption.

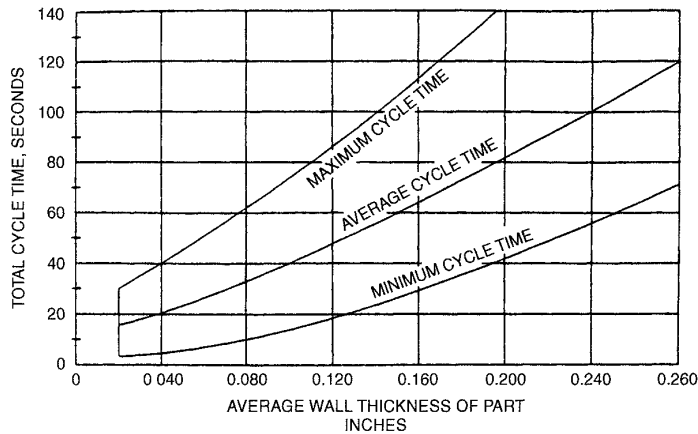


Fig. 5-19 Chart showing approximate cycle time as a function of part wall thickness.

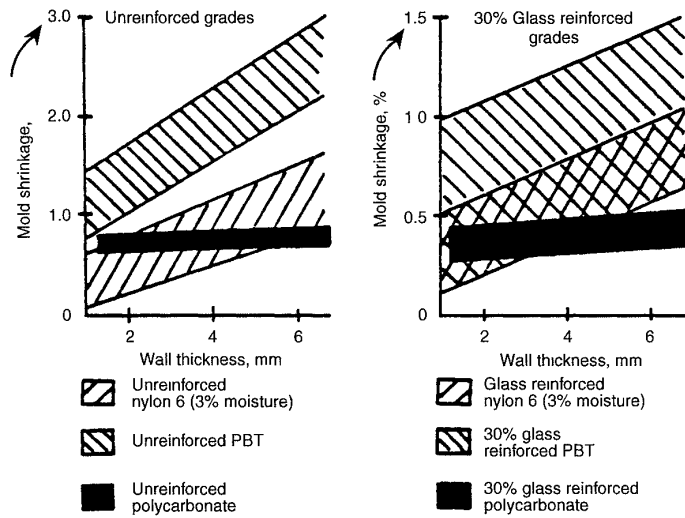


Fig. 5-20 How wall thickness affects shrinkage.

Compared to TPs, TSs generally have more filler. The type and amount of filler, such as its reinforcement, can significantly reduce shrinkage and tolerances (see Figs. 5-20 and 5-21).

Like metals, plastics generally expand when heated and contract when cooled. Usually, for a given temperature change TPs change more than metals. The coefficient of linear thermal expansion (CLTE) is the ratio

between the change of a linear dimension to the original dimension of the material per unit change in temperature (per ASTM standards). It is generally given as  $\text{cm}/\text{cm}/^{\circ}\text{C}$  or  $\text{in.}/\text{in.}/^{\circ}\text{F}$  (Table 5-8 and Fig. 5-22). Figure 5-22 provides information on contraction at low temperatures.

Because this CLTE value usually has to be determined at the part's operating temperature to specify a plastic that will do the

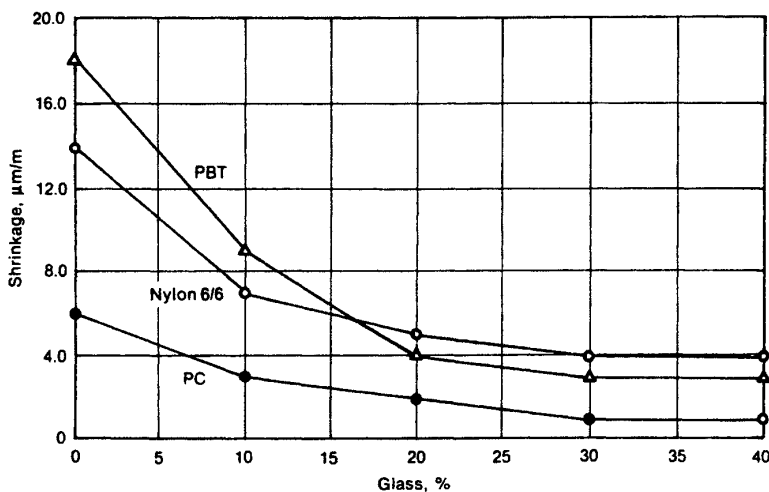


Fig. 5-21 How glass reinforcement affects shrinkage.

**Table 5-8** Coefficients of linear thermal expansion (CLTEs) for plastics and other materials<sup>a</sup>

| Material          | in./in. °F × 10 <sup>-5</sup><br>(cm/cm °C × 10 <sup>-5</sup> ) |         |
|-------------------|-----------------------------------------------------------------|---------|
| Fused quartz      | 0.02                                                            | (0.036) |
| Liquid crystal-GR | 0.3                                                             | (0.54)  |
| TS polyester-GR   | 0.3                                                             | (0.54)  |
| Phenolic-GR       | 0.4                                                             | (0.72)  |
| Silicone-GR       | 0.4                                                             | (0.72)  |
| Pine wood         | 0.4                                                             | (0.72)  |
| Glass             | 0.4                                                             | (0.72)  |
| DAP-GR            | 0.5                                                             | (0.9)   |
| Epoxy-GR          | 0.6                                                             | (1.08)  |
| Nylon-GR          | 0.6                                                             | (1.08)  |
| Steel             | 0.6                                                             | (1.08)  |
| Concrete          | 0.8                                                             | (1.44)  |
| Copper            | 0.9                                                             | (1.62)  |
| Bronze            | 1.0                                                             | (1.8)   |
| Brass             | 1.0                                                             | (1.8)   |
| PPO-GR            | 1.2                                                             | (2.2)   |
| Aluminum          | 1.2                                                             | (2.2)   |
| PC-GR             | 1.3                                                             | (2.3)   |
| TP polyester      | 1.3                                                             | (2.3)   |
| Polyimide         | 1.3                                                             | (2.3)   |
| Magnesium         | 1.4                                                             | (2.5)   |
| ABS-GR            | 1.6                                                             | (2.9)   |
| Zinc              | 1.7                                                             | (3.1)   |
| PS/PI             | 1.8                                                             | (3.2)   |
| PP-GR             | 1.8                                                             | (3.2)   |
| PPS-GR            | 2.0                                                             | (3.6)   |
| Acetal-GR         | 2.2                                                             | (4.0)   |
| Zinc              | 2.2                                                             | (4.0)   |
| PVC/rigid         | 2.7                                                             | (4.9)   |
| Acrylic           | 2.8                                                             | (5.0)   |
| TS polyester      | 3.0                                                             | (5.4)   |
| Polysulfone       | 3.0                                                             | (5.4)   |
| Epoxy             | 3.0                                                             | (5.4)   |
| Polycarbonate     | 3.6                                                             | (6.5)   |
| Phenolic          | 3.8                                                             | (6.8)   |
| ABS               | 4.0                                                             | (7.2)   |
| Nylon             | 4.5                                                             | (8.1)   |
| Acetal            | 4.8                                                             | (8.6)   |
| Polypropylene     | 4.8                                                             | (8.6)   |
| TP polyurethane   | 5.6                                                             | (10.1)  |
| Polyethylene/LD   | 5.6                                                             | (10.1)  |
| Fluorocarbon      | 5.6                                                             | (10.1)  |
| Epoxy             | 6.0                                                             | (10.8)  |
| Polyethylene/HD   | 6.1                                                             | (11.0)  |
| TPX               | 6.5                                                             | (11.7)  |
| TP polyester      | 6.9                                                             | (12.4)  |

<sup>a</sup> These are only typical values to account for many different grades, molding conditions, product shapes, wall thicknesses, and other variants. The plastics presented are basically unfilled or reinforced. GR refers to glass-fiber-reinforced compounds that usually have 10 to 40%, by weight, reinforcement. Other reinforcements, particularly graphite, and different fillers can result in significantly different CLTEs. CLTEs on specific plastics or compounds are available from material suppliers. Those data or your derived data can then be applied to the design.

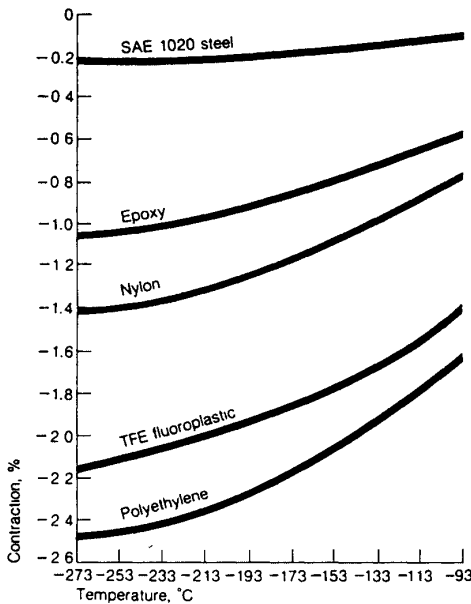


**Fig. 5-22** Example of low temperature thermal contraction in unfilled TPs. With filled and particularly certain reinforced TSs, dimensional change is significantly reduced with some having no contraction.

job. It is important to include in the design specifications the operating temperature conditions. All the extremes in CLTEs can be provided by plastics, including graphite-filled compounds that could work in reverse. Upon heating, they contract rather than expand, and vice versa.

The CLTE is an important consideration if dissimilar materials such as one plastic to another or a plastic to metal and so forth are to be assembled. The CLTE is influenced by the type of plastic (liquid crystal, amorphous, etc.) and composite, particularly the glass-fiber content and its orientation. It is especially important if the temperature range includes a thermal transition such as  $T_g$ . Normally, all this activity with dimensional changes is available from material suppliers readily enough to let the designer apply a logical approach and understand what could happen.

The design of products has to take into account the dimensional changes that can occur

during fabrication (see Chaps. 3 to 7) and its useful service life. With a mismatched CLTE, there could be destruction of plastics from factors such as cracking or buckling.

Expansion and contraction can be controlled in plastic by its orientation, cross-linking, adding fillers or reinforcements, etc. With certain additives, the CLTE value could be zero or near zero. For example, plastic with a graphite filler contracts rather than expands during a temperature rise (see Fig. 5-14, "Thermal Expansion"). As shown in Table 5-8, composites with only glass-fiber reinforcement can be used to match those of metal and other materials. In fact, TSs are especially compounded to have little or no change (Fig. 5-22).

In a TS, the ease or difficulty of thermal expansion is dictated for the most part by the degree of cross-linking, as well as the overall stiffness of the units between the cross-links. The less flexible units are also more resistant to thermal expansion. Such influences as secondary bonds have much less effect on the thermal expansion of TSs.

Any cross-linking has a substantial effect on TPs. With the amorphous type, expansion is reduced. In a crystalline TP, however, the decreased expansion as a result of cross-linking may be partially offset by a loss of crystallinity.

### *Tolerances and Designs*

Computer programs developed since the 1980s have continued to make possible the modeling of complex interactions of the many processing factors. These include plastic properties and behaviors, geometry of the part, toolmaking quality applied to manufacturing dies or molds, and the processing conditions and fluctuations inherent in the equipment and materials (see Chap. 9, Computer Capabilities for Part and Mold Design).

### *Tolerance Allowances*

Tolerance allowances are basically an intentional difference between material limits of mating parts. It is the minimum clearance

(positive allowance) or maximum interference (negative allowance) between such parts.

### *Tolerances and Shrinkages*

Two different forms of product shrinkage must be considered when designing to meet tolerances: the initial shrinkage that occurs while a part is cooling after fabrication, called the mold or tool shrinkage, and that which occurs after as many as 24 hours, called the after-shrinkage or after-swell. Some plastics are extremely stable and others are very close to being stable so that once cooled, dimensions (and other factors) do not change. However, many plastics shrink and do not influence performance of the parts when in service.

In many cases low shrinkage may indicate more stability of the plastic part. Large, unpredictable shrinkages can make close tolerance designing almost impossible. However, in such situations, one can use a material where the shrinkage is controllable; there are many of these plastics in use. Various kinds of compounds with their additives and fillers are available from which to choose (consider graphite powder additive). If a part has to be postcured or annealed to relieve internal stresses, allowance must be made if the material shrinks during this secondary operation (Chap. 4, Mold Shrinkages and Tolerances; Chap. 8, Tolerances and Shrinkages; and Chap. 9, Tolerances and Dimensional Controls).

The transition from room temperature to a high processing temperature may decrease a plastic's density by up to 25%. Cooling causes possible volume shrinkage of up to 3% and may cause surface distortions or voiding with internal frozen strains. As discussed in other sections of this book, this situation can be eliminated or reduced by choosing another material and/or a process control such as cooling under pressure.

### *Tolerances and Warpages*

A fabricated part that warps is usually caused by the shrinkage behavior of plas-

tic, which may be characteristic of the plastic but more probably a result of the way it was processed. Corrective action can be taken by controlling the fabricating process to eliminate or (if permitted) almost eliminate the warpage, which in turn permits meeting tolerance requirements.

### *Thin-Wall Tolerances*

In the past, such as just over a decade ago, thin-wall molding meant 2.5 mm with a tight tolerance of about 0.002 in./in. Now it means 0.5 mm wall thickness with a 10 micron tolerance. Processing thin-wall products is reviewed in Chap. 7 (Molding Thin Walls) (18, 82, 137, 376, 487, 569).

### *Micron Tolerances*

Some injection molding parts are in micron sizes. To meet their specialty miniaturization market requirements, some parts have total weight of 0.0022 g and have to meet very tight shrinkage requirements (Chap. 15, Micro Injection Molding).

### *Tolerance Damage*

Tolerance damage is the design measure of crack growth rate. Cracks in damage-tolerant designed structures are not permitted to grow to critical size during their expected lifetime (18).

### *Full Indicator Movements (FIMs)*

FIM is a term used to identify tolerance with respect to concentricity. Terms used in the past were full indicator reading (FIR) and total indicator reading (TIR).

### *Tolerance Selection*

Tolerance selection is not a random process; rather, it requires careful judgement based on logical calculations and an understanding of factors such as material behavior, processing capabilities, quality control,

and cost influence. As a general rule, tolerance should be as large as possible because it can simplify the fabricating process. However, tighter tolerances usually result in significant cost reduction particularly for high production quantities (resin reduction, energy reduction, etc.).

### *Tolerance Stack-Ups*

An accumulation, or *stack-up*, of tolerances can cause an inoperable or malfunctioning assembly.

### *Standard Tolerances*

Tables on standard tolerances (see Tables 5-9 and 5-10) have been prepared by the Custom Molders of the Society of Plastics Industry (SPI). These tables (and others prepared by SPI) are to be used only as a guide. The dimensions are based on a hypothetical molded article, whose cross section is explained by the adjoining text. The text only pertains to specific low density polyethylene and glass-reinforced alkyd/polyester (TS).

Guidelines are available from different organizations, for instance the Standards and Practices of Plastics Molders from SPI. These are periodically updated. SPI provides guides that can be used for wall thicknesses, holes, flatness, thread size, corners, ribs, fillets, thread sizes, concentricity, draft allowances, surface finish, and color stability.

*Molding shrinkage of products* When a plastic material is heated, it expands. Upon cooling to its original temperature, it will contract to the original volume, neglecting the effects of crystallinity, but this is not the only parameter. During injection molding an additional factor, pressure, is introduced. The material basically follows the equation of state: Pressure times volume equals the gas constant times the absolute temperature,  $PV = RT$ . Mold shrinkage should not be confused with tolerance; tolerance is the variation in mold shrinkage rather than the shrinkage itself.

During injection molding, the following things happen: The hot material is injected into the cold cavity, initially under low pressure. Cooling starts immediately, as the parts in contact with the wall solidify. Because the specific volume (the volume of a unit weight of plastic) decreases with the temperature, the solid will occupy less room than the molten polymer. The material fills the cavity, and the pressure builds up rapidly. The pressure does two things: It adds more material to the cavity to make up for the decrease in volume of the material that is already solidified, and it adds more material to compensate for the decrease in volume that will occur when the rest of the material solidifies. If not enough material is put in, there will be excess shrinkage. If too much material is put in, there will be a highly stressed area at the gate. This process of material addition is called packing. The correct amount of material is found by trial and error. The effect of the machine pressure ceases when the injection pressure is stopped or the gate seals. A second, lower injection pressure is used until the machine is opened.

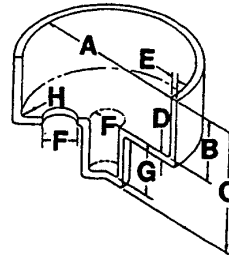
Overstressing of the gate section of an opaque part is impossible to detect during molding, yet highly stressed parts are much more likely to fail than less stressed parts. Thus, one of the drawbacks of molding is that quality cannot be immediately determined. This constraint also exemplifies why economic conditions should not force improper molding.

To decrease shrinkage, the molder should reduce wall thickness, increase injection pressure and injection forward time, increase injection speed, increase the overall cycle, raise the material temperature slightly, lower the mold temperature, decrease the molecular weight distribution, and usually increase the gate size.

*Mold dimensioning* The dimensions of the part design have to be converted into those of the mold, taking the respective shrinkage into consideration. For that reason, the final decision on what kind of plastic material will be used has to be made beforehand. Very often, the moldmaker requires half the

**Table 5-9** Standard tolerance chart for a LDPE

| Drawing Code                               | Dimensions (Inches)                                         | Plus or Minus in Thousands of an Inch |        |    |    |    |
|--------------------------------------------|-------------------------------------------------------------|---------------------------------------|--------|----|----|----|
|                                            |                                                             | 5                                     | 10     | 15 | 20 | 25 |
| A = Diameter<br>(See note #1)              | 0.000                                                       |                                       |        |    |    |    |
|                                            | 0.500                                                       |                                       |        |    |    |    |
|                                            | 1.000                                                       |                                       |        |    |    |    |
|                                            | 2.000                                                       |                                       |        |    |    |    |
|                                            | 3.000                                                       |                                       |        |    |    |    |
|                                            | 4.000                                                       |                                       |        |    |    |    |
| B = Depth<br>(See note #3)                 | 5.000                                                       |                                       |        |    |    |    |
|                                            | 6.000                                                       |                                       |        |    |    |    |
|                                            | 6.000 to 12.000<br>for each additional<br>inch add (inches) | Comm. ±                               | Fine ± |    |    |    |
| D = Bottom Wall                            | (See note #3)                                               | 0.006                                 | 0.003  |    |    |    |
| E = Core Wall                              | (See note #4)                                               | 0.005                                 | 0.003  |    |    |    |
| F = Hole Size<br>Diameter<br>(See note #1) | 0.000 to 0.125                                              | 0.004                                 | 0.002  |    |    |    |
|                                            | 0.126 to 0.250                                              | 0.005                                 | 0.003  |    |    |    |
|                                            | 0.251 to 0.500                                              | 0.006                                 | 0.004  |    |    |    |
|                                            | 0.501 & over                                                | 0.007                                 | 0.005  |    |    |    |
| G = Hole Size<br>Depth<br>(See note #5)    | 0.000 to 0.250                                              | 0.004                                 | 0.003  |    |    |    |
|                                            | 0.251 to 0.500                                              | 0.005                                 | 0.004  |    |    |    |
|                                            | 0.501 to 1.000                                              | 0.007                                 | 0.005  |    |    |    |
| H = Corners,<br>Ribs, Fillets              | (See note #6)                                               | 0.025                                 | 0.011  |    |    |    |
| Flatness<br>(See note #4)                  | 0.000 to 3.000                                              | 0.025                                 | 0.012  |    |    |    |
|                                            | 3.001 to 6.000                                              | 0.030                                 | 0.020  |    |    |    |
| Thread Size<br>(Class)                     | Internal                                                    | 1                                     | 2      |    |    |    |
|                                            | External                                                    | 1                                     | 2      |    |    |    |
| Concentricity                              | (See note #4) (F.I.M.)                                      | 0.011                                 | 0.007  |    |    |    |
| Draft Allowance<br>Per Side                | (See note #5)                                               | 2.0°                                  | 0.75°  |    |    |    |
| Surface Finish                             | (See note #7)                                               |                                       |        |    |    |    |
| Color Stability                            | (See note #7)                                               |                                       |        |    |    |    |

**REFERENCE NOTES**

1. These tolerances do not include allowance for aging characteristics of material.
2. Tolerances are based on 0.125 inch wall section.
3. Parting line must be taken into consideration.
4. Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is sometimes impossible to achieve. Walls of non-uniform thickness should be gradually blended from thick to thin.
5. Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.
6. These values should be increased whenever compatible with desired design and good molding techniques.
7. Customer-Molder understanding is necessary prior to tooling.

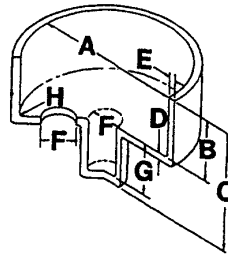
tolerances permissible for the part in question for his or her job. This, in most cases, is not justified. Today's accuracy of metalworking permits tolerances as low as one-tenth of those on a drawing, if we assume the latter are reasonable for plastics. Under difficult circumstances, it has been proved that a good

practice is to keep critical dimensions smaller in the mold first and then revise them after a test run under production conditions.

In any case, close tolerances should be applied on such dimensions only as directly related to invariable mold dimensions. Any other dimension that is related to a mold

**Table 5-10** Standard tolerance chart for an alkyd/polyster (TS) glass fiber compound

| Drawing Code                                                                                       | Dimensions (Inches)                                         | Plus or Minus in Thousands of an Inch |        |    |    |    |
|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------------------------------|--------|----|----|----|
|                                                                                                    |                                                             | 5                                     | 10     | 15 | 20 | 25 |
| A = Diameter<br>(See note #1)<br><br>B = Depth<br>(See note #3)<br><br>C = Height<br>(See note #3) | 0.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 0.500                                                       |                                       |        |    |    |    |
|                                                                                                    | 1.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 2.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 3.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 4.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 5.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 6.000                                                       |                                       |        |    |    |    |
|                                                                                                    | 6.000 to 12.000<br>for each additional<br>inch add (inches) | Comm. ±                               | Fine ± |    |    |    |
|                                                                                                    |                                                             | 0.001                                 | 0.001  |    |    |    |
| D = Bottom Wall                                                                                    | (See note #3)                                               | 0.003                                 | 0.002  |    |    |    |
| E = Side Wall                                                                                      | (See note #4)                                               | 0.001                                 | 0.001  |    |    |    |
| F = Hole Size Diameter                                                                             | 0.000 to 0.125                                              | 0.001                                 | 0.001  |    |    |    |
|                                                                                                    | 0.126 to 0.250                                              | 0.001                                 | 0.001  |    |    |    |
|                                                                                                    | 0.251 to 0.500                                              | 0.002                                 | 0.001  |    |    |    |
|                                                                                                    | 0.501 & over                                                | 0.002                                 | 0.001  |    |    |    |
| G = Hole Size Depth<br>(See note #5)                                                               | 0.000 to 0.250                                              | 0.001                                 | 0.001  |    |    |    |
|                                                                                                    | 0.251 to 0.500                                              | 0.001                                 | 0.001  |    |    |    |
|                                                                                                    | 0.501 to 1.000                                              | 0.002                                 | 0.001  |    |    |    |
| H = Corners, Ribs, Fillets                                                                         | (See note #6)                                               | 0.062                                 | 0.031  |    |    |    |
| Flatness<br>(See note #1)                                                                          | 0.000 to 3.000                                              |                                       |        |    |    |    |
|                                                                                                    | 3.001 to 6.000                                              |                                       |        |    |    |    |
| Thread Size (Class)                                                                                | Internal                                                    | 1                                     | 2      |    |    |    |
|                                                                                                    | External                                                    | 1                                     | 2      |    |    |    |
| Concentricity                                                                                      | (See note #4) (F.I.M.)                                      |                                       |        |    |    |    |
| Draft Allowance Per Side                                                                           | (See note #5)                                               | 1.0°                                  | 0.5°   |    |    |    |
| Surface Finish                                                                                     | (See note #7)                                               |                                       |        |    |    |    |
| Color Stability                                                                                    | (See note #7)                                               |                                       |        |    |    |    |

**REFERENCE NOTES**

1. These tolerances can vary greatly, depending on method of molding and gate location.
2. Tolerances are based on 0.125 inch wall section.
3. Parting line must be taken into consideration.
4. Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is sometimes impossible to achieve. Walls of non-uniform thickness should be gradually blended from thick to thin.
5. Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.
6. These values should be increased whenever compatible with desired design and good molding techniques.
7. Customer-Molder understanding is necessary prior to tooling.

dimension in two different mold parts should allow a generous tolerance (Fig. 5-23).

**Tolerance Measurement and Quenching**

The capacity to measure parts immediately after being molded is of great value in gain-

ing a real-time understanding of the process characteristics. Generally, dimension data are not collected and correlated to the process at the molding machine. This fact is generally related to concerns with part shrinkage.

Shrinkage of the part during measurement can induce large measurement error and reduce measurement reliability. To circumvent

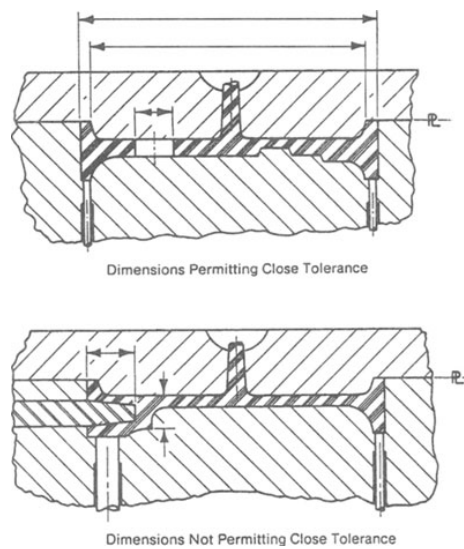


**Fig. 5-23** The design of the product has a definite influence on dimensions and tolerances that can be met.

this problem a water quenching technique, for temporarily arresting shrinkage, can be used. If measurements are taken on hot parts, the parts are shrinking while the measure-

ment is being taken. The capacity to measure parts immediately after they are molded is of great value in gaining an understanding of the process characteristics (18, 283, 333). Another technique is to use cooling fixtures if products tend to warp.

**Dimensional Properties**

It is difficult to obtain from a handbook specific information concerning dimensions for your specific product. This is because many factors influence the end result when fabricating a product. These include the behavior of the material interrelated to the processing controls. Initially trial and error procedures are used. With experience one can almost predict what will happen. Regardless, some materials and processes are definitely capable of providing very close tolerance to the point that the parts are almost perfect. The goal is to follow a processing flow chart whereby one can control the process to meet the tightest (required) tolerance. Table 5-11 provides some helpful parameters to set up such a chart.

**Table 5-11** Parameters that influence product tolerances

|                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Part design        | Part configuration (size and shape). Relate shape to flow of melt in mold to meet performance requirements that should at least include tolerances.                                                                                                                                                                                                                                                                                                                                           |
| Material           | Chemical structure, molecular weight, amount and type of fillers and additives, heat history, storage, handling.                                                                                                                                                                                                                                                                                                                                                                              |
| Mold design        | Number of cavities, layout, and size of cavities, runners, gates, cooling lines, side actions, knockout pins, etc. Relate layout to maximize proper performance of melt and cooling flow patterns to meet part performance requirements; preengineer design to minimize wear and deformation of mold (use proper steels); lay out cooling lines to meet temperature to time-cooling rate of plastics (particularly crystalline types).                                                        |
| Machine capability | Accuracy and repeatability of temperature, time, velocity, and pressure controls of injection unit, accuracy and repeatability of clamping forces, flatness and parallelism of platens, even distribution of clamping on all tie-rods, repeatability of controlling pressure and temperature of oil, oil temperature variation minimized, no oil contamination (by the time you see oil contamination, damage to the hydraulic system could have already occurred), machine properly leveled. |
| Molding cycle      | Set up the complete molding cycle to repeatedly meet performance requirements at the lowest cost by interrelating material, machine, and mold controls.                                                                                                                                                                                                                                                                                                                                       |

### Dimensional Tolerances

The specific dimensions that can be obtained on a molded product basically depend on the performance and control of the plastic material, the fabrication process, and in many cases, properly integrating the materials with the process. In turn, a number of variable characteristics exist with the material itself, as described in Chaps. 6 to 8, 12, and 13. Unfortunately, many designers tend to consider dimensional tolerances on plastic products to be complex, unpredictable, and not susceptible to control. This is simply not true, though they can be complex. Plastics are no different in this respect than other materials. If steel, aluminum, and ceramics were to be made into complex shapes but no prior history on their behavior during processing existed, a period of trial and error would be required to ensure their meeting the required measurements. If relevant processing information or experience did exist, it would be possible for these metallic products to meet the requirements with the first part produced. This same situation exists with plastics. To be successful with this material requires experience with its melt behavior, melt-flow behavior during processing, and the process controls needed to ensure meeting the dimensions that can be achieved in a complete processing operation. Based on the plastic to be used and the equipment available for processing, certain combinations will make it possible to meet extremely tight tolerances, but others will perform with no tight tolerances or any degree of repeatability.

Fortunately, there are many different types of plastics that can provide all kinds of properties, including specific dimensional tolerances. It can thus be said that the real problem lies not with the different plastics or processes, but rather with the designer, who requires knowledge and experience to create products to meet the desired requirements. The designer with no knowledge or experience has to become familiar with the plastic-design concepts expressed throughout this book and work with capable people such as the suppliers of plastic materials.

Certain injection molding parts can be molded to extremely close tolerances of less than a thousandth of an inch, or very close to 0.0%, particularly when TPs are filled with additives or TS compounds are used. To practically eliminate shrinkage and provide a very smooth surface, one should use a small amount of chemical blowing agent (< 0.5% by weight) and regular packing procedure. For conventional molding, tolerances can be met of  $\pm 5\%$  for a part 0.020 in. (0.051 cm) thick,  $\pm 1\%$  for 0.050 in. (0.127 cm),  $\pm 0.5\%$  for 1.000 in. (2.54 cm),  $\pm 0.25\%$  for 5.000 in. (12.7 cm), etc. Thermosets generally are more suitable than TPs for meeting the tightest tolerances.

Economical production requires that tolerances not be specified tighter than necessary. However, after a production target is met, one should mold "tighter" if possible for greater profit. Many plastics change dimensions after molding, principally because molecular orientations and molecules are not relaxed. To ease or eliminate the problem, one can change the processing cycle so that the plastic is "stress-relieved," even though this may extend the cycle time, and/or heat-treat per the resin supplier's suggestions.

### Product Specifications

Tight tolerances on dimensions should be specified only when absolutely necessary. Too many drawings show limits on sizes when other means of attaining the desired results would be more constructive. For example, if the outside dimensions of certain drill-housing halves were to have a tolerance of  $\pm 0.008$  cm (0.003 in.), this would be a tight limit. Yet if half of the housing were to be on the minimum side and the other on the maximum side, there would be a resulting step that would be uncomfortable to the feel of the hand while gripping the drill. A realistic specification would call for the matching of halves so as to provide a smooth joint between them, with the highest step not exceeding 0.002 in. The point is that limits should be specified in such a way that those responsible for the manufacture of a product

will understand the goal that is to be attained. Thus, we may indicate “dimensions for gear centers,” “holes as bearing openings for shafts,” “guides for cams,” etc. This type of designation would alert a moldmaker as well as the molder to the significance of the tolerances in some areas and the need for matching parts in other places and the clearance needed for assembly in still other locations.

Most of the engineering plastics faithfully reproduce the mold configuration, and when the processing parameters are appropriately controlled, they will repeat with excellent accuracy.

We see plastic gears and other precision parts made of acetal, nylon, polycarbonate, and Noryl with tooth contour and other precision areas made with a limit of 0.0002 in. and in which the spacing of the teeth is uniform to meet the most exacting requirements.

The problem with any precise part is to recognize what steps are needed to reach the objective and to follow through every phase of the process in a thorough manner, to safeguard the end product. Throughout this book, shrinkage is discussed based on the material's given characteristics. Different factors can cause a variation in shrinkage; indeed, the way processing parameters can influence dimensional variation is very important. Some materials perform better than others in that respect.

Generally, if we approach tolerances according to their purposes—(1) functional requirements, such as running fit, sliding fit, gear tooth contour, etc.; (2) assembly requirements—that is, to accommodate parts with their own tolerances; and (3) matching parts for appearance or utility—we should come up with feasible tolerances that will be reasonable and useful. This will be more productive than trying to apply tolerances strictly on a dimensional basis.

Tight tolerances should be indicated only when they are needed, carefully analyzed for their magnitude, and of proven usefulness. It is important to determine if the tolerances shown are realistic for the specified plastic and process. The designer should recognize

that attaining extreme accuracy of dimensions is expensive and, in some cases, impossible to hold in processing.

The adaptation of metal tolerances to plastics is not advisable. The reaction of plastics to moisture and heat, for example, is drastically different from that of metals, so that pilot testing under extreme use conditions is almost mandatory for establishing adequate tolerance requirements.

### *Using Geometric Tolerancing*

By clearly showing design intent on the drawing that, in turn, is transferred to the mold manufacturer, geometric dimensioning and tolerancing can play an important role in the success of integrated manufacturing or computer-aided manufacturing. (See Chap. 9.) Experts in integrated manufacturing continually cite the need for clear design specifications as an essential element of technology. They recognize that a unified network of communication and control is one of the larger hurdles standing in the way of effective integration.

Unified communications will ultimately require a uniformly interpreted and understood means of linking marketing, design, manufacturing, and quality assurance (see Chaps. 12 and 13) departments at not only one location, but also other plant sites. Moreover, the information-centered concept of integrated manufacturing could fail before it has really begun if companies lack a standardized basis for precise internal communication.

The physical elements of mass-produced products must be described clearly, concisely, and precisely so they can be produced efficiently and profitably. Geometric dimensioning and tolerancing (GD & T) is one way to enhance this critical communication with minimal expense.

GD & T is a system of symbols and internationally accepted notation that greatly increases the expressive power of the drafting language. The GD & T language system has evolved through the efforts of engineering, design, and manufacturing personnel familiar

with the added costs caused by inadequate drawings.

The current standard of dimensioning and tolerancing is ANSI Y14.5M. The goal of the standard is to increase production efficiencies by enhancing one's ability to express design intent and critical functional relationships on the drawing itself.

Drawings are essentially contracts governing the production of a manufactured product. Quite often, designers and manufacturers find that the old plus and minus or coordinate dimensioning system falls short of expressing the true limits of production variability. Therefore, functional design integrity at minimum cost cannot be ensured. The plus and minus system of dimensioning frequently forces some good products to be rejected and some bad products to be accepted. This is largely due to the fact that the coordinate system is somewhat inadequate for expressing dimensions that logically follow the product function.

A datum is one component of the GD & T language that allows dimensional networks to be established in ways that make functional sense. Datums enable designers to clearly express relationships between key elements of a product; to guide how a product should be aligned in manufacturing and set up at inspection; and to reflect on how a product will operate or be installed at assembly.

Datum referencing is just one of many aspects of GD & T that ensures more functional products while saving money. GD & T as a total language system is a practical and straightforward way to document functional design requirements. GD & T develops 100% interchangeable and 100% functional products at minimum cost, unlike the old plus or minus tolerancing language (95).

### **Design Features That Influence Performance**

Although there is no limit theoretically to the shapes that can be created, practical considerations must be met. These relate not only to part design but also to mold design, since these must be considered one entity in the

total creation of a usable, economically feasible part. (See Fig. 5-24.) Throughout this book and particularly in Chap. 8, reviews are presented on basic detractors and constraints that influence the performance of injection-molded products.

### **Plastics Memory**

Thermoplastics can be bent, pulled, or squeezed into various useful shapes. But eventually, especially if you add heat, they return to their original form. This behavior, known as plastic memory, can be annoying. However, when properly applied, plastic memory offers some interesting design possibilities for blow molded parts.

When most materials are bent, stretched, or compressed, they somehow alter their molecular structure or grain orientation to accommodate the deformation permanently. This is not so with polymers. Polymers temporarily assume the deformed shape but always maintain internal stresses that act to force the material back to its original shape.

This so-called plastic memory is often unwelcome. Sometimes, people prefer that thermoplastic parts forget their original shape and stay put, especially when the parts must be coined, formed, machined, or rapidly cooled. Occasionally, however, this memory or instability can be used advantageously.

The time and temperature-dependent change in mechanical properties results from stress relaxation and other viscoelastic phenomena typical of polymers. When the change is an unwanted limitation, it is called creep. When the change is skillfully adapted to the overall design, it is termed plastic memory.

Most plastic parts can be produced with a built-in memory. That is, the tendency to move into a new shape is included as an integral part of the design. So then, after the parts are assembled in place, a small amount of heat can coax them to change shape. Plastic parts can be deformed during assembly and then allowed to return to their original shape. In this case, parts can be stretched around

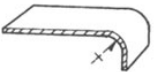
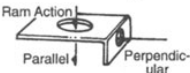
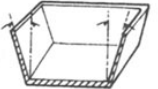
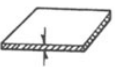
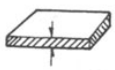
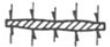
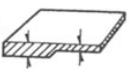
|                                                          |                                                                                     |                                                    |
|----------------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------|
| Minimum Inside Radius (in.)                              |    | 1/16" Minimum                                      |
| Molded-in Holes                                          |    | Yes—Parallel Or Perpendicular To RAM Action        |
| Trimmed in Mold                                          |    | No                                                 |
| Core Pull & Slides                                       |    | Yes                                                |
| Undercuts                                                |    | Yes                                                |
| Minimum Draft Recommended                                |    | 1/4"—6" Depth—1°—3°<br>6"+Depth—3°+ or as Required |
| Minimum Practical Thickness (in.)                        |    | 0.035                                              |
| Maximum Practical Thickness (in.)                        |    | 0.500                                              |
| Normal Thickness Variation (in.)                         |    | ± 0.005                                            |
| Maximum Thickness Buildup: Heavy Buildup Increases Cycle |   | As Desired                                         |
| Corrugated Sections                                      |  | Yes                                                |
| Metal Inserts                                            |  | Yes                                                |
| Bosses                                                   |  | Yes                                                |
| Ribs                                                     |  | Yes                                                |
| Molded-in Labels                                         |  | No                                                 |
| Raised Numbers                                           |  | Yes                                                |
| Finished Surfaces<br>•Reproduces Mold Surface            |  | Two                                                |

Fig. 5-24 Design guide for injection molded glass fiber reinforced molding compounds.

obstacles or made to conform to unavoidable irregularities without permanent damage.

Potential memory exists in all thermoplastics. Polyolefins, neoprene, silicone, and other cross-linkable polymers can be given a memory either by radiation or chemically cur-

ing. Fluorocarbons, however, need no curing. And when the phenomenon is applied to fluorocarbons such as TFE, FEP, ETFE, ECTFE, CTFE, and PVF<sub>2</sub>, interesting high-temperature or wear-resistant applications are possible.

### Residence Time

The residence time is the amount of time a plastic is subjected to heat during fabrication. With recycled plastics, properties are affected by previous fabrication and granulating heat. This residence time can cause relatively minor to major undesirable variations in its reprocessing and/or the performance of the finished product. This action can occur even when the same plastic (from the same source) and same fabricating machine are used. Different thermal tests are available and used to meet specific requirements (Chap. 12).

### Computerized Knowledge-Based Engineering

Recognize that what comes naturally to us in conceptualizing a design is a real unavailable extension for a computer. Thus, “we are needed” since computers do not have the capabilities of translating our continually new thought processes into computational and cognitive models that will make intelligent computer-aided designs. This capability of the human mind to conceptualize the engineering approach to software programming continues to provide new solutions. It remains difficult to codify the activities of alternating abstract and refined thoughts into computer program languages.

### Orientation

Orientation consists of a controlled system of stretching thermoplastic molecules in unioreinted [unidirectional (UD)] or bioriented [biaxial direction (BD)] to improve their strength, stiffness, optics, electrical, and/or other properties with the usual result that improved product performance-to-cost occurs. This technique is used during the processing of many different products such as injection blow molded bottles (Chap. 15, Stretched Blow Moldings) (22). It is also extensively used in orienting extruded products such as plastic films, sheets, and fibers (3, 18).

Depending on the properties of a specific plastic, the stretch ratio usually varies from  $2\frac{1}{2}:1$  to as high as  $10:1$ . Used for almost a century, orientation became prominent during the 1930s for stretching plastic fibers up to ten times. Later it was adapted principally to films and other products such as stretched blow molded bottles to take advantage of their property improvements. Practically all TPs can undergo orientation, although certain types offer particularly advantageous cost reductions (PET, PP, PVC, PE, PS, PVDC, PVA, PC, etc.).

### Accidental Orientation

Generally, when discussing orientation, we mean deliberate orientation; however, orientation can also accidentally occur during injection molding. Acceptable accidental orientations can occur during the processing of thermoplastics. With the usual proper process control, however, accidental orientation is avoided (Chap. 7). The frozen-in stresses caused by accidental orientation can be extremely damaging if parts are subjected to environmental stress cracking or crazing in the presence of heat, chemicals, etc. Initially the molecules are relaxed. Molecules in the amorphous regions are in random coils; those in crystalline regions are relatively straight and folded. During processing the molecules tend to be more oriented than relaxed, particularly when the melt is subjected to excessive shearing action.

After temperature and pressure is applied over time and the melt goes through restrictions (sprue, gate, etc.), the molecules tend to be stretched and aligned in a parallel form. This can lead to undesirable changes in the directional properties and dimensions immediately when processed and/or thereafter when in use if stress relaxation occurs.

### Orientation and Chemical Properties

Simple orientation alone increases sorption and solubility; but when it induces crystallization, the overall net effect is to decrease these properties. Similarly, residual stresses

in structural foamed plastics make them more susceptible to chemical attack. The orientation of amorphous plastics affects molecular mobility and permeability in similar ways; permeability decreases in the direction of orientation and increases perpendicular to it. The orientation of crystallizable or crystalline plastics decreases permeability. Many properties significantly improve, for instance stiffness, strength, and toughness as well as resistance to liquid and gas permeation, crazing, microcracks, and other effects in the direction or plane of orientation. Orientation in effect provides a means of tailoring and improving the properties of plastics (Chap. 6).

#### *Orientation and Mechanical Properties*

Mechanical properties depend directly upon the relationship between the axis of orientation of the plastic molecules and the axis of mechanical stress upon the molecules. Modulus, strength, etc. increase in the direction of stretch and decrease in the perpendicular direction. This is the mechanism of pseudoplastic and thixotropic rheology typical of a non-Newtonian plastic flow behavior. After processing, some degradation in properties may occur when the part is subjected to heat during further processing, such as thermoforming, heat sealing, or solvent sealing.

#### *Orientation and Optical Properties*

Biaxial orientation of crystalline plastics generally improves clarity. This occurs because stretching breaks up large crystalline structures into objects smaller than the wavelength of visible light. With uniaxial orientation, the result is an anisotropic refractive index and thus birefringence, especially in crystalline plastics.

#### *Orientation Processing Characteristics*

Some general rules for orienting by stretching are: (1) the lowest temperature will give the greatest orientation (tensile strength,

etc.), (2) the highest rate of stretching will give the greatest orientation at a given temperature and percent stretch, (3) the highest percent stretch will give the greatest orientation at a given temperature and rate of stretching, and (4) the greatest quench rate will preserve the most complete orientation under any stretching condition.

With orientation, the thickness is reduced and the surface enlarged. As an example, if film is longitudinally stretched, its thickness and width are reduced in the same ratio. If lateral or transverse contraction is prevented, stretching reduces the thickness only. The orientation is normally 60 to 75% of the range between the plastic's glass transition temperature and melting point (Chap. 6).

*Balanced orientation* Results when stretch in the machine and transverse directions are uniform.

*Biaxial orientation (also called bi-orientation or BO)* It is the stretching of material in two directions (biaxially) at right angles: along machine direction (MD) and across or transverse direction (TD). The difference in the amount of stretch in both directions varies, depending on product requirements. If they are equal, then it is a balanced orientation. An example is using stretched injection blow molding (Chap. 14).

*Random orientation* A condition of a crystalline aggregate in which the constituent crystals have orientation completely random with respect to one another.

#### *Orientation and Cost*

The process of orientation is fairly expensive. It increases the cost per unit weight of the product. However, the yield increases considerably and the quality improves greatly. Many plastics are made much stronger, more flexible, tougher, etc., resulting in significant product cost advantages. Maximum ultimate economic value depends upon the relative cost of stretching versus the increase in yield and properties.

**Molecular Orientation: Design of Integral Hinges**

Injection molding techniques are used to fabricate thermoplastic hinges. These so-called living hinges take advantage of molecular orientation to provide the bending action in the plastic hinge. An integral hinge can be molded by conventional processing techniques providing certain factors are observed. The required molecular orientation runs transverse to the hinge axis. This can best be achieved by a proper fast melt flow through a thin hinge section, using a proper high melt temperature. The number of cycles the hinge can operate will depend on the plastic used. With a low cost plastic, such as a styrene compound, after a few bends it breaks. If very long life is required plastics such as nylon are used.

The main concern in integral-hinge molding is to avoid conditions that can lead to delamination in the hinge section. These include filling the mold too slowly, having too low a melt temperature, having a nonuniform flow front through the hinge section, suffering material contamination as from pigment agglomerates, and running excessively high mold temperatures near the hinge area. Post-mold flexing while the hinge is still hot is usually required to ensure that it operates efficiently in service.

Coining can be used to form the plastic hinge section. The plastic is compressed to the desired thickness shape at the hinge section using matching bars with or without heat. Depending on the type of plastic and configuration of the hinge, heating the plastic and/or the bars may be required. The plastic in the hinge section is stressed beyond its yield point after creating a necking down effect that causes stretching or orienting of its molecules across the hinge.

**Interrelation of Material and Process with Design**

As mentioned, with plastics, there is an important interrelationship among shape design, material selection (including orien-

tation), and manufacturing selection. This interrelationship is different from that of most other materials, for which the designer basically is limited to obtaining specific prefabricated forms or profiles that are bent, welded, etc.

Many different products can be designed using plastics. Plastics provide the designer with a combination of often unfamiliar and unique advantages and limitations that can challenge his or her ability. By understanding their many different structures, viscoelastic properties, design freedoms, and molded fabrication techniques, the designer can meet this challenge. The major consideration for a designer is to analyze properly what is available and develop a logical selection process to meet performance requirements, which generally are related to cost factors (7) (Chap. 15).

Part design is a combination of understanding both the practical and theoretical viewpoints. It is usually a compromise between the artist who emphasizes aesthetics, the production person who desires economical and efficient production, and the end user who seeks certain desired properties.

**Design Shapes**

One advantage of plastics is their formability into almost any conceivable shape. Plastic shapes can be almost infinitely varied in the early design stages, and for a given weight of material they can provide a whole spectrum of strength properties, especially in the most desirable areas of stiffness and bending resistance.

In all materials, elementary strength-of-material theory demonstrates that some shapes resist deformation resulting from external loads or residual processing stresses better than others. Deformation in beam and sheet sections depends on the product of the modulus and second moment of inertia, commonly expressed as  $EI$ . Physical performance can be changed by varying the moment of inertia or modulus or both (18).

Using thick plastic panels to meet stiffness requirements is an expensive design method

because inefficiently large quantities of material are used, and the long heating and cooling times required affect the economics of production considerably by increasing cycle times.

Therefore, the desired stiffness is better obtained by the use of ribbing, double curvature, or shaping. Although these devices tend to increase tool costs, in long production runs these investments are more than offset by shortened molding cycles and the use of less raw material. Also, such techniques as using integral skin foam cores further extend the stiffness of the thinner sheet.

Adding material to a structural component does not always make it stronger. For example, ribs are often added to stiffen a structure, particularly in large molded plastic parts that normally use many ribs for weight savings. However, the addition of a rib to a plate loaded in bending may increase stress rather than decrease it. Although a rib increases the moment of inertia of the structure, the distance from the structure's center of gravity to its outer edge may become relatively greater, and stress increases accordingly. The key to reducing stress is adding ribs in the correct proportions.

Lengthy equations for moments of inertia, deflection, and stress normally are required to determine the effect of ribs on stress. However, nondimensional curves have been developed to allow a quick determination of proper rib proportions, whereas a corresponding program for a pocket calculator permits direct calculation if greater precision is required.

With the potential limitations of rib panels, the use of foamed material with or without a solid outer skin in structural applications can be a way to offer a high stiffness-to-weight ratio with a wide range of depths for improvement of the moment of inertia and the torsional stiffness. Integral skin molding techniques offer the additional advantage that the surface of the panel of the material is effectively unfoamed.

With the latitude that exists in designing shapes with plastic materials, designs using large amounts of materials do not necessarily work the best or give the best physical

performance per unit weight of material. Sometimes, quite minute amounts of material judiciously placed in, say, injection-molded bottle crates can make an important difference to the behavior of the crates when stacked. In one example, the removal of eight corner ribs weighing 0.7 lb (0.32 kg) from a crate originally weighing 14 lb (6.36 kg) can reduce the crushing strength by 25% and increase compressive creep by about 40%.

### Shapes and Stiffness

Plastic parts, in most cases, can take advantage of a basic beam structure in their design. Much of the conventional design with other materials is based on single rectangular shapes or box beams, because in timber and steel, these are commonly produced as standard shapes. Their use in plastics components is often accompanied by a wasteful use of material, as in large steel sections.

Hollow-channel, I-, and T-shapes designed with generous radii (and other basic plastic flow considerations) rather than sharp corners are more efficient on a weight basis in plastics because they use less material, providing a high moment of inertia. The moments of inertia of such simple sections, and hence stresses and deflections, can be fairly easily calculated using simple theories.

Such nonrectangular sections are common in many thermoplastics articles. Channels, T-sections, and hollow corner pillars are found in many parts such as crates and stacking containers, and inverted U-sections and cantilevers are common in items such as street lamp housings and aircraft.

Processing any plastics (unreinforced or reinforced) into curved panels is relatively easy and inexpensive. Such panels conform to recognized structural theories that curved shapes can be stiffer in bending than flat shapes of the same weight. Putting it differently, we see that a square-section component built to withstand external pressure will usually be heavier than one of circular section and the same volume. Both single and double curvature designs are widely used to make more effective use of plastics materials.

An example of single curvature in a structural element is a corrugated roofing panel, which is inherently much stiffer than the same volume of material would be in a flat sheet. Some calculation can be made of the stiffness of corrugated panels under certain loading conditions. To improve the stiffness further, the corrugated panels can sometimes be slightly curved along the length of the corrugations.

Double curve shells can take the form of spherical domes, be saddle-shaped, or use hyperbolic shapes. Some of these features are found in well-known architectural designs using plastics materials. These domes can be made in modular form molded of composite or reinforced plastics, providing an efficient structural shape with a higher buckling resistance than spherical domes of comparable curvature and thickness.

The following brief and partial list outlines what reinforcements can do in plastics design:

1. Increase tensile strength.
2. Increase flexural strength.
3. Increase torsional strength.
4. Increase impact strength.
5. Increase the modulus.
6. Increase creep resistance.
7. Decrease the coefficient of thermal expansion.
8. Increase thermal conductivity.
9. Extend the available supply of resin.
10. In many cases, lower the cost of the compound, as with glass fibers and other low-cost reinforcements.

### Stress Relaxation

The properties of plastics are strongly dependent on temperature and time, compared to those of other materials such as metals. This dependence is due to the viscoelastic nature of plastics (Fig. 5-13). Consequently, the designer must know how the product is to be loaded with respect to time.

In structural design, it is important to distinguish between various failure modes in the

product. The behavior of any material in tension, for example, is different from its behavior in shear. So it is with plastics, metals, or concrete. For viscoelastic materials such as plastics, the history of deformation also has an effect on the response of the material, since viscoelastic materials have time- and temperature-dependent material properties.

Whether the part is deformed in tension or shear, continued straining under a sustained load is called *creep*. Either type of deformation leads to a material property termed *creep compliance*. There is a creep compliance that describes the tensile behavior of the material, and there is a creep compliance for shear behavior.

However, if the material is subjected to a sustained constant strain rather than constant stress, the force or torque necessary to sustain this constant strain decays with time. This process is called *relaxation*. As in creep, there is a fundamental material property associated with relaxation, the *relaxation modulus*. There are practical problems in which relaxation is important, just as there are practical problems where creep matters. A designer must be able to recognize which of these fundamental modes is involved in a particular situation.

These stress relaxation modes can occur in all types of design and different materials, including low-performance plastics. Note that with the very high strength or high modulus of elasticity composite plastics, this stress relaxation condition is easier to analyze than those of the high-performance steels. Creep and stress relaxation behavior are illustrated in Fig. 5-13.

The creep behavior of a plastic can go through certain specific phases. Load can be applied instantaneously, resulting in strain point *A* (Fig. 5-13), a reaction that can be called the *elastic response*. With the stress maintained, the plastic deforms or creeps with time to point *B*. The *viscoelastic deformation* that occurs identifies the strain from *A* to *B*. When the load is removed, the plastic strain is reduced immediately to point *C*; this phase can be identified as the *elastic recovery*. The next phase has the plastic gradually relieving its strain (with time) to point

*D* (*viscoelastic recovery*). Based on the type of plastic used and amount of load applied, the final recovery could be a return to zero strain.

The stress relaxation behavior of a plastic can be analyzed after load is applied instantaneously to stress point *A* (*elastic response*). As the strain is maintained, the plastic relaxes with time to point *X*. With load removed, the plastic recovers elastically (immediately) to point *Y*, less than point *X*. With time, residual stress induces *viscoelastic deformation* to point *Z*. The amount of strain due to this type of stress relaxation behavior will depend on the type of plastic used and amount of load applied.

### Predicting Performance

Avoiding structural failures can depend, in part, on one's ability to predict performance for all types of materials (plastics, metals, glass, etc.). Design engineers have developed sophisticated computer methods for calculating stresses in complex structures using different materials. These computational methods have replaced the over-simplified models of materials behavior formerly relied on. The result is early comprehensive analysis of the effects of temperature, loading rate, environment, and material defects on structural reliability. This information is supported by stress-strain behavior data collected in actual materials evaluations.

With computers, the finite element method has greatly enhanced the capability of the structural analyst to calculate displacement, strain, and stress values in complicated plastic structures subjected to arbitrary loading conditions. In its most fundamental form, the finite element technique is limited to static, linear elastic analyses. However, there are advanced finite element computer programs that can treat highly nonlinear dynamic problems efficiently. Important features of these programs include their ability to handle sliding interfaces between contracting bodies and the ability to model elastic-plastic material properties. These program features have made possible the analysis of impact prob-

lems that only a few years ago had to be handled with very approximate techniques. Finite element techniques have made these analyses much more precise, resulting in better and more optimum designs.

Nondestructive testing (NDT) is used to assess a component or structure during its operational lifetime. Radiography, ultrasonics, eddy currents, acoustic emissions, and other methods are used to detect and monitor flaws that develop during operation. (See Chap. 12.)

The selection of the evaluation method(s) depends on the specific type of plastic, type of flaw to be detected, environment of the evaluation, effectiveness of the evaluation method, size of the structure, and economic consequences of structural failure. Conventional evaluation methods are often adequate for baseline and acceptance inspections. However, there are increasing demands for more accurate characterization of the size and shape of defects that may require advanced techniques and procedures and may involve the use of several methods.

### Choosing Materials and Design

The procedure for designing a product in a plastic follows the same logic that applies in any product design cycle; that is, to engineer a new design and select the proper materials for the component parts, a series of questions must be addressed.

#### *Design Concept*

(1) What are the end-use requirements for the part or product (aesthetic, structural, mechanical)? (2) How many functional items can be designed into the part for cost-effectiveness? (3) Can multiple parts be combined into one large part?

#### *Engineering Considerations*

(1) What are the structural requirements? (2) Are the loads static, dynamic, cycling? What are the stress levels? (3) What

deflection can be tolerated? (4) Is the part subject to impact loads? (5) What tolerances are required for proper functioning and assembly? (6) What kind of environment will the part see? (7) What operating temperature will it have? (8) What will its chemical exposure be? (9) What is the expected life of the product? (10) How will the product be assembled? (11) What kind of finish will be required on the parts? (12) Are agency requirements or codes involved, such as UL, DOT, MIL? (13) Can the proposed product be molded and finished economically?

Once the above questions have been considered, the next step is usually to consult property data sheets to compare materials. Properties presented in these sheets are for comparative purposes and not generally for design. Seldom will a part's design conditions match the conditions used for generating the data on the property sheets, but the standardized tests are a valuable tool. Without standardized property data, fair comparisons could not be made. The standardized information on mechanical strength, impact, chemical resistance, etc. must be adjusted for the end-use environments and life of the product.

After one selects the proper material for the part, calculations of wall thicknesses and part geometry are made, followed by the next design step, which is to improve the effectiveness of the design. In the case of injection molded parts, the design should be reviewed in terms of the following questions: (1) Can a tool be built and the part molded? (2) Are the wall thicknesses adequate for the flow of the material to fill the part? (3) Have all internal corners been "radiused" to reduce all high localized stress points? (4) Do all changes in wall thickness have smooth transitions? (5) Are heavy wall sections cored out to give a uniform wall when possible? (6) Is the ratio of rib or boss thickness to adjacent wall thickness proper? (7) Is it possible to gate into the thicker wall sections and flow to the thinner sections? (8) Are weld lines going to present strength or appearance problems? (9) Have adequate draft angles been included on all surfaces? (10) Have reasonable tolerances been selected for all parts?

If you have properly evaluated the needs of the product, chosen the proper material, optimized the design for that material, and, finally, carefully considered proper manufacturing practices, you will be on the way to obtaining a part that works.

### Design Considerations

Design in the plastics context is a concept with many connotations. Essentially, however, it is the process of devising a product so that it fulfills as completely as possible the total requirement of the end user. The needs of the producer from the standpoints of both sales and cost effectiveness should be automatically fulfilled if the design function is properly performed. The economic use of available materials and production processes, including the all-important tooling aspects, must be effected in one design effort. Considerations include:

1. *General.* (a) Performance requirements (structural, aesthetic, etc.); (b) possible combination of multiple parts or functions; (c) structural load requirements (static, dynamic, cycling, impact, etc.); (d) environment (temperature, time, chemical, etc.); (e) tolerance requirements; (f) life of product; (g) quantity of product versus fabrication process; (h) secondary operations; (i) others.

2. *Environmental conditions that principally affect plastics.* (a) Temperature; (b) time; (c) load; (d) other environments (chemical, water, etc.).

3. *Engineering design facts.* (a) Type of load (viscoelastic concept); (b) frequency of load; (c) stress rate; (d) strain amplitude; (e) load deformation (tensile, compression, shear, etc.); (f) apparent modulus (includes strain due to creep); (g) direction of load; (h) sound dampening (foam); (i) others.

4. *Plastics characteristics that affect engineering design.* (a) Polymer structure; (b) molecular weight; (c) molecular orientation; (d) plastic (with or without reinforcement) orientation; (e) types of additives, fillers, and/or reinforcements used; (f) heat history; (g) glass transition (mechanical properties

change during the glass transition  $T_g$ , as the plastic basically changes from a hard, stiff, glasslike polymer to a soft, elastic polymer); (h) process to fabricate; (i) thermal stress (coefficient of expansion, frozen stresses); (j) economics; (k) others.

5. *Tests (ASTM, LP-406, etc.)*. (a) Tension (takes into account flows); (b) compression (tends to represent a pure polymer with no flow); (c) flexural, shear, etc.; (d) creep; (e) dynamic, fatigue, torsion; (f) impact; (g) Poisson's ratio; (h) heat distortion; (i) others.

6. *Stress-strain data*. (a) As influenced by viscoelastic polymer behavior; (b) directional loading; (c) models in understanding shape of stress-strain using Maxwell's "spring and dashpot" concept [in which (1) short-time constant behavior (impact) is more influenced by the elastic component of polymer behavior (spring concept) and (2) time-dependent properties for long-time constant forces (cold flow, creep) are influenced by the viscous component (dashpot concept)]; (d) different curves for different tests [(1) compression modules usually higher than tensile modules; (2) compression strength of a brittle plastic higher than tensile strength by a factor of  $1\frac{1}{2}$  to 4; (3) flexural strength tending to be greater than tensile strength; (4) tensile strength generally less than twice shear strength]; (e) correlating test data with end use (most tests are too limited, such as a simple temperature condition); (f) others.

7. *Relating properties to materials and processes*. (a) Directional flow of plastic; (b) directional layout of reinforcements; (c) frozen stresses; (d) regrind; (e) prototype (machining, casting, molds, etc.); (f) others.

### Design Parameters

In contrast to conventional materials such as metals, design in plastics cannot, except in rare elementary design cases, be based on one key property (as, e.g., tensile or shear stress with a steel or metal). The designer rarely can call on standard sections (as in structural steel work) or standard metal components for mechanical engineering applications. Also, plas-

tics are constrained by a much larger set of production variables, all of which must be examined by the designer. Moreover, plastics materials vary greatly from each other in their property spectrum, so that their selection is one of the key early decisions in a design.

Figure 1-10 provides a simplified flow diagram for setting up a design program. It shows what can be referred to as the practical engineering approach (predominantly used) and the advanced engineering approach.

*Practical engineering approach* Most plastic products are required to withstand mechanical load without static or dynamic loads (appliance housings, containers, etc.). Property requirements could include mechanical strength and stiffness, chemical resistance, heat resistance, electrical insulation, etc. Short-term, conventional static tests generally suffice.

*Advanced engineering approach* Many plastic products that have been in use since 1940 have been exposed to long-term static or dynamic loads based on varying environmental condition such as time and temperature (large chemical tanks, boat hulls, gears, automobile parts, pressure pipe, aircraft principal structures, etc.). When a part is exposed to any load for a long period, the design engineer is provided long-time data, such as creep, fatigue, tensile-temperature-time, and other data. These data provide common stress analysis, using creep or other data for the determination of permissible stresses or strains.

### Types of Plastics

Plastics, like other materials, exhibit many different properties. Plastics have many different names; they can also be called polymers, resins, reinforced plastics, and composites.

Their properties, advantages, and limitations must be understood if they are to be used intelligently. No quick and easy definition is possible; the materials called

plastics—like metals, for example—cover a wide range of behaviors. However, plastics share some common properties. They are “plastic” (flow) at some stage—that is, they are soft and pliable and can be shaped, usually by the application of heat, pressure, or both, into desired forms. Some can be cast, requiring no pressure. Some plastics can be resoftened and rehardened by heating and cooling; others, once they have hardened, cannot be resoftened. (See Chap. 6.)

### Long-Term Behavior of Plastics: Creep

Meaningful ASTM and UL tests are conducted and used in the design of plastic products. Static and dynamic tests are used efficiently and when necessary are properly related to time–temperature or any other time–environment condition. The ASTM tests include D149, D150, D256, D570, D621, D632, D638, D648, D671, D696, D746, D785, D790, D792, D955, D1003, D1044, D1435, D1525, D1693, D2863, and D2990; there are also UL94 and other UL tests. (See Chap. 12 for more information on testing and quality control.)

Certain plastics provide long-term behavior (creep) data when exposed continuously to stresses, the environment, excessive heat, abrasion, and continuous contact with liquids. Tests outlined by ASTM D2990 are intended to produce consistency in observations and records by various manufacturers, so that they can be correlated to provide meaningful information to product designers. This long-time creep and stress-relaxation test procedure provides useful data.

The creep developed is also called cold flow. In this test when a load is initially applied to a specimen, there is an instantaneous strain or elongation. Subsequent to this, there is the time-dependent part of the strain, called creep, that results from the continuation of the constant stress at a constant temperature. In terms of design, creep means changing dimensions and the deterioration of product strength when a product is subjected to a steady load over a prolonged period of time.

All the mechanical properties described in tests for data sheet properties represent values of the short-term application of forces; in most cases, the data obtained from such tests are used for comparative evaluation, or as controlling specifications for the quality determination of materials along with short-duration and intermittent-use design requirements.

A stress–strain diagram is a significant source of data for a material. In metals, for example, most of the data needed for mechanical property considerations are obtained from such diagrams. (See Fig. 5-25.) In plastics, however, the viscoelasticity causes an initial deformation at a specific load and temperature, followed by a continuous increase in strain under identical test conditions until the product is either dimensionally out of tolerance or fails in rupture as a result of excessive deformation. (See Fig. 5-13.)

This viscoelastic behavior can be explained with the aid of a Maxwell model. (See Fig. 5-26.) With a load applied to the system, shown diagrammatically, the spring will deform to a certain degree. The dashpot will at first remain in a stationary position under the applied load; if the same load continues to be applied, the viscous fluid in the dashpot will slowly leak past the piston, causing the dashpot to move. The dashpot movement corresponds to the strain or deformation of the plastic material.

When the stress is removed, the dashpot does not return to its original position, as the spring does. Thus, we can visualize a viscoelastic material as having dual actions: one of an elastic material, like the spring, and the other like the viscous liquid in the dashpot. The properties of the elastic phase are independent of time; however, the properties of the viscous phase are very much a function of time, temperature, and stress. The phenomenon is further explained by looking at the dashpot again, where we can visualize that a thinner fluid resulting from increased temperature under a higher pressure (stress) will have a higher rate of leakage around the piston during the time that the above conditions prevail. Translated into plastic creep, this means that at higher use

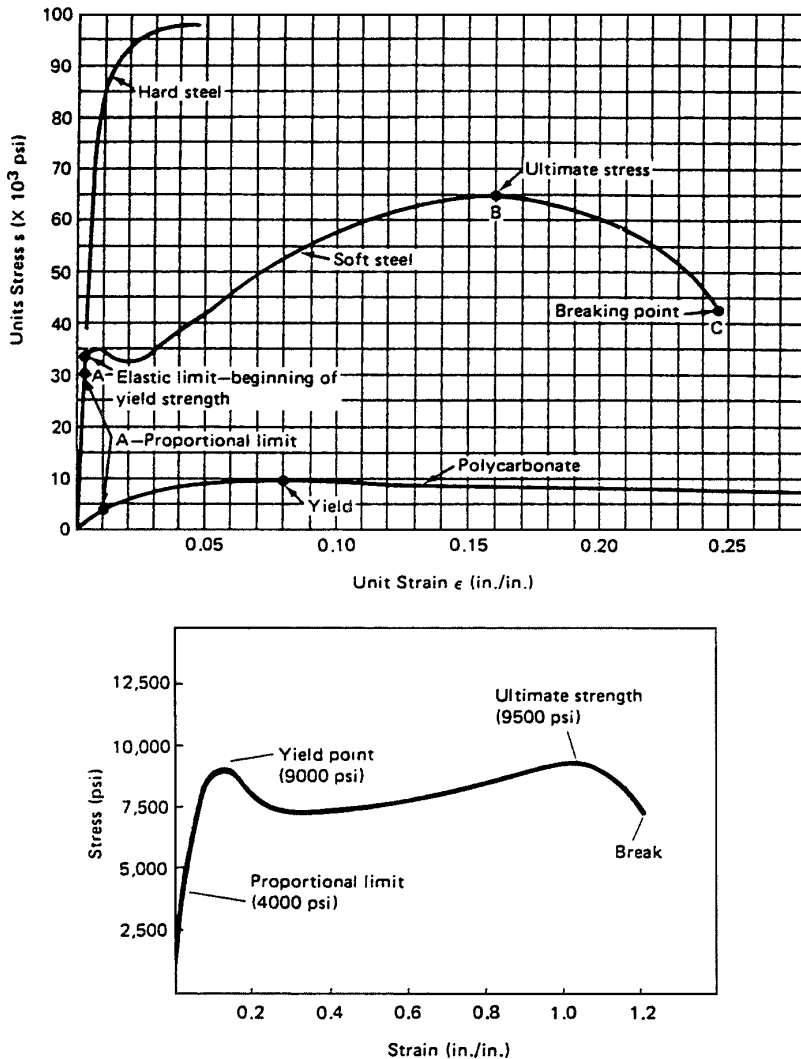


**Fig. 5-25** Tensile stress-strain diagram (top) refers to hard and soft steels and polycarbonate plastic. With PC diagram (bottom) on extended scale, specific characteristics are used for design.

temperature and higher stress levels the strain will be higher, therefore resulting in greater creep.

The visualization of the reaction to a load (without time) by such a dual-component interpretation is valuable to our understanding of the creep process, but basically meaningless for design purposes. For this reason, the designer is interested in actual deformation or part failure over a specific time span.

Observations of the amount of strain at certain time intervals must be made, which will make it possible to construct curves that can be extrapolated to longer time periods. Initial readings are at 1, 2, 3, 5, 7, 10, and 20 h, followed by readings every 24 h up to 500 h, and then readings every 48 h up to 1,000 h.

The time segment of the creep test is common to all materials. Strains are recorded until the specimen ruptures or is no longer

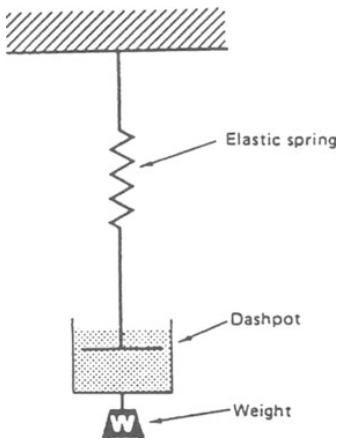


**Fig. 5-26** Maxwell model to explain viscoelasticity behavior of plastics.

useful because of yielding. In either case, a point of failure of the test specimen has been reached.

#### *Designing with Creep Data*

The strain readings of a creep test can be more convenient to a designer if they are presented as a creep modulus. In a viscoelastic material, strain continues to increase with time while the stress level remains constant. Since the modulus equals stress divided by strain, we have the appearance of a changing modulus (18).

The creep modulus, also known as apparent modulus or viscous modulus when graphed on log-log paper, is normally a straight line and lends itself to extrapolation for longer periods of time. The apparent modulus should be differentiated from the modulus given in the data sheets, because the latter is an instantaneous value derived from the testing machine (per ASTM D638).

Generally, creep data application is limited to the identical material, temperature use, stress level, atmospheric conditions, and type of test (tensile, compression, flexure) with a tolerance of  $\pm 10\%$ . Only rarely do product requirement conditions coincide with those of the test or, for that matter, are creep data available for all grades of material that may

be selected by a designer. In those cases a creep test of relatively short duration—1,000 h—can be instigated, and the information extrapolated to the long-term needs. In evaluating plastics, it should be noted that reinforced thermoplastics and thermosets display much higher resistance to creep than unreinforced plastics.

There have been numerous attempts to develop formulas that could be used to predict creep information under varying usage conditions. In practically all cases, suggestions are made that the calculated data be verified by actual test performance. Furthermore, numerous factors have been introduced to apply such data to reliable predictions of product behavior.

Creep data can be very useful to the designer. The data in Fig. 5-27 have been plotted from material available from or published by material manufacturers. The first point is the 100-h time interval. The data for shorter intervals do not, as a rule, fit the straight-line configuration that exists on log-log charts for the long-term duration beyond the first 100-h test period. The circled points are the 100-, 300-, and 1,000-h (and other observed values) test periods, and a straight line is fitted either through the circles or tangent to them to give the line a slope for long-term evaluation (18).

From this line, we can estimate at what time the strain will be such that it will cause tolerance problems in product performance; or, by using the elongation at yield as the point at which the material has attained the limit of its useful life, we can estimate the time at which this limit is reached.

The formula “modulus (apparent) = stress/strain” enables us to locate the modulus that corresponds to the test stress and strain (strain is obtained by using the dimensional change or elongation limit) where it intersects the straight line leading to an appropriate time value. The polycarbonate creep line shows that a limit of 0.010-in. (0.025-cm) elongation is reached at the end  $10^5$  h [apparent modulus = 200,000 psi (1,378 MPa) in Fig. 5-27], and an elongation of 0.06 (yield) is arrived at after  $10^7$  h, or indefinitely if the 0.010 limitation does not exist (1).

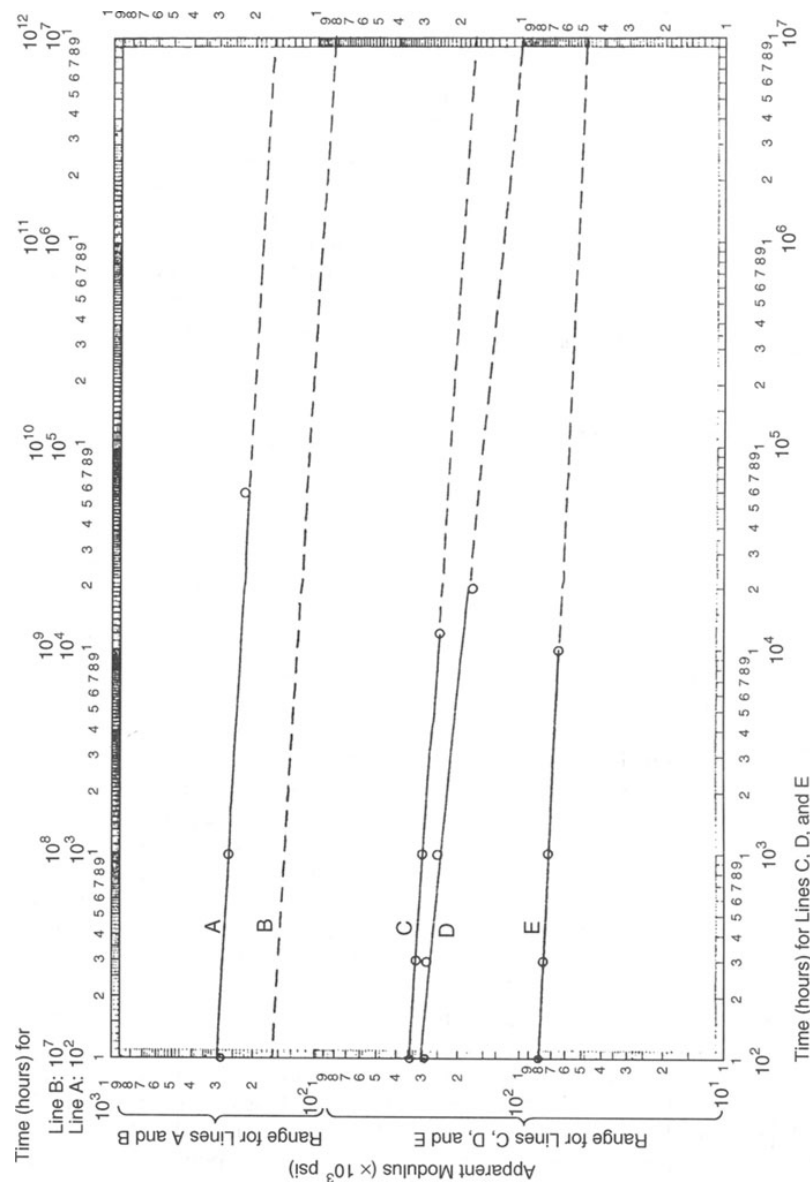


**Fig. 5-27** Examples of apparent modulus versus time for different general type plastics. A is polycarbonate at 2,000 psi (14 MPa), 73°F (23°C); B is an extrapolation of A beyond  $10^7$  h; C is polyethylene-oxide at 2,000 psi, 73°F; D is acetal at 1,000 psi, 73°F; and E is nylon 6/6, at 50% relative humidity and 1,000 psi, 73°F. The broken lines represent extrapolated values where the circles are actual test reading points. Note that the log-log graph sheets are 9 in.  $\times$  15 in. (23 cm  $\times$  38 cm) containing  $3 \times 5$  cycles. The end of the first time cycle represents 1,000 h.

Creep information is not as readily available as short-term property data. From a designer's viewpoint, it is important to have creep data available for products subjected to a constant load for prolonged periods of time. Even if standard test creep data are available, most likely the conditions of the test will not reasonably correspond to those of the contemplated product use, such as stress level, temperature, or environmental surroundings.

In the interest of sound designing procedure, the necessary creep information should be procured on the prospective material and under conditions of product usage. In addition to the creep data, a stress-strain diagram, also at conditions of product usage, should be obtained. The combined information will provide the basis for calculations of the predictability of material performance.

#### *Allowable Working Stress*

The viscoelastic nature of the material requires not merely the use of data sheet information for calculation purposes but also the actual long-term performance experience gained, which can be used as a guide. The allowable working stress is important for determining dimensions of the stressed area and also for predicting the amount of distortion and strength deterioration that will take place over the life span of the product. The allowable working stress for a constantly loaded part that is expected to perform satisfactorily over many years has to be established, using creep characteristics for a material with enough data to make the reliable long-term prediction of short-term test results (1,506).

The creep test data when plotted on log-log paper usually form a straight line and lend themselves to extrapolation. The slope of the straight line, which indicates a decreasing modulus, depends on the nature of the material (principally its rigidity and temperature of heat deflection), temperature of the environment in which the part is used, and amount of stress in relation to tensile strength.

Creep test data plotted (200) resulted in conclusions such as:

1. For practical design purposes, the data accumulated up to 100 h of creep are of no real benefit. There is usually too much variation during this test period, which is of relatively short duration.

2. The apparent modulus values, starting with a test period of 100 h and continuing up to 1,000 h, from a straight line when plotted on log-log paper.

3. This line may be continued for longer periods on the same slope for interpolation purposes, provided the stress level is one-quarter to one-fifth that of the ultimate strength and the test temperature is no greater than two-thirds of the difference between room temperature and the heat deflection temperature at 264 psi (1.82 MPa). This conclusion was verified by plotting the available creep data for time periods greater than 1,000 h.

When the limitations outlined above are exceeded, there is a sharp decrease in apparent modulus after 1,000 h, with indications that failure due to creep is approaching (i.e., the material has attained the limit of its usefulness).

Since the designer will be expected to plot curves to suit his or her requirements, some examples will be cited that can serve as a guide for potential needs. (See Fig. 5-28.)

One example (an ABS) uses creep data for 1,000-psi (6.89-MPa) stress at 73°F (23°C). When the line is extended to  $10^5$  h, the apparent modulus is 140,000 psi (965 MPa). If the product is designed for the duration of  $10^5$  h and calculations are made for

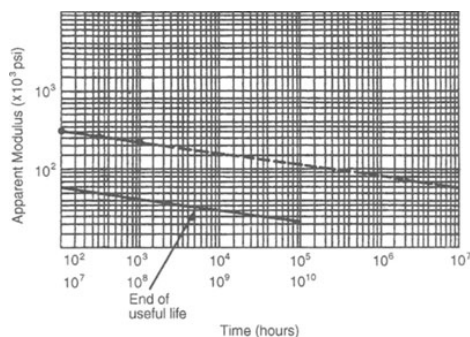


**Fig. 5-28** Creep data for ABS.

part dimensions, the modulus of 140,000 psi should be inserted into any formula in which the modulus appears as a factor.

At  $10^5$  h, total strain is

$$E = \frac{\text{stress}}{\text{strain}}$$

$$140,000 = \frac{1,000}{\text{strain}}$$

$$\text{Strain} = \frac{1,000}{140,000}$$

$$= 0.007 \text{ or } 0.7\%$$

Based on this calculation, if the product can tolerate this type of strain without affecting its performance, then the dimensional requirements are met.

The elongation at yield for this particular ABS is 0.0275, which could be considered the end of the useful strength of the material. The apparent modulus corresponding to this strain at 1,000 psi (6.89 MPa) and 73°F (23°C) is

$$E = \frac{1,000}{0.0275}$$

$$= 36,364 \text{ psi (250.55 MPa)}$$

In the lower part of the graph in Fig. 5-28, we draw at the point of  $56 \times 10^3$  on the left side a line parallel to the original creep line and find that it intersects the apparent modulus line at a time of  $10^9 \times 0.5$  h. The product would fail at that time owing to loss of strength even if dimensional changes permitted satisfactory functioning of the product.

Some charts show creep test data beyond the 1,000-h duration; under most conditions, the straight line between the 100- and 1,000-h points is continued into the 10,000- and 20,000-h range. Even in these charts, a deviation from the straight line occurs occasionally, which should not be considered unreasonable because of all the variables that enter into the test data.

The selection of an allowable continuous working stress at the required temperature must be such that we can make an estimation of the elongation at the end of the product life. For example, if a product will be stressed to 1,700 psi (11.7 MPa) at a tem-

perature of 150°F (66°C), and data are available for 2,000-psi (13.8-MPa) stress at 160°F (71°C), this information plotted on log-log paper should allow us to extrapolate the long-term behavior of the material.

### Creep Behavior Guidelines

There are a number of factors to consider when reviewing creep properties and behavior. Predictions can be made based on creep and relaxation data. Generally plots of creep versus relaxation made on log-log paper facilitate their extrapolations because of the less pronounced curvature. Particulate fillers may provide better creep resistance than unfilled plastics and are less effective than fibrous reinforcements. During the twentieth century worldwide plastic products have been successfully designed for long-term creep performance based on laboratory testing and analyzing data particularly since the 1940s.

### Design Examples

As reviewed in this chapter and throughout this book, many different simple to complex shapes can be injection molded. A few examples of the multitude that exist are presented here.

#### Stapler

The acetal injection molded stapler (Fig. 5-29) illustrates a type of spring design with

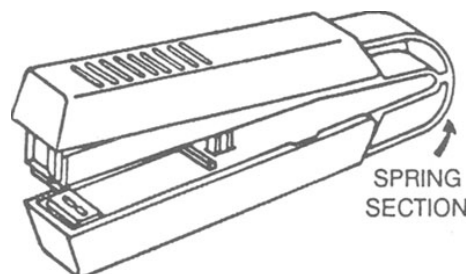


**Fig. 5-29** Injection molded stapler with a special spring design.

the body and curved spring molded together in a single product. This complex shape could not have been achieved in a single operation in steel. The molding technique took advantage of plastics' versatility to reinforce the curved, frequently stressed back section. When the stapler is depressed the outer curved shape in the spring section is in tension. Its ribbed center section is put into compression. When the pressure is released the tension and compression forces are, in turn, released and the molded product returns to its original position. This repeated spring action has a virtually unlimited life span using a plastic such as nylon.

### *Snap-Fits*

The snap-fit is a method of mechanically fastening in which two parts are joined by a properly designed interlocking configuration that is molded directly into the parts. A protrusion molded on one part, such as a hook or bead, is briefly deflected during assembly and engages a depression or undercut molded into the other part. The joint should be stress-free after joining. Cantilever snap-fits are the most common; other types include annular and torsion.

### *Springs*

To illustrate how traditional materials, such as metals with their limited manufacturing processes, limit the design process consider a spring. Recognize that metal springs have an important and useful market but are basically limited to three shapes, namely the torsion bar, the helical coil, and the flat-shaped leaf spring. By comparison, thermoplastics and thermoset plastics can easily be fabricated into a variety of shapes (such as the stapler just reviewed). They can be used in many different environments such as in blood where the spring action might be required in a bag for pumping.

By using different plastics, various performance requirements can be met. There are plastics with excellent damping and fatigue

performance. For example, for use in aircraft, cars, trucks, etc. reinforced plastic, basically unidirectional springs with variable widths and thicknesses along their lengths can provide high specific energy storage capability and save weight. Plastic spring designs that started on military aircraft in the 1940s have been well documented in various SAE and STP design manuals from the 1970s (18).

### **Design Approach Example**

A design exercise is provided in Table 5-12. The concept here is to recognize that setting up requirements for a product can be extensive. The exercise also provides the opportunity to review requirements that may be overlooked. Based on the requirements that have to be met when a product is being designed directly affects (1) material requirements, (2) required capability of the injection molding machine, (3) mold design, and (4) the cost to mold. Throughout this book this theme is reviewed. Examples that summarize this subject include those reviewed by Figs. 1-1, 1-2, 1-14, and 5-30.

### **Design Accuracy**

Design accuracy is a concept of exactness. When applied to a method, it denotes the extent to which bias is absent; when applied to a measured value, it denotes the extent to which both bias and random error are absent. Accuracy can refer to freedom from making errors or conformity to a standard. A fabricating system can be very "precise" and have poor accuracy. Manufacturing a consistent, repeatable product requires more than tight mechanical equipment standards, tight plastic material standards, and precise instruments with fast-integrated control response. Although these conditions can go a long way to meeting the target, calibrating instruments to fixed standards is crucial.

To achieve accuracy the pressure, temperature, speed, and other control devices must be calibrated to traceable standards. By measuring against known standards, the accuracy of

**Table 5-12** Example of a design approach

| Design Category                                   | Subcategories                        | Detailed Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|---------------------------------------------------|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Establish functional and performance requirements | Estimate allowable size and shape    | Product basic functions<br>Aesthetics and marketing<br>Shipping<br>Available space<br>Weight<br>Standardization<br>Strength and stiffness criteria<br>Flexibility<br>Process limitations                                                                                                                                                                                                                                                                                                                                                                            |
|                                                   | Establish structural requirements    | Loads:<br><i>Gravity</i><br>Dead—Own weight superimposed<br>Live—Occupancy<br>Snow<br>Misc.<br><i>Pressure</i><br>Fluid<br>Earth<br>Wind<br><i>Dynamic</i><br>Impact<br>Seismic<br>Handling and shipping<br>Cyclic<br>Temperature:<br>Service range— $\left\{ \begin{array}{l} \text{Interior} \\ \text{Exterior} \end{array} \right.$<br>Gradient across component thickness<br>No. of cycles—high to low<br>No. of cycles—freeze-thaw<br>Solar gain, surface air flow<br>Liquid, moisture, and/or vapor tightness<br>Strength-weight ratios—relative significance |
|                                                   | Establish nonstructural requirements | Service environment:<br>Corrosion resistance $\left\{ \begin{array}{l} \text{Interior} \\ \text{Exterior} \end{array} \right.$ $\left\{ \begin{array}{l} \text{Chemical} \\ \text{Soil} \\ \text{Moisture} \\ \text{Organic} \end{array} \right.$<br>Weathering Moisture $\left\{ \begin{array}{l} \text{Wet-dry cycles} \\ \text{Freeze-thaw cycles} \end{array} \right.$<br>UV exposure<br>Rain abrasion<br>Aging<br>Moisture<br>Temperature<br>Fire safety Incombustibility<br>Flame spread rate<br>Toxic gases<br>Fuel content                                  |

(Continues)

**Table 5-12** (Continued)

| Design Category                 | Subcategories                                               | Detailed Requirements                                                                                                                                                                                                                                     |
|---------------------------------|-------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Preliminary design of component | Establish cost targets                                      | Light transmission                                                                                                                                                                                                                                        |
|                                 |                                                             | Transparency                                                                                                                                                                                                                                              |
|                                 |                                                             | Translucency                                                                                                                                                                                                                                              |
|                                 |                                                             | Opaque                                                                                                                                                                                                                                                    |
|                                 |                                                             | Surface texture                                                                                                                                                                                                                                           |
|                                 |                                                             | Surface coatings                                                                                                                                                                                                                                          |
|                                 |                                                             | Thermal insulation                                                                                                                                                                                                                                        |
|                                 |                                                             | Moisture and vapor penetration                                                                                                                                                                                                                            |
|                                 |                                                             | Electrical insulation                                                                                                                                                                                                                                     |
|                                 |                                                             | Examine economics for successful competition with similar products in conventional materials                                                                                                                                                              |
|                                 | Establish production and marketing requirements             | Consider total effect of new design on end product costs: materials, tooling, finishing, assembly, warehousing and inventory, quality control, packaging and shipping, and installation                                                                   |
|                                 |                                                             | Consider effect on operating costs. Light weight is important in some applications                                                                                                                                                                        |
|                                 |                                                             | Number of identical pieces                                                                                                                                                                                                                                |
|                                 |                                                             | Minimum and maximum probable production rates                                                                                                                                                                                                             |
|                                 |                                                             | Available plant                                                                                                                                                                                                                                           |
|                                 |                                                             | Market locations                                                                                                                                                                                                                                          |
|                                 |                                                             | Shipping costs                                                                                                                                                                                                                                            |
|                                 |                                                             | Method of marketing                                                                                                                                                                                                                                       |
|                                 |                                                             | Installation criteria, if applicable                                                                                                                                                                                                                      |
|                                 |                                                             | Cost restrictions imposed by competing products or technology. Prices can shift with short- and long-term changes in market conditions                                                                                                                    |
|                                 | Select size and general configuration                       | Consider end use and limitations of suitable plastics, efficient manufacturing processes, requirements for sufficient strength and stiffness with efficient use of materials, and cost                                                                    |
|                                 | Select feasible plastics material or materials              | Satisfy structural requirements with favorable cost ratios                                                                                                                                                                                                |
|                                 |                                                             | Satisfy nonstructural criteria with acceptable compromises and tradeoffs where necessary                                                                                                                                                                  |
|                                 | Select feasible manufacturing process or processes          | Is efficient fabrication process available?                                                                                                                                                                                                               |
|                                 |                                                             | Provide required size and configuration                                                                                                                                                                                                                   |
|                                 |                                                             | Tooling and plant capital costs to be appropriate for number of pieces and rate of production                                                                                                                                                             |
|                                 | Determine structural response based on approximate analysis | Compatible with available plant and marketing plan                                                                                                                                                                                                        |
|                                 |                                                             | Provides required structural properties and quality control                                                                                                                                                                                               |
|                                 | Determine structural response based on approximate analysis | Develop suitably simplified concept of structural behavior to permit approximate determination of structural response—reactions, stress resultants, stability and stiffness requirements. Make appropriate assumptions within confines of laws of statics |

(Continues)

**Table 5-12** (Continued)

| Design Category                        | Subcategories                                                                     | Detailed Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Revise preliminary design of component | Establish design criteria for trial materials selected                            | Determine suitable allowable design strengths and stiffness, taking into account type and duration of load, service environments, process effects, quality expectations, etc.                                                                                                                                                                                                                                                                              |
|                                        | Proportion component for specific configuration and thickness                     | Determine trial shape of plates, shells, and ribs, depth of ribs and sandwiches, and wall thicknesses to meet strength, deflection, and stability criteria<br>Review economics and suitability                                                                                                                                                                                                                                                             |
|                                        | Develop significant details                                                       | Determine concept and principal details for shop and field connections, penetrations, and other subparts (if required)<br>Determine materials for connections, coatings, subparts, etc.                                                                                                                                                                                                                                                                    |
|                                        | Evaluate preliminary design                                                       | Review economics and suitability of materials and process based on preliminary proportions.<br>Consider overall compatibility and practicality of all materials and parts in component as a system<br>Does it meet functional and performance requirements?<br>Is it compatible with other components that may interact with it, relative to effects of expansion and contraction, structural support or movement, fire safety, etc.?                      |
|                                        | Review performance and functional requirements                                    | Determine if all original performance requirements are feasible within economic objectives, or whether compromises and tradeoffs should be considered                                                                                                                                                                                                                                                                                                      |
| Develop final design of component      | Optimize design to reduce cost or satisfy functional and performance requirements | General configuration<br>Configuration proportions such as rib depths, shell radii, fillet radii, etc.<br>Material thickness<br>Material alternatives—consider additives to tailor properties<br>Process alternatives                                                                                                                                                                                                                                      |
|                                        | Perform structural analysis of acceptable accuracy                                | Determine structural response—stresses, support reactions, deflections, and stability—based on a structural analysis of acceptable accuracy.<br>Determine acceptable accuracy based on economic value of component, consequences of failure, state-of-the-art capability in stress and stability analysis, margin of safety, knowledge about loads and materials properties, conservatism of loads, provisions for further evaluation by prototype testing |
|                                        | Establish final design criteria                                                   | Allowable stresses, strains, deflections<br>Margins of safety against local and overall instability, vibrations, etc.                                                                                                                                                                                                                                                                                                                                      |
|                                        |                                                                                   | Take into account type and duration of load, service environments, process effects, equality expectations                                                                                                                                                                                                                                                                                                                                                  |

(Continues)

**Table 5-12** (Continued)

| Design Category                                  | Subcategories                                                              | Detailed Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                |
|--------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Evaluate design by prototype and materials tests | Evaluate proportions and design details; revise if necessary               | Shape of plates, shells, ribs<br>Depth of ribs and sandwiches<br>Thickness of shells, flanges, and stiffeners<br>Connections: Shop<br>Field<br>Edge conditions<br>Penetrations<br>Subparts, Inserts                                                                                                                                                                                                                                                  |
|                                                  | Prepare engineering drawings                                               | Drawings are sometimes prepared in two stages:<br>Design drawings<br>Detail or fabrication drawings                                                                                                                                                                                                                                                                                                                                                  |
|                                                  | Prepare specifications for technical requirements of product and materials | Materials requirements including composition, quality standards, and minimum structural properties<br>Fabrication requirements and standards, including dimensional tolerances, allowable defects, and minimum structural properties<br>Requirements for prototype and quality control tests and procedures<br>Shipping and handling<br>Requirements for field assembly, installation, or erection                                                   |
|                                                  | Prepare manuals or instructions for maintenance and repair                 | Periodic maintenance, recoating<br>Service conditions: temperature limits, chemical exposure limits<br>Repair procedures                                                                                                                                                                                                                                                                                                                             |
|                                                  | Develop practical full-scale prototype for structural tests                | Develop practical test program to demonstrate components ability to meet structural and performance criteria. Extent of such test program, if any, depends on economic value of component, number of units to be produced, consequences of failure, accuracy of structural analysis and design, margins of safety used in design, knowledge about service loads and environments, and difficulty of duplicating service loads and conditions in test |
|                                                  | Test materials for structural properties and effect of service environment | Determine that materials produced in actual fabrication process will have the minimum structural properties and resistance to service environment assumed in the design. Extent of testing, if any, depends on available information about specific materials and processes to be used                                                                                                                                                               |
|                                                  | Revise design, if required                                                 | Correct design and detail problems, if any, revealed in tests<br>Modify materials, or process, if production materials' properties not adequate<br>Protect or modify materials if service environment causes excessive degradation of properties                                                                                                                                                                                                     |
|                                                  |                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Develop production and distribution system       | Pattern design and drawings                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|                                                  | Mold design and drawings                                                   | Take into account shape limitations and design rules that facilitate molding                                                                                                                                                                                                                                                                                                                                                                         |

(Continued)

Table 5-12 (Continued)

| Design Category | Subcategories                                             | Detailed Requirements                                                                                                                              |
|-----------------|-----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
|                 | Production process design and layouts                     | Take into account materials and configuration characteristics that simplify processes<br>Automated processes are needed for high-volume production |
|                 | Develop any special equipment                             |                                                                                                                                                    |
|                 | Distribution and marketing plan                           | Production for inventory, or by special order<br>Replacement part inventory<br>Locate production facilities to optimize distribution               |
|                 | Procedures for packaging, storing, handling, and shipping | Identify special requirements for protection in handling and shipment                                                                              |
|                 | Installation requirements                                 | Specify special requirements for assembly or installation                                                                                          |

the measurements can be determined. There can be parameters that cannot be quantified; these will contribute to the variability and limit the accuracy that can be obtained. Variations in molecular weight, pellet size, virgin/recycled mixes, etc. can affect the process. Unfortunately, these variations are not often recognized or easily identified (Chaps. 12 and 13).

Risks and the Products

Examples of the different types of risks follow (1,414).

Acceptable Risks

People are subjected to many risks in the plant, at home, and elsewhere that can cause

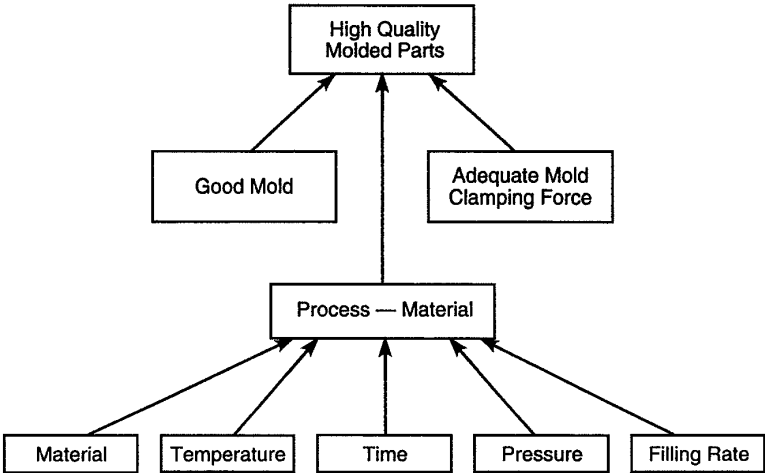


Fig. 5-30 Summary chart highlighting the importance of understanding the complete injection molding operation.

harm, health problems, and/or death. Precautions should be taken and enforced based on what is practical, logical, and useful. However, those involved in laws and regulations, as well as the public and particularly the news media, should recognize that there is acceptable risk. The concept of acceptable risk was developed decades ago in connection with toxic substances, food additives, air and water pollution, and fire safety and related environmental concerns. It can be defined as a level of risk at which a seriously adverse result is highly unlikely to occur, but it cannot guarantee 100% safety.

Thus acceptable risk means living with reasonable assurance of safety and acceptable uncertainty. Practically all elements around us encompass some level of uncertainty, and so risk enters into all aspects of our lives including the use of automobiles, aircraft, boats, lawnmowers, food, medicine, water, and the very air we breathe.

#### *Acceptable Goals*

The goal is to approach perfection in a zero-risk society. Basically, no product is without risk; failure to recognize this factor may put excessive emphasis on achieving an important goal while drawing precious resources away from product development and approval. The target or goal should be to attain a proper balance between risk and benefit using realistic factors and not the “public-political panic” approach. People are exposed to many risks. Some pose a greater threat than others. The following data illustrate the probability over a lifetime of premature death per 100,000 people. In the United States 290 pedestrians will be hit by a car and die, 200 will be killed by tobacco smoke, 75 by diagnostic X rays, 75 while bicycling, 16 will die as passengers in a car, 7 will succumb to Miami and New Orleans drinking water, 3 will be killed by lightning, 3 by hurricane, and 2 by fire.

#### *Acceptable Packaging Risks*

In 1995 a young intern at the FDA made some interesting calculations. If the govern-

ment permitted the packaging of Coca Cola in acrylic barrier plastic bottles, and if you drank 37,000 gallons of coke per day for a lifetime, you would have a 10% risk of getting cancer. Since normally people have a 25% risk of getting cancer, reducing it by 10% looks like a real plus for the acrylic barrier plastic bottles. Must the unrealistic public then enact a law that everyone should drink lots of coke?

#### *Risk Assessments*

The designer, equipment installer, user, and all others involved in production should each consider performing a risk assessment. The production is reviewed for hazards created by each part of the line when operating as well as when equipment fails to perform or complete its task. This action includes startups and shutdowns, preventative maintenance, QC inspection, material and mold handling, repair, and maintenance.

#### *Fire Risks*

In case of fire the potential for harm to life or damage to property resulting from its occurrence exists. A fire risk assessment standard can be determined where no harm (or major harm) occurs (Chap. 12).

#### *Risk Management*

There are liability insurance management firms that sell forward contracts at fixed prices and then settle them against market prices established by various consultant firms. A cap is a typical method in which the risk management firm reimburses the client (fabricator) if prices rise above a fixed, pre-agreed level.

#### *Risk Retention*

With risk retention the client (fabricator) funds its own losses instead of paying a management firm.

### Perfection

Achievable program plans begin with the recognition that smooth does not mean perfect. Perfection is an unrealistic ideal. It is a fact of life that the further someone is removed from a task, the more they are apt to expect perfection from those performing it. The expectation of perfection blocks genuine communication among workers, departments, management, customers, and vendors.

Therefore one can define a smoothly run program as one that creates a product that meets the specifications, is delivered on time, falls within the price guidelines, and stays close to budget. Perfection is never reached; there is always room for improvements as summarized in the FALLO approach (Fig. 1-1) and throughout history. To live is to change and to reach perfection is to have changed often (in the right direction). Perfection is like stating that no one on earth is without sin. The term perfection is nonetheless useful as a target in designing-to-molding products, one that is approached asymptotically.

### Cost Modeling

The computer supports rather routine tasks of embodiment and detailed operation rather than the human creative activities of conceptual operation. The computer can make things better (fact) but usually at the cost of increased complexity. An asset is to be knowledgeable of the computer's capability in specific areas of interest such as machine settings, product design, mold design, etc.

Using computer tools properly results in a much higher level of processing and minimizes guesswork. Successfully designed products require the combination of various factors including sound judgment and knowledge of processing. Although incorporating technical changes in the plant to test their viability may have been appropriate in the past, it is usually economically not feasible to explore today's wide range of alternatives in this fashion. Technical cost modeling (TCM) has

been developed as a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial-and-error innovation and process utilization (Chap. 14).

### Innovative Designs

A skilled designer blends knowledge of materials, an understanding of manufacturing processes, and imagination of new or innovative designs. Recognizing the limits of design with traditional materials is the first step in exploring the possibilities for innovative design with plastics. Some designers operate by creating only the stylish outer appearance, allowing basic engineers to work within that outside envelope. This approach is used very successfully in certain products or parts such as for furniture. However, combining design appearance with engineering can produce a stylish product that incorporates the best combination with ease of processing when using a specific plastic, simplified assembly, capability of repair, streamlined quality control, and/or other conditions. The stylish envelope that eventually emerges will be a logical and aesthetic answer to the design challenge.

### Protect Designs

Five different methods of protecting your design exist in the United States. Each is weighed according to its advantages and disadvantages based on specific needs. They are: (1) contracts, in which other party agrees not to make, use, etc. without designer's permission; (2) copyrights, which offer protection upon creation of design; (3) trade dress, which protect the design when it is either inherently distinctive or has become distinctive; (4) utility patents, which protect the functional and structural features of a product; and (5) design patents, which protect the ornamental appearance of a product without regard to how it functions (see Chap. 16, Legal Matters).

**Basics in Design with Plastics**  
**Three Dimensional Illustration**  
**of the Contour Plots**

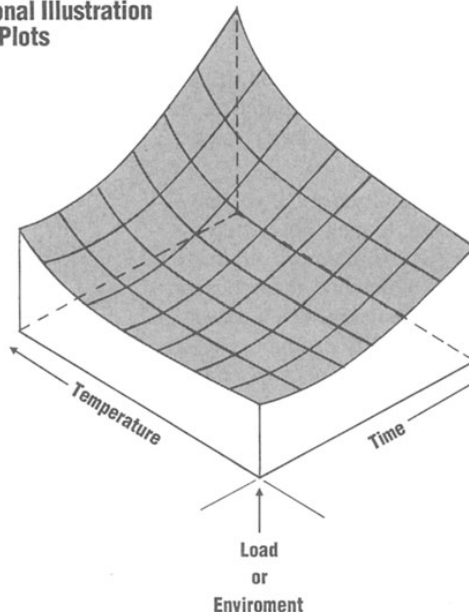


**Fig. 5-31** To be effective, the evaluation of new product ideas should proceed according to a logical step-by-step procedure as summarized in this contour plot diagram.

### Summary

Most successful designers have the ability to develop products that are instantly acceptable to the buyer. These designs offer a recognizable, functional improvement along with visual appeal that sets the product apart from other products. As summarized in Figs. 1-15 and 5-31 there is a logical and effective approach to designing a new product (1, 10, 18, 278, 573).

Too many new product designs or redesigns are nothing more than slight improvements that basically any reliable designer could make with a minimum of thought. Many companies inch their way to progress with just a slight change every now and then. This is the easy way to “improve” the product line with the least disruption of the manufacturing process and, with the exception of printing new brochures, requires little adjustment by the sales staff.

A new design, redesign, design update, or model change in order to catch the interest of

the design engineer who must use it should offer at least one clear-cut advantage over the model it supercedes. The inching ahead process can offer the writer of promotional copy a number of things to write about, but there should be one or several technically sound and verifiable advantages. This gives the design engineer reason to spend time learning about the product, testing it, and perhaps eventually buying it.

A new design or redesign should also incorporate some visual indication of change. A new shape or form is great if you can get it, but a new color or label will do. When the buyer purchases something new, the product itself should look like it is new and different. Radical changes can be upsetting, but a big change is better than no change when dealing with the needs of the design community. Here is a checklist for designers looking for good things to say about their design:

1. Tell how it improves the intended function. What is its principal advantage,

speed of operation, reliability, size, cost, material of construction, etc.? Focus on main user benefits.

2. Describe efficiency of operation. If you can, document any improved operation in terms of dollars, power, time, etc. This gets the attention of other engineers.

3. Emphasize the quality story. If you have a quality product with longer life, better appearance, quieter operation, improved durability, and greater convenience, many design engineers will be interested in such a component for use in their quality product. This is particularly true now in terms of office equipment and home appliances where environmental effect is a sales factor (30, pp. 139 to 143).

4. Size, weight, portability, ease of handling, neatness of layout, fit, and compatibility are often crucial factors in design product selection. Visual appearance is always important to call attention to its advantages.

5. A designer's headache is the product that cannot be maintained, repaired, replaced, or renewed once it is incorporated in the design assembly. Most of us have been amazed by such items and we respond favorably to component designs that can be fixed.

6. Safety considerations are a plus factor when incorporated in the design component, rather than left as a final assembly project or add-on. Safety should be a prime consideration whenever there are exposed moving parts, pressure, hazardous substances, or unknown conditions that could result in injury during assembly or subsequent product use.

Change, or more specifically rate of change, is the key to nearly all design activity. Change creates the need for new and better products and it also provides designers with the technical tools for making better products. There is little excuse for lack of technical improvement of engineered products. There is also little excuse for not making these products attractive, easy to use, and easy to maintain for the benefit of the buyer.

### *Molders' Contributions*

Molders can always provide important contributions at the product design stage (when they are allowed to do so). With the development of computerized design systems the molder is automatically part of the team effort, rather than next in line. Any molder who is seriously considering staying in business at a strong technical level cannot ignore the advantages of CAD/CAM/CAE/CIM (Chap. 9). Moreover, the manufacturing and planning aspects will certainly help the business prosper. Many end users have taken the initiative and are requiring their regular molders to be able to read and contribute to their computerized design work.

The molder may have the capability to mold parts that do not limit the use of plastics and thereby help the customer meet new design challenges. To illustrate how traditional materials such as metals limit the design process, consider a spring. Because the manufacturing process in metals limits the options in producing a variety of shapes in this material, steel springs are produced in only three basic shapes: the torsion bar, helical coil, and flat-shaped leaf spring. By comparison, thermoplastics and thermoset plastics can be easily molded into a variety of shapes.

The molder can also participate in reducing or using the required amount of plastic material in a design. In product design, there has always been the desire to use less of any plastic, because the result is usually a lower-cost product. On the other side of the issue is the use of more material to provide for a higher design safety factor beyond what is required. Thus, unfortunately, there are designs using more material than needed, particularly in the case of plastics. It is inexperience in designing with plastics that causes this problem. Many designers lack the knowledge of at least relating a material's performance to the processing variables that directly influence safety factors and the amount of a plastic to be used. With the flexibility that exists in designing with plastics, different approaches may be used to reduce part weight, such as applying internal ribbing,

corrugations, or sandwich structures and orienting or prestretching.

All this activity is aimed at producing products that use less in the way of materials and, in turn, let less material enter the solid-waste stream. Some designers, including myself, have habitually listed in product design specifications that specific environmental requirements should be met.

A designer sometimes has an opportunity to use a material that provides no problem in the solid-waste stream or a design that allows lower-cost recycled plastics to be used. In fact, blends of virgin (not previously processed) plastics with recycled plastics could permit the meeting of required product performance requirements. Although this approach has been used for the past century, its use will become crucial as more and more recycled plastics become available. However, the designer must take into account the usual lower performances that will occur with recycled plastics unless modified to provide improved performance.

### Terminology

**Aesthetic** The external surface appearance of an object or product. Its elements may include color, shape, or particular features of the product. In packages, the texture or “feel” of the object may also be part of the special desirable responses. With the varieties of plastics available, one can obtain virtually any desired aesthetic appearance desired.

**Anisotropy** A layup, laminate construction, etc. in which properties differ in different directions along the flat plane.

**Art and science** Product design is as much an art as a science. Guidelines exist regarding meeting and complying with art and science.

**Artwork** Original design including drawings and text.

**Asymptotic approach** Relates to never meeting one’s target or objective. Mathematically or in engineering terms the asymptote is a line that is the limiting position of a tangent to a curve as its point of contact recedes indefinitely along an infinite branch of the curve. That point gets closer and closer to the line but never reaches it.

**Collapsible bottle** Bellows-style collapsible containers, such as bottles and tanks, that are foldable. The series of bellows overlap and fold to retain their folded condition without external assistance, thus providing a self-latching feature. This latching is the result of bringing together under self-pressure two adjacent conical sections of unequal proportions and different angulations to the bottle axis. The swing action of one conical section around a fixed pivot point from an outer to an inner resting position. The two symmetrically opposed pivot points and rotating segments keep a near constant diameter as they travel along the bottle axis. These blow molded bottles provide advantages and conveniences such as reduced storage space, transportation, disposal space, etc. as the content is dispersed, reducing oxidation that affects freshness of certain products (e.g., mayonnaise).

**Computer finite element mesh operation** Engineering method for determining the structural integrity of a mechanical part by mathematical simulation. Automatic mesh generation creates grid points and elements for specific regions of a model allowing creation of necessary data for finite element analysis programs.

**Disassembly design** Plastics with their different properties provide design approaches to simplify disassemblies. All the methods for fastening plastics are amenable to one of the two basic methods of disassembly, namely reverse assembly or brute force. Joining processes that are not reversible and require the use of brute force disassembly include most inserts and welding procedures.

**Shall** Word used in many standards denoting a mandatory requirement.

**Should** Word used in many standards for nonmandatory requirement.

**Stress relaxation** Also called stress relieving or stress decay. The decrease in stress after a given time at constant strain. Stress relaxation can cause warpage, internal and/or external dimensional changes, or complete damage to the part.

**Stripping torque** The torque at which threads are stripped out of the molded part. High stripping torque is optimal.

**Structure, primary** Mainframe of a product. Examples include aircraft main supports, building main beams, and automobile frames. If the primary structure fails, it would be damaging or catastrophic to the product and/or people.

**Structure, secondary** A structure that is not critical to the survival of the primary structure.

**Surface, class A** Definition of the highest quality surface technically achievable on exterior auto body panels, etc.

**Weathering and design** Weather is the given state of the atmosphere and its impact on human life, products, etc. Weathering and design normally refer in the industry to the effect on materials with short or prolonged outdoor exposure. With certain plastics the process of disintegration and decomposition can occur as a consequence of exposure to the atmosphere with its oxygen, contaminants (smoke, chemicals, etc.) and through the action of frost, water, heat, etc.

**x axis** The axis in the plane of a material used as 0° reference; thus the y axis is the axis in the plane of the material perpendicular to the x axis; the z axis is the reference axis normal to the x-y plane. The term plane or direction is also used in place of axis.

**y axis** See *x axis*.

**z axis** See *x axis*.

# Molding Materials

## Overview

With a little effort practically any plastic injection molding machine is capable of producing melts to produce products. However, different interrelationships exist between materials and processing equipment operations so that if results are not properly analyzed and applied inferior products and usually more expensive products are produced. The many different plastics with their many different fabricating characteristics produce all kinds of products worldwide (Fig. 1-17). Total consumption of all plastics is summarized in Table 6-1. Of the total consumption about 32 wt% go through IMMs. Extruders process about 36 wt%. Even though injection molding comes in second plastic consumptionwise, in the United States alone about 80,000 injection molding machines are operating versus about 18,000 extruders.

Plastics comprise a large and varied group of materials totaling over 17,000 worldwide. They usually consist of, or contain as an essential ingredient, an organic substance of high molecular weight. Most are produced synthetically; very few occur in nature (Fig. 6-1). Plastic materials to be processed are in the form of pellets, granules, powder, flock, liquid, etc. There are about 200 basic types or families that are commercially recognized with less than 20 that are popularly

used. Examples of these plastics are shown in Table 6-2.

Within the most common plastic families there are five major thermoplastic types that constitute about two-thirds of all thermoplastics. Approximately 18 wt% is low density polyethylene, 17% polyvinyl chloride, 12% high density polyethylene, 16% polypropylene, and 8% polystyrene. In turn each has literally thousands of different formulated compounds. The relatively new generation of high performance metallocene and elastomeric plastics belong in this group. The basic types, with their many modifications of different additives and fillers, grafting, alloying, etc., provide different processing capabilities and/or product performances. Table 6-3 provides examples of the family of plastics with examples of the families of other materials.

The usual use of a virtually endless array of additives, colorants, reinforcements, fillers, etc. permits compounding the raw materials (polymers/plastics) to impart specific performance qualities and expand plastic performance. Compounding relies on factors such as polymerization chemistry to combine a base plastic with modifiers, additives, and other plastics to develop new plastics so that within each group of plastics literally thousands of molding compounds can be produced from each type of plastic (Chap. 11, Plastic Material and Equipment Variables).

**Table 6-1** World plastics consumption (million lb)\*

| Plastic                     | Region | United States | Canada | Mexico | Brazil | Other Latin America <sup>a</sup> | Western Europe <sup>b</sup> | Eastern Europe <sup>c</sup> | Japan  | China  | Other Asia-Pacific <sup>d</sup> | Africa and Middle East | Rest of World | Grand Total |
|-----------------------------|--------|---------------|--------|--------|--------|----------------------------------|-----------------------------|-----------------------------|--------|--------|---------------------------------|------------------------|---------------|-------------|
| LLDP                        |        | 8,468         | 610    | 480    | 610    | 900                              | 4,093                       | 1,023                       | 1,439  | 2,661  | 6,121                           | 580                    | 367           | 27,352      |
| LDPE                        |        | 7,748         | 1,281  | 1,176  | 1,590  | 619                              | 10,254                      | 2,563                       | 1,804  | 1,938  | 3,391                           | 1,210                  | 457           | 34,031      |
| HDPE                        |        | 14,065        | 1,136  | 952    | 1,388  | 417                              | 9,178                       | 2,294                       | 2,158  | 1,218  | 4,967                           | 1,325                  | 532           | 39,630      |
| Urethane                    |        | 5,265         | 475    | 380    | 410    | 390                              | 5,481                       | 1,808                       | 1,512  | 1,825  | 4,850                           | 390                    | 310           | 23,096      |
| PVC                         |        | 14,698        | 1,394  | 605    | 1,456  | 1,837                            | 12,388                      | 2,477                       | 3,761  | 5,338  | 11,633                          | 1,250                  | 773           | 57,610      |
| Polystyrene                 |        | 6,589         | 725    | 405    | 280    | 495                              | 6,180                       | 1,236                       | 2,175  | 2,299  | 5,275                           | 190                    | 352           | 26,201      |
| Polypropylene               |        | 13,739        | 796    | 695    | 1,366  | 1,307                            | 13,566                      | 2,713                       | 5,001  | 2,667  | 11,176                          | 1,275                  | 738           | 55,039      |
| ABS                         |        | 1,409         | 145    | 175    | 365    | 290                              | 1,410                       | 282                         | 948    | 460    | 950                             | 305                    | 92            | 6,831       |
| Acrylic                     |        | 613           | 75     | 80     | 165    | 140                              | 576                         | 115                         | 302    | 155    | 325                             | 140                    | 37            | 2,723       |
| Unsaturated Polyester       |        | 1,681         | 180    | 125    | 250    | 210                              | 1,036                       | 207                         | 1,285  | 645    | 1,175                           | 215                    | 95            | 7,104       |
| Nylon                       |        | 1,267         | 110    | 90     | 170    | 145                              | 1,210                       | 242                         | 339    | 170    | 425                             | 155                    | 59            | 4,382       |
| PET                         |        | 4,350         | 410    | 192    | 482    | 386                              | 2,464                       | 493                         | 1,178  | 715    | 5,441                           | 390                    | 224           | 16,705      |
| Poly-carbonate              |        | 857           | 90     | 70     | 155    | 140                              | 607                         | 121                         | 443    | 215    | 475                             | 145                    | 45            | 3,363       |
| Thermoplastic Polyester     |        | 346           | 45     | 30     | 65     | 50                               | 243                         | 48                          | 164    | 85     | 322                             | 42                     | 20            | 1,460       |
| Acetal                      |        | 389           | 40     | 30     | 70     | 45                               | 317                         | 63                          | 212    | 106    | 235                             | 63                     | 21            | 1,591       |
| Recycle Plastics            |        | 1,800         | 166    | 121    | 195    | 162                              | 1,625                       | 220                         | 502    | 453    | 1,254                           | 165                    | 88            | 6,751       |
| Other Plastics <sup>e</sup> |        | 8,150         | 763    | 412    | 875    | 74                               | 7,250                       | 1,750                       | 255    | 198    | 5,310                           | 740                    | 344           | 26,121      |
| Total                       |        | 91,414        | 8,441  | 6,018  | 9,892  | 7,607                            | 77,878                      | 17,655                      | 23,478 | 21,148 | 63,325                          | 8,580                  | 4,554         | 339,990     |

<sup>a</sup> Argentina, Chile, Columbia, Venezuela & all other.<sup>b</sup> European Union plus Norway & Switzerland.<sup>c</sup> Includes Russia and Balkans.<sup>d</sup> Australia, India, Indonesia, Malaysia, North Korea, Pakistan, South Korea, Taiwan, Thailand, Philippines, Singapore, Vietnam.<sup>e</sup> High Performance, other thermosets, specialty elastomers, tailored blends, and alloys.

\*Source: Modern Plastics/PlastiSource. Estimates/DVR.

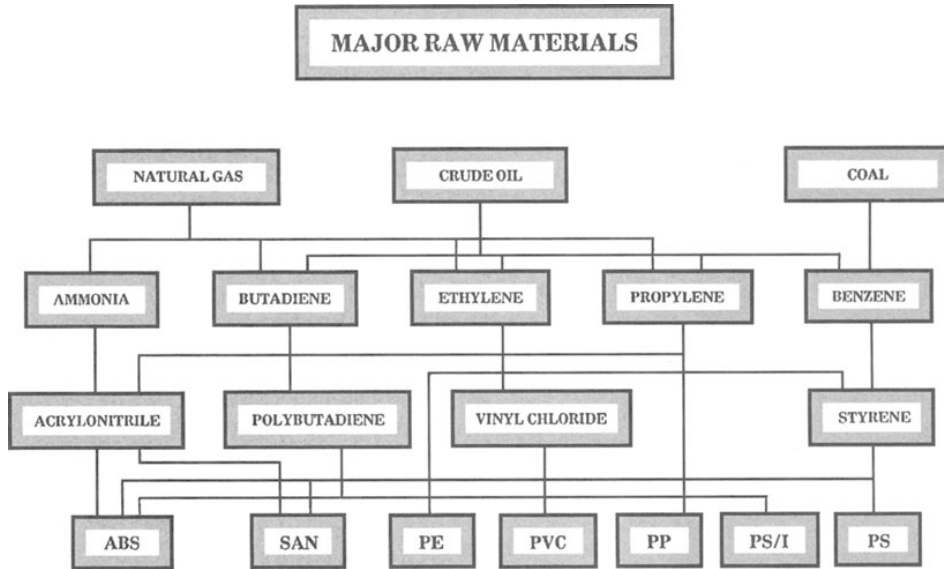


**Fig. 6-1** Simplified flow diagram from raw materials to plastic materials.

Plastics can be made to be hard, elastic, rubbery, crystal clear, opaque, electrically conductive (261), strong, stiff, outdoor weather-resistant, electrically conductive, or practically anything that is desired, depending on the choice of starting materials and method of molding (Figs. 6-2, 5-9, 5-12, and 5-14). This chapter will review some of the properties and processing techniques of plastics as they relate to meeting the performance requirements after injection molding. Not all plastics will be reviewed. Information presented shows the typical different properties that can be obtained, based on the plastic used and how it is molded. As an example, a specific plastic can be molded using different IMM settings so that dimensional tolerances on a part can vary after each molding, or the machine can be set so that extremely close tolerances are met repeatedly.

The dimensional accuracy that can be met depends on different factors, such as accuracy of mold and machine performance, properties of materials, operation of the complete molding cycle, wear or damage of machine and/or mold, shape, size, and thicknesses of part, postshrinkage (which can reach 3%

for certain materials), and the degree of repeatability in performance of the machine, mold, material, etc. (Chap. 5).

Thermosets generally are more suitable for meeting the tightest tolerances. With thermoplastics, the situation can be more complicated. As is well known, crystalline plastics (PE, PP, etc.) generally have different rates of shrinkage in the longitudinal and transverse directions of melt flow. In turn (but not recognized by many molders), these directional shrinkages can significantly vary due to changes in injection pressure, melt heat, mold heat, and part thickness or shape. The changes can occur at different rates in different directions. To minimize and control tolerances, consider using the highest melt heat, keep a gate surrounding area where tight tolerances are required, use a machine that requires at least 70% (50% is usually better) of shot capacity, minimize time that the melt is in the barrel, and understand the complete operation of the machine, mold, and material to ensure part tolerance repeatability. Not every material is suitable for molded parts requiring tight tolerances.

**Table 6-2** Types of plastics

|                                       |                                         |
|---------------------------------------|-----------------------------------------|
| Acetal (POM)                          | Polybutylene terephthalate (PBT)        |
| Acrylics                              | Polyethylene terephthalate (PET)        |
| Polyacrylonitrile (PAN)               | Unsaturated polyester (TS polyester)    |
| Polymethylmethacrylate (PMMA)         | Polyetherketone (PEK)                   |
| Acrylonitrile butadiene styrene (ABS) | Polyetheretherketone (PEEK)             |
| Alkyd                                 | Polyetherimide (PEI)                    |
| Allyl diglycol carbonate (CR-39)      | Polyimide (PI)                          |
| Allyls                                | Thermoplastic PI                        |
| Diallyl isophthalate (DAIP)           | Thermoset PI                            |
| Diallyl phthalate (DAP)               | Polymethylmethacrylate (acrylic) (PMMA) |
| Aminos                                | Polymethylpentene                       |
| Melamine formaldehyde (MF)            | Polyolefins (PO)                        |
| Urea formaldehyde (UF)                | Chlorinated PE (CPE)                    |
| Cellulosics                           | Cross-linked PE (XLPE)                  |
| Cellulose acetate (CA)                | High-density PE (HDPE)                  |
| Cellulose acetate butyrate (CAB)      | Ionomer                                 |
| Cellulose acetate propionate (CAP)    | Linear LDPE (LLDPE)                     |
| Cellulose nitrate                     | Low-density PE (LDPE)                   |
| Ethyl cellulose (EC)                  | Polyallomer                             |
| Chlorinated polyether                 | Polybutylene (PB)                       |
| Epoxy (EP)                            | Polyethylene (PE)                       |
| Ethylene vinyl acetate (EVA)          | Polypropylene (PP)                      |
| Ethylene vinyl alcohol (EVOH)         | Ultra-high-molecular-weight PE (UHMWPE) |
| Fluorocarbons                         | Polyoxymethylene (POM)                  |
| Fluorinated ethylene propylene (FEP)  | Polyphenylene ether (PPE)               |
| Polytetrafluoroethylene (PTFE)        | Polyphenylene oxide (PPO)               |
| Polyvinyl fluoride (PVF)              | Polyphenylene sulfide (PPS)             |
| Polyvinylidene fluoride (PVDF)        | Polyurethane (PUR)                      |
| Furan                                 | Silicone (SI)                           |
| Ionomer                               | Styrenes                                |
| Ketone                                | Acrylic styrene acrylonitrile (ASA)     |
| Liquid crystal polymer (LCP)          | Acrylonitrile butadiene styrene (ABS)   |
| Aromatic copolyester (TP polyester)   | General-purpose PS (GPPS)               |
| Melamine formaldehyde (MF)            | High-impact PS (HIPS)                   |
| Nylon (Polyamide) (PA)                | Polystyrene (PS)                        |
| Parylene                              | Styrene acrylonitrile (SAN)             |
| Phenolic                              | Styrene butadiene (SB)                  |
| Phenol formaldehyde (PF)              | Sulfones                                |
| Phenoxy                               | Polyether sulfone (PES)                 |
| Polyallomer                           | Polyphenyl sulfone (PPS)                |
| Polyamide (nylon) (PA)                | Polysulfone (PSU)                       |
| Polyamide-imide (PAI)                 | Urea formaldehyde (UF)                  |
| Polyarylethers                        | Vinyls                                  |
| Polyaryletherketone (PAEK)            | Chlorinated PVC (CPVC)                  |
| Polyaryl sulfone (PAS)                | Polyvinyl acetate (PVAc)                |
| Polyarylate (PAR)                     | Polyvinyl alcohol (PVA)                 |
| Polybenzimidazole (PBI)               | Polyvinyl butyrate (PVB)                |
| Polycarbonate (PC)                    | Polyvinyl chloride (PVC)                |
| Polyesters                            | Polyvinylidene chloride (PVDC)          |
| Aromatic polyester (TS polyester)     | Polyvinylidene fluoride (PVF)           |
| Thermoplastic polyesters              |                                         |
| Crystallized PET (CPET)               |                                         |

## 6 Molding Materials

**Table 6-3** Example of different families of materials

|          |                         |                         |
|----------|-------------------------|-------------------------|
| Plastics | Polyethylene            |                         |
|          | Polyvinylchloride       |                         |
|          | Polytetrafluoroethylene |                         |
|          | Polymethylmethacralate  |                         |
|          | Polyacetal              |                         |
|          | Phenolics               |                         |
|          | Polyimides              |                         |
|          | Polyamides              |                         |
|          | Polycarbonate           |                         |
|          | Elastomers              | Urethanes               |
|          |                         | Silicones               |
|          |                         | Polychloroprene         |
| Ceramics | Aluminum oxide          |                         |
|          | Plasma coatings         | Chromium oxide          |
|          |                         | Zirconia                |
|          |                         | Titanium carbide        |
|          |                         | Chromium carbide        |
|          | Cemented carbides       |                         |
|          | Vitrified mica          |                         |
|          | Carbon products         |                         |
| Metals   | Carbon steels           | 1010                    |
|          |                         | 1020                    |
|          |                         | 1040                    |
|          |                         | 1050                    |
|          |                         | 1090                    |
|          |                         | B1112                   |
|          | Tool Steels             | O1                      |
|          |                         | A2                      |
|          |                         | D2                      |
|          |                         | S1                      |
|          |                         | H13                     |
|          |                         | M2                      |
|          | Cast irons              | Class 20                |
|          |                         | Class 35                |
|          |                         | Ductile 60-45-10        |
|          | Copper alloys           | ETP copper CDA 110      |
|          |                         | DHP copper CDA 122      |
|          |                         | Tin bronze CDA 905      |
|          |                         | Be copper CDA 172       |
|          |                         | Yellow brass CDA 360    |
|          |                         | Phosphor bronze CDA 521 |
|          | Nickel alloys           | Monel                   |
|          |                         | Hastelloys              |
|          |                         | Ni, Cr, 8 alloys        |
|          |                         | Pure nickel             |
|          | Alloy steels            | 4140                    |
|          |                         | 4340                    |
|          |                         | 4620                    |
|          |                         | 9310                    |
|          |                         |                         |
|          | Special steels          | Nitralloy               |
|          |                         | Marage 200-350          |
|          |                         | Weathering              |
|          | Stainless steels        | 303                     |
|          |                         | 304 (CF-8)              |
|          |                         | 316 (CF-8M)             |
|          |                         | 420                     |
|          |                         | 440C                    |
|          |                         | 17-4 PH (CB-7Cu)        |
|          | Aluminum alloys         | 3003                    |
|          |                         | 5052                    |
|          |                         | 6061                    |
|          |                         | 7075                    |
|          |                         | 355                     |
|          |                         | 380                     |
|          | Zinc                    | ASTM B86-48             |
|          |                         | No <del>XX</del> 5      |
|          | Titanium                | Pure Ti (Gr 1-3)        |
|          |                         | Ti-6Al-4V               |
|          | Magnesium               | AZ51                    |
|          |                         | AZ63                    |

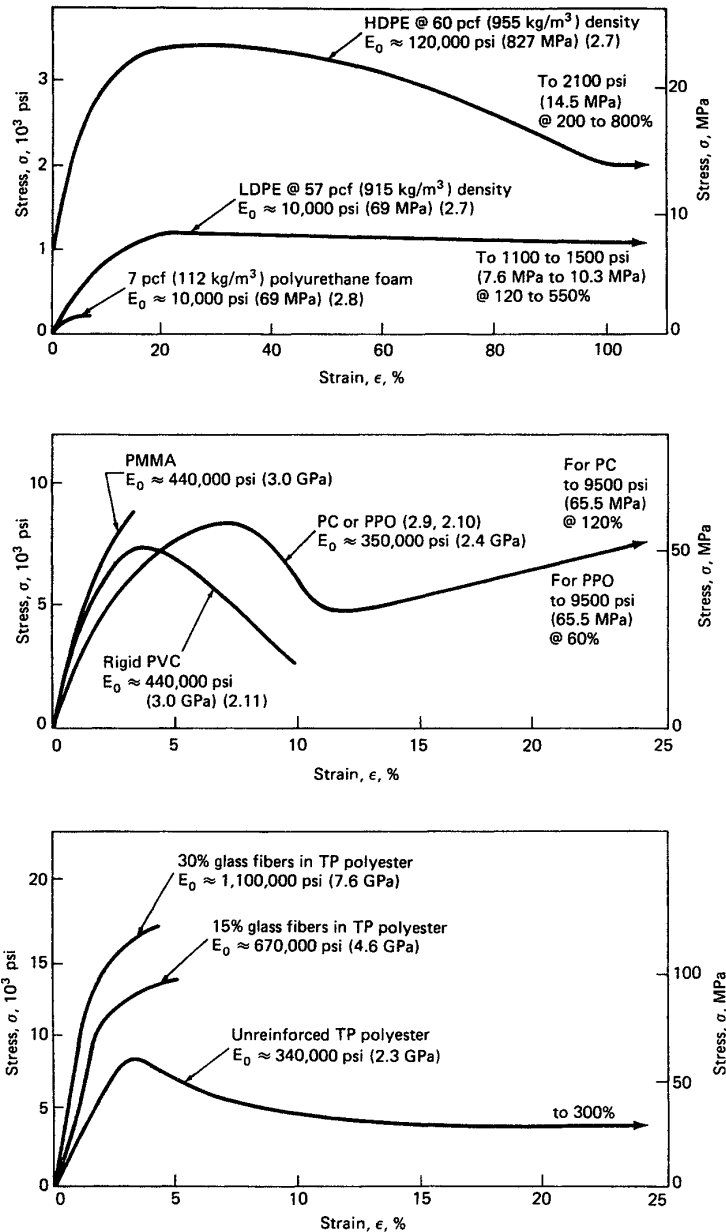


Fig. 6-2 Basic stress-strain relationship for several thermoplastics.

### Definition of Plastics

There is a general accepted definition for plastics that goes like this: Any one of a large and varied group of materials consisting

wholly or in part of combinations of carbon with oxygen, hydrogen, nitrogen, and other organic and inorganic elements that, while solid in the finished state, at some stage in its manufacture is made liquid, and thus capable

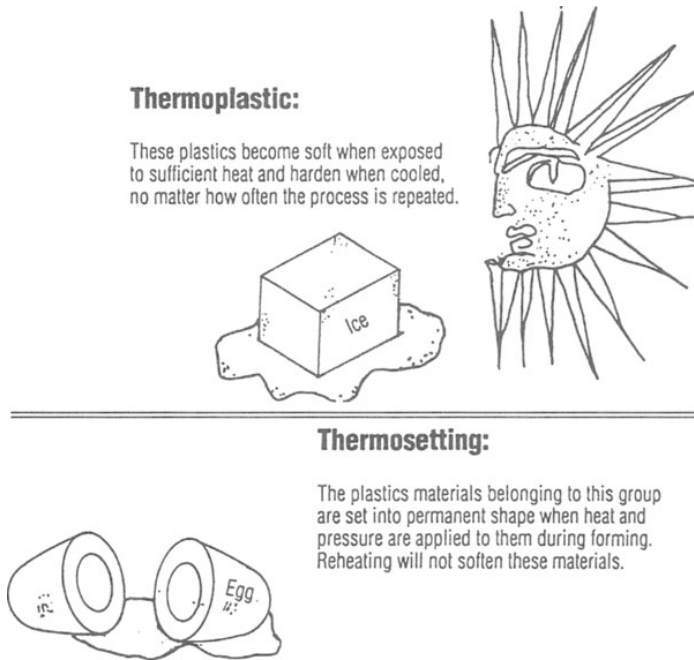


**Fig. 6-3** Characteristics of thermoplastics (TPs) and thermosets (TSs).

of being formed into various shapes, most usually (although not necessarily) through the application, either singly or together, of heat and pressure.

Plastics are a family of materials, not a single material, each member of which has its own distinct and special advantages. (See Table 6-2 for typical names of materials in the plastic families.) Whatever their properties or form, however, most plastics fall into one of two groups: *thermoplastics* and *thermosets*.

*Thermoplastics and thermoset plastics*  
The thermoplastic (TP) resins consist of long molecules, either linear or branched, having side chains or groups that are not attached to other polymer molecules. Thus, they can be repeatedly softened and hardened by heating and cooling. Usually, thermoplastic resins are purchased as pellets or granules that are softened by heat under pressure allowing them to be formed. When cooled, they harden into the final desired shape. No chemical changes generally take place during forming. The analogy would be to a block of ice

that can be softened (i.e., turned back into a liquid), poured into any shape of cavity, and then cooled to become a solid again (Fig. 6-3).

In thermosetting resins, reactive portions of the molecules form cross-links between the long molecules during polymerization. The linear polymer chains are thus bonded together to form a three-dimensional network. Therefore, once polymerized or hardened, the material cannot be softened by heating without degrading some linkages. Thermosets (TSs) are usually purchased as liquid monomer-polymer mixtures or a partially polymerized molding compound. In this uncured condition, they can be formed to the finished shape with or without pressure and polymerized with chemicals or heat. The analogy in this case would be to a hard-boiled egg, which has turned from a liquid to a solid and cannot be converted back to a liquid (Fig. 6-3).

The dividing line between TPs and TSs is not always distinct. Cross-linked TSs are thermoplastic during the initial heat cycle and prior to the chemical cross-linking action.

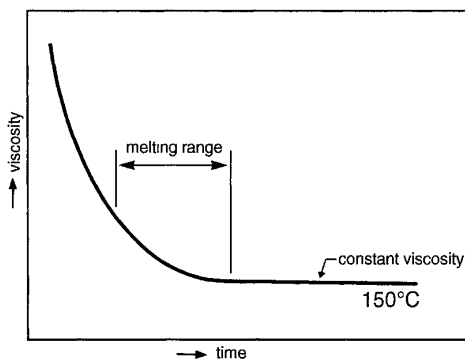


**Fig. 6-4** Viscosity versus time graph of a thermoplastic under constant temperature.

Other plastics may behave like cross-linked high-density polyethylene, which normally is a TP but can be cross-linked, by high-energy radiation or chemically while being processed, to become a TS called XHDPE.

There is a basic difference in the behavior of molten TP and TS plastics. Figure 6-4 shows how viscosity decreases with time in a thermoplastic polymer as it changes from a solid to a liquid state under the action of heat. Once the melting point is attained after a certain time, if no temperature change occurs, the molten mass viscosity also remains constant for a certain time (10 to 20 min), beyond which the thermal degradation of material may set in.

A TP melt has the lowest viscosity (and consequently the highest fluidity), which is maintained for several minutes. This allows the melt to be injected or otherwise processed within relatively long time intervals. A TS melt exhibits a substantially different behavior. The viscosity of a TS is shown in Figs. 6-5 and 6-6. Initially, heat causes the plastic to soften and melt, attaining its minimum viscosity (and highest fluidity) in a few seconds.

If more heat is added, a condensation reaction sets in, and the melt viscosity gradually increases until the plastic is fully hardened. The plot of viscosity curves at different temperatures shows that the higher the temperature at which processing occurs, the shorter the time interval (its "plastic life") within which a TS can be molded. This is a simpli-

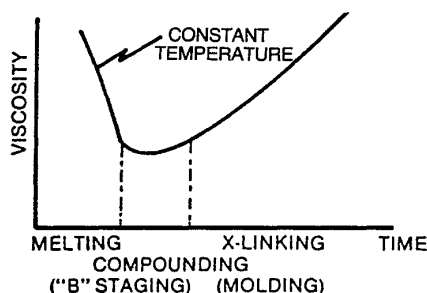


**Fig. 6-5** Viscosity changes during the processing of thermoset plastics. The B stage represents the start of the heating cycle that recycles viscosity and is then followed by a chemical reaction (cross-linking) and the solidification of the plastic.

fied description of the reaction that is actually much more complex.

The structure of TSs, like TPs, is also chain-like. Prior to molding, TSs are similar to TPs. Cross-linking is the principal difference between TSs and TPs. In TSs, during curing or hardening the cross-links are formed between adjacent molecules, resulting in a complex, interconnected network that can be related to the material's viscosity and performance (see Figs. 6-4 and 6-5). These cross-bonds prevent the slippage of individual chains, thus preventing plastic flow under the addition of heat. If excessive heat is added after cross-linking has been completed, degradation rather than melting will occur. TSs generally cannot be used alone structurally and must be filled or reinforced

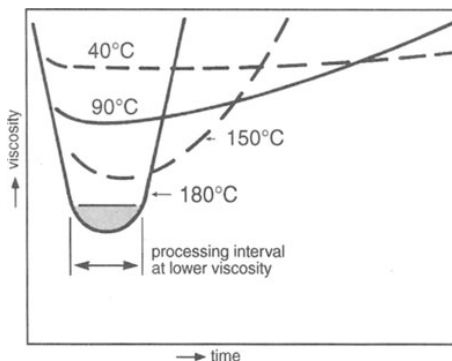


**Fig. 6-6** Viscosity versus time graph of a thermoset plastic (phenolic) at various temperatures.

with materials such as calcium carbonate, talc, or glass fiber. The most common reinforcement is glass fiber.

By using different modifiers, additives, fillers, and reinforcements with the various plastics, more than 17,000 compounds are commercially available. They are classified as commodity (90%) and engineering resins. Commodities such as PE, PP, PS, and PVC account for two-thirds of plastics sales. Engineering resins are characterized by better heat resistance, higher impact strength, high stiffness, and/or many other “improved” properties, and thus they bring a higher price than commodity resins. Among the more significant engineering resins are PA, PC, PS, PEEK, and ABS. Some commodity resins contain certain reinforcements and/or are alloyed with other resins that place them in the engineering categories. Perhaps the major distinction between them is cost.

For each family of plastics, such as polyethylene, there are many different grades; each grade is tailored to provide certain performance and/or process characteristics. This diversity allows the processor and product designer considerable freedom in selecting a particular grade. Actually, only a few dozen important families of plastics are used and blended into different grades (Table 6-2), so rather than 17,000 grades, only a few hundred are the big sellers. The others usually meet speciality requirements and may be of limited use. Plastic selection should be based on the performance required and process capability. Just as there are guidelines in this book for selecting the process, there are guidelines in the references for selecting plastic. Even though selection can be complex because of the many variations available, a logical approach will provide the answer. However, compromises or tradeoffs are inevitable when one is dealing with the complex but controllable (within limits) operation of processing plastics.

Many engineering resins must be molded at high temperature and within extremely narrow processing windows. They require strict temperature control, especially in complex molds that are subject to steep temperature gradients.

In high-performance materials, the melt front can cool too much as it is pushed to fill cooler cavities at the corners farthest from the sprue. Pushing the hardening melt results in high injection pressures, poor melt distribution, and poor welding of fused molding areas.

Traditionally, hot water was circulated through a mold to provide the basic heat, allowing high-temperature resins to fill the mold. However, this method does not provide consistent temperature without drifting during operation. Nor does it compensate for heat gradients within the mold. All melt passes through the sprue, making it hotter than the rest of the mold. In the hottest molding areas, elevated temperatures slow the cycle substantially and promote surface sinks and warpage in the finished part.

However, when used in conjunction with electrical heating elements, the system allows for extremely close temperature control, even with the high temperatures required for engineering resins. Typically, the heaters are connected in series since the watt-density requirements are low. A permanent connection jack is mounted on the mold. When the mold is installed, the heater circuit is connected and monitored continuously by a control. When the operating temperature is reached, the pulses of coolant maintain the desired set-point temperature.

When molding is begun, the cooling pulses increase in duration and frequency to match the total heat input of the heating element plus the melt. When the cycle is interrupted, the cooling pulses automatically are reduced and the temperature maintained at the desired level, ready to continue molding. Zero-defect parts are possible since the mold is constantly operating under strictly controlled temperatures.

The reduced gradient from the last molding area to fill results in reduced part stress and reduced injection pressure. It increases the operating window without drift, providing higher part quality, higher productivity, or both.

As there are many different plastics, a number of techniques for defining and quantifying their characteristics exist. Important

techniques that relate to processing will be reviewed in this book. Molecular weight (MW) relates to the size of the molecules that make up a resin. These molecules are not of the same length or weight, and MW has a significant effect on processability and performance. Resins with low MWs are easier to process but are weaker and more brittle than those with high MWs. The latter are tougher, more chemically resistant, etc. and require tighter process controls. Generally, processing the higher-MW plastics requires more energy in the form of temperature and pressure.

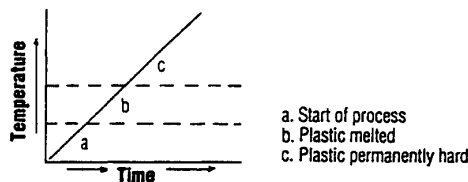
Molecular weight distribution (MWD) is an indication of the relative proportions of molecules of different weight and lengths. It shows the breadth of distribution, or the ratio of large, medium, and small molecular chains in the resin. If most of the molecules have about the same MW, the MWD is classified as "narrow." A "wide or broad" MWD implies a large variation in MW. The MWD is independent of both the density and melt index (MI) (see Chap. 12) and must be taken into account in considerations of both processing and product performance. A narrow MWD enables much better and narrower process control. Two plastics with the same MI and density will process very differently if their MWDs are dissimilar.

**Preferred term** The term preferred worldwide is *plastics*. Other terms include resins, polymers, and elastomers; each have their specific definitions with plastics including all the other terms (1). The fact is that: (1) This industry identifies itself as a plastics industry; (2) practically all people worldwide use the term plastics; (3) practically all materials, products, exhibition shows, technical meetings, advertising, etc. use the term plastics; and (4) as it is repeatedly said, this is a world of plastics. Polymer identifies a material that contains no other material (additive, filler, etc.). Resin is an alternate for plastics; however, it generally is used to identify thermoset (TS) plastics. As shown in this book, these and other groups of terms overlap and also interfere with each other. A major example is stating that TPs are cured during processing; cure occurs with TSs and so on (1).

### Heat Profiles

To obtain the best processing melts for any plastics, one starts with the plastic manufacturer's recommended heat profiles and/or one's own experience. These are starting points for various types of plastics, as shown in Fig. 6-7 and Tables 6-4 to 6-7. The time and

#### Example of a Thermoset Processing Heat-Time Profile Cycle



#### Example of a Thermoplastic Processing Heat-Time Profile Cycle

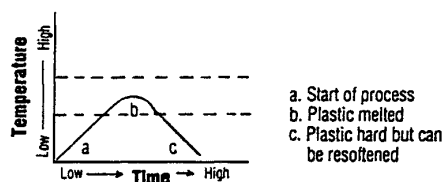


Fig. 6-7 Melting characteristics of TPs and TSs.

**Table 6-4** Melt processing temperatures for thermoplastics<sup>a</sup>

| Material      | Processing Temperature |         |
|---------------|------------------------|---------|
|               | °C                     | °F      |
| ABS           | 180–240                | 356–464 |
| Acetal        | 185–225                | 365–437 |
| Acrylic       | 180–250                | 356–482 |
| Nylon         | 260–290                | 500–554 |
| Polycarbonate | 280–310                | 536–590 |
| LDPE          | 160–240                | 320–464 |
| HDPE          | 200–280                | 392–536 |
| Polypropylene | 200–300                | 392–572 |
| Polystyrene   | 180–260                | 356–500 |
| PVC, rigid    | 160–180                | 320–365 |

<sup>a</sup> Values are typical for injection molding and most extrusion operations. Extrusion coating is done at higher temperatures (i.e., about 600°F for LDPE).

effort spent on start-up make it possible to achieve maximum efficiency of performance versus cost for the processed plastics. By the application of logic, the information gained can be stored and applied to future setups. One must recognize that in all probability similar machines (even from the same manufacturer) will not permit duplication of a process, but knowledge thus gained will guide the processor in future setups.

An amorphous material usually requires a fairly low initial heat in a screw plasticator; its purpose is to preheat material but not melt it in the feed section before it enters the compression zone of the screw. (See, e.g., Chap. 2.) In contrast, crystalline material requires a higher heat initially to ensure that it melts prior to reaching the compression zone; otherwise, satisfactory melting will not occur. Careful implementation of these procedures results in the best melt, which in turn pro-

**Table 6-6** Mold temperatures

| Resin                      | Mold Temperatures (°F) |
|----------------------------|------------------------|
| ABS                        | 100–140                |
| ABS, filled or reinforced  | 140–200                |
| Acetal                     | 170–200                |
| Acrylic                    | 100–175                |
| Cellulose acetate          | 110–165                |
| Ionomer                    | 40–120                 |
| LCP                        | 85–200                 |
| LCP, filled                | 150–220                |
| Nylon 6                    | 150–200                |
| Nylon 6/6                  | 100–200                |
| Nylon 6/10                 | 130–200                |
| Nylon 4/6                  | 180–300                |
| Nylon 11                   | 100–150                |
| Nylon 12                   | 150–200                |
| PBT                        | 130–180                |
| PBT, filled                | 140–250                |
| PC                         | 160–240                |
| PET                        | 180–250                |
| PET (high heat)            | 300                    |
| PETG                       | 60–100                 |
| Plastomer                  | 50–85                  |
| Polyaryletherketone        | 300–400                |
| Polyetherimide             | 250–350                |
| Polyethersulfone           | 200–350                |
| Polyethylene, high density | 40–100                 |
| Polyethylene, low density  | 80–150                 |
| Polyimide                  | 300–400                |
| Polypropylene              | 70–140                 |
| Polystyrene                | 100–180                |
| Polysulfone                | 200–300                |
| Polyurethane               | 60–140                 |
| PPE                        | 150–220                |
| PPS                        | 200–300                |
| PVC                        | 50–150                 |
| SAN                        | 120–175                |
| Styrene butadiene          | 50–120                 |

duces the best part. (Filled plastics, particularly those with thermally conductive fillers, usually require different heat profiles, i.e., a reverse profile where the feed throat area is better than the front zone.)

### Costs

On average, at least half of the costs in molding plastics are incurred in plastic

**Table 6-5** Examples of melt and mold temperatures

| Material       | Melt Temperature | Mold Temperature |
|----------------|------------------|------------------|
| Polypropylene  | 450°F            | 150°F            |
| Polycarbonate  | 550°F            | 200°F            |
| Polyetherimide | 750–800°F        | 300°F            |
| Flexible vinyl | 340°F            | 100–200°F        |

**Table 6-7** Example of IM processing temperature used with heat resistant and engineering plastics [typical commodity plastics use about 400–550°F (204–288°C)]

| Polymer                     | Type                | $T_g$ (°F) | Processing Temperature (°F) |
|-----------------------------|---------------------|------------|-----------------------------|
| Polyetheretherketone (PEEK) | Semicrystalline     | 290        | 650                         |
| Polyphenylene sulfide (PPS) | Semicrystalline     | 185        | 630                         |
| Polyarylene ketone          | Semicrystalline     | 400        | 700–780                     |
| Polyarylene sulfide         | Amorphous           | 410        | 625–650                     |
| Polyetherimide (PEI)        | Amorphous           | varies     | varies                      |
|                             |                     | 450        | 575–650                     |
|                             |                     | 545        | 650–700                     |
| Polyarylether               | Amorphous           | 476        | 650                         |
| Polyethersulfone (PES)      | Amorphous           | 510        | 575                         |
| Polyamide-imide (PAI)       | Amorphous           | 470        | 650                         |
| Polyimide                   | Pseudothermoplastic | 480        | 680                         |
|                             |                     | 482        | 660                         |
|                             |                     | 536        | 660                         |
|                             |                     | 536        | 660                         |

materials and services; wages, utilities, and capital costs account for the rest. Thus, it is important to purchase the raw materials at favorable prices, to have them delivered punctually, to use as little as possible (do not overpack material in a cavity if not necessary and mold to tight tolerances), and to ensure that their quality remains constant. Savings may be effected by judicious selection of the form in which materials are supplied (Chap. 14).

The system for ordering materials depends on the production program. It may be based on requirements, stocks, or agreed upon deadlines. Costs can be saved by determining the qualities that can be supplied on the most favorable terms. Decreases in price effected by purchasing larger amounts must be balanced against the extra costs for storage and larger amount of tied-up capital; a certain amount must represent an optimum. Purchasers must also allow for delivery times. Frequently, materials in a natural color can be supplied directly from stocks.

#### *Behavior of Plastics*

To obtain the best melt, start with the plastic manufacturers' heat profiles, which are

starting points for various types of materials. Or you can start with the profile used on another machine, but it is important to continue changing the barrel temperature profile to obtain the best heat profile that is repeatable during the plasticizing process. Details on polymers, properties of plastics, and the effect of polymer structure on injection molding are given in Chap. 6.

An amorphous material, such as PS, PVC, SAN, ABS, cellulosic, or acrylic, usually needs a fairly low feed end heat, as the purpose is to preheat the material, but not really melt it, before it reaches the compression zone of the screw. Crystalline materials, such as PE, PP, nylon, or acetals, require a higher heat load in the rear to ensure melting by the time the material reaches the compression zone.

Molded part properties and machine cycle times are very strongly influenced by the plasticating process. The success of injection molding as a production technique to date is largely due to the efficiency of reciprocating screw plasticating units, in both melting the plastic feedstock and simultaneously providing sufficient mixing to ensure good melt uniformity. The melt quality desired essentially is good-quality melt (based on visual observation) coming out of the nozzle, which

gives good moldings without welds, sinks, etc. Since molds and materials are uniquely related to each other, one cannot generalize about what makes a good melt. Experience of the molder and knowledge of needs constitute the final determining factor. There are several ways in which you can determine the efficiency of the heat profile being used. One is to observe the screw drive pressure. If the right heat profile is being used, the screw drive pressure should be at about 75% of the maximum. If it is below that level, lower the rear zone heat until the drive pressure starts to rise.

With melt quality changing, raise the center zone to bring in quality. Changes to the temperature should be made in increments of 10 to 15°F, with a 10- to 15-min stabilizing time allowed before the next change. Once the rear zone is set, lower the front zones to whatever level will still give you good molding conditions. The target is a good-quality melt at the lowest practical temperature. With crystalline materials such as nylon or propylene, watch the screw return. If the screw is moving backward in a jerky manner, there is not enough heat in the rear zone, and the unmelt is jamming or plugging the compression zone of the screw. Recognize that the heat energy required to melt crystalline plastics is different from that for amorphous plastics. Also, additives and fillers influence the heat energy required.

### *Checking Materials Received*

An important factor in the production of parts is that the quality of the raw materials must always conform to specification. Certain properties must be checked when the goods are received. In view of the wide variety of applications for plastic articles, a testing schedule of general validity cannot be submitted here. Each case must be treated individually.

Over the years, many hours have been devoted to designing methods for testing materials to develop values for their properties. These tests, conducted under procedures established by organizations such as the American Society for Testing and Mate-

rials (ASTM), are a means of extracting basic knowledge about materials. (See Chap. 12 for testing.)

Although raw materials of constant properties are essential for high-quality moldings, they do not suffice for this purpose by themselves. In particular, mistakes in processing could adversely affect product properties. If possible, allowance must be made for this potential problem in the testing schedule.

The first task in checking goods received is to make sure that they conform to type. In other words, they must be checked to ensure that they agree with samples of former deliveries. This check includes examination for contamination and is followed by specific tests, such as simply determining bulk density. Often, samples are sent in advance of materials dispatched in tankcars or large containers. In this case, statistical rules must be observed in selecting the random samples.

The preliminary check must proceed without loss of time, so rapid tests with specific aims are frequently used. Since injection molding has been caught up in the automation trend, it is feasible for checking the goods received to become part and parcel of the actual production process. However, this entails that any deviations from standard must remain within narrow limits. For technical and economic reasons, this adaptive process control, as it is called, is still a long way from being realized.

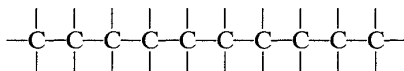
### **Neat Plastics**

A *neat plastic* is a plastic with Nothing Else Added To it; thus it is a polymer. It is a true virgin polymer since it does not contain additives, fillers, etc. They are rarely used alone; literally all polymers are compounded with additives, fillers, colors, etc.

### **Polymer Synthesis and Compositions**

The chemical composition of plastics are basically organic polymers: very large molecules composed of chains of thousands of

carbon atoms

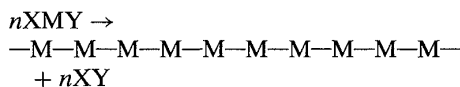


generally connected to hydrogen atoms (H), and often also to oxygen (O), nitrogen (N), chlorine (Cl), fluorine (F), and sulfur (S). The first polymers were synthesized by nature—natural rubber, cellulose and starch in trees and plants, proteins in plant and animal life—and during the past century and a half were utilized by man, who modified them chemically to meet emerging industrial needs. More recently, modern industrial organic chemists have learned to synthesize a much greater variety of new polymers, controlling and varying their structures to balance processability and properties in tens of thousands of different end-products. During the first half of the twentieth century, their raw materials were most often coal tar chemicals, salt, water, and air. For the past half century, petroleum chemistry has offered the easiest and most economical starting point for the manufacture of most polymers, but if petroleum supplies should become too scarce or too expensive, industrial organic chemists could make all of our commercial polymers from coal and completely renewable raw materials such as wood and plants (7).

The key step in the manufacture of polymers is the polymerization reaction, a chemical process in which many hundreds or thousands of small monomer molecules are linked together permanently to form each large polymer molecule. When all the monomer molecule (M) is incorporated into the polymer molecule



we speak of addition polymerization; when only part (M) of the monomer molecule (XMY) is incorporated into the polymer molecule, and the remainder (XY) is formed as a by-product



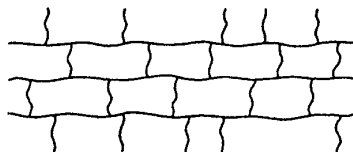
we speak of condensation polymerization.

Although monomers are generally quite reactive (polymerizable), we usually use catalysts, initiators, pH control, heat, and vacuum to speed and control the polymerization reaction and thus optimize the manufacturing process and final product. When pure monomers can be converted directly to pure polymers, we call the process bulk polymerization, but often it is more convenient to run the polymerization reaction in an organic solvent (solution polymerization), in a water emulsion (emulsion polymerization), or as organic droplets dispersed in water (suspension polymerization). Since the pioneer work of Ziegler and Natta 30 years ago, we now often choose catalyst systems that exert precise control over the structure of the polymer they form, and we refer to these as stereospecific systems.

The greatest tonnage of polymers used today is in the form of large, linear, stable molecules



which soften when heated and solidify when cooled and are therefore called thermoplastics. Offering the greatest variety and often the highest performance, however, are thermosetting materials, which are polymerized in two or more steps: first to small soluble fusible molecules of high reactivity



which can still be melt-processed into the desired shape, and finally to highly cross-linked structures of almost infinite dimensions



which cannot be dissolved or fused again and are therefore called thermosets. The efficient economical processing of thermosets remains a major challenge to the polymer chemist and plastics processor.

Although polymers thus form the structural backbone of plastics, they are rarely used in pure form. In almost all plastics, other chemical ingredients are added to modify and optimize the properties for each desired process and application. These additives most often include stabilizers, fillers and reinforcements, and colors; often processing aids, plasticizers, flame retardants, blowing agents, cross-linking agents, and more specialized types of additives are also included. All these additives affect both processability and end-use properties in many ways.

The structures of the more common polymers are presented in Fig. 6-8. Beyond the structure of these individual polymer molecules, many polymer systems form larger-scale structures that have important effects on processing and properties. Thus, a molecule of regular structure may fold back and forth on itself to form a submicroscopic crystallite, and these tiny crystals may further group radially into microscopic circular structures called spherulites; this crystallization process can greatly speed the molding cycle, and the resulting structures can greatly harden and strengthen the final product. Also, unidirectional flow through a gate or thin wall section, or along a mold surface, can orient polymer molecules and crystallites axially in the flow direction and thus produce anisotropic properties. On a still larger scale, fillers and reinforcements, polymer blends, and foamed plastics separate into phases on a microscopic scale; these multiphase structures are influenced by molding conditions and, in turn, greatly modify composite properties.

The effects of polymer structure on injection moldability involve the following rationale:

1. *Individual atoms and functional groups* in the polymer molecule determine the thermal stability of thermoplastics during melt processing and the reactivity and cure processes of thermosets.

2. *Molecular weight* determines resistance to melt flow during melt processing.

3. *Molecular flexibility* determines melt fluidity and crystallizability (both the rate and extent of crystallization).

4. *Intermolecular order (crystallinity and orientation)* is affected by the conditions of the molding process, and the rate of crystallization, in turn, determines the length of the molding cycle.

5. *Intermolecular bonding* determines molding temperature and restriction to melt flow; cure cycles during thermoset molding are controlled by process temperature, pressure, and time.

6. *Additives* may improve or hinder moldability and also modify the molding process in a variety of more specialized ways. Accidental impurities, particularly atmospheric moisture, are also frequently involved.

### Polymerization

Polymerization is basically the bonding of two or more monomers to produce a polymer or plastic. It involves a chemical reaction (addition or condensation type) in which the molecules of monomers are linked together to form large molecules whose molecular weight is a multiple of that of the original substance resulting in high molecular weight components.

*Addition polymerization* A chemical reaction (polymerization) in which simple molecules (monomers) are added to each other to form long chain molecules (polymers) but no by-products (e.g., water, gases) are formed.

*Condensation polymerization* Also called polycondensation. A chemical reaction in which two or more molecules combine often but necessarily accompanied by the separation of water or some other simple substance.

### Copolymers

Copolymers are long-chain molecules formed by the reaction of two or more dissimilar monomers (bipolymer, terpolymer, quadripolymer, etc.). The final properties of a copolymer depend on the percentage of each monomer, the properties of each,

|                                                  |                                                                                                                                                                                                                                             |
|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| High-density polyethylene                        | $-(\text{CH}_2\text{CH}_2)-$                                                                                                                                                                                                                |
| Low-density polyethylene                         | $-(\text{CH}_2\text{CH}_2)-(\text{CH}_2\text{CH})-(\text{CH}_2\text{CH})-(\text{CH}_2\text{CH})-$<br>$\begin{array}{ccc} & \text{C}_2\text{H}_5 & \text{C}_4\text{H}_9 \\ &   &   \\ & \text{CH}_3 & \text{C}_n\text{H}_{2n+1} \end{array}$ |
| Ionomer                                          | $-(\text{CH}_2\text{CH}_2)-(\text{CH}_2\text{C})-$<br>$\begin{array}{c}   \\ \text{O}=\text{C}-\text{O}^- \text{Na}^+ \end{array}$                                                                                                          |
| Ethylene/vinyl acetate copolymer                 | $-(\text{CH}_2\text{CH}_2)-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \\ \text{OCCH}_3 \\    \\ \text{O} \end{array}$                                                                                                                  |
| Polypropylene                                    | $-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \\ \text{CH}_3 \end{array}$                                                                                                                                                               |
| Polystyrene                                      | $-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \\ \text{C}_6\text{H}_5 \end{array}$                                                                                                                                                      |
| Styrene/acrylonitrile copolymer                  | $-(\text{CH}_2\text{CH})-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \qquad \qquad   \\ \text{C}_6\text{H}_5 \qquad \text{C}\equiv\text{N} \end{array}$                                                                                 |
| Impact styrene                                   | $-(\text{CH}_2\text{CH}=\text{CHCH})-$<br>$\begin{array}{c}   \\ (\text{CH}_2\text{CH})- \\   \\ \text{C}_6\text{H}_5 \end{array}$                                                                                                          |
| Acrylonitrile/butadiene/styrene terpolymer (ABS) | $-(\text{CH}_2\text{CH}=\text{CHCH})-$<br>$\begin{array}{c}   \\ (\text{CH}_2\text{CH})-(\text{CH}_2\text{CH})- \\   \qquad \qquad   \\ \text{C}_6\text{H}_5 \qquad \text{C}\equiv\text{N} \end{array}$                                     |
| Polyvinyl chloride                               | $-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \\ \text{Cl} \end{array}$                                                                                                                                                                 |
| Vinyl chloride/vinyl acetate copolymer           | $-(\text{CH}_2\text{CH})-(\text{CH}_2\text{CH})-$<br>$\begin{array}{c}   \qquad \qquad   \\ \text{Cl} \qquad \text{OCCH}_3 \\ \qquad \qquad    \\ \qquad \qquad \text{O} \end{array}$                                                       |
| Polyvinylidene chloride                          | $-(\text{CH}_2\text{C})-$<br>$\begin{array}{c}   \\ \text{Cl} \end{array}$                                                                                                                                                                  |
| Polytetrafluoroethylene                          | $-(\text{CF}_2\text{CF}_2)-$                                                                                                                                                                                                                |

Fig. 6-8 Structures of common polymers.

|                                          |                                                                                                                                                                                                                                            |
|------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Fluorinated ethylene/propylene copolymer | $\text{---}(\text{CF}_2\text{CF}_2)\text{---}(\text{CF}_2\underset{\text{CF}_3}{\text{CF}})\text{---}$                                                                                                                                     |
| Polychlorotrifluoroethylene              | $\text{---}(\text{CF}_2\underset{\text{Cl}}{\text{CF}})\text{---}$                                                                                                                                                                         |
| Polyvinylidene fluoride                  | $\text{---}(\text{CH}_2\text{CF}_2)\text{---}$                                                                                                                                                                                             |
| Polymethyl methacrylate                  | $\text{---}(\text{CH}_2\underset{\text{O}=\text{COCH}_3}{\text{C}}\text{---})\text{---}$                                                                                                                                                   |
| Polyacrylonitrile                        | $\text{---}(\text{CH}_2\underset{\text{C}\equiv\text{N}}{\text{CH}})\text{---}$                                                                                                                                                            |
| Phenoxy resin                            | $\text{---}(\text{CH}_2\underset{\text{OH}}{\text{CH}}\text{CH}_2\text{O}\text{---}\text{C}_6\text{H}_4\text{---}\text{C}(\text{CH}_3)_2\text{---}\text{C}_6\text{H}_4\text{---}\text{O})\text{---}$                                       |
| Epoxy resin                              | $\text{CH}_2\text{---}\text{CH}\text{---}\text{CH}_2\text{O}\text{---}\text{C}_6\text{H}_4\text{---}\text{C}(\text{CH}_3)_2\text{---}\text{C}_6\text{H}_4\text{---}\text{OCH}_2\text{---}\text{CH}\text{---}\text{CH}_2$                   |
| Poly(2,6-dimethylphenylene oxide) (PPO)  | $\text{---}(\text{C}_6\text{H}_3(\text{CH}_3)_2\text{---O})\text{---}$                                                                                                                                                                     |
| Polysulfone                              | $\text{---}(\text{C}_6\text{H}_4\text{---}\text{C}(\text{CH}_3)_2\text{---}\text{C}_6\text{H}_4\text{---}\text{O}\text{---}\text{C}_6\text{H}_4\text{---}\text{S}(=\text{O})_2\text{---}\text{C}_6\text{H}_4\text{---}\text{O})\text{---}$ |
| Polyoxymethylene (acetyl)                | $\text{---}(\text{CH}_2\text{O})\text{---}$                                                                                                                                                                                                |
| Cellulose triacetate                     | $\text{---}(\text{OCH}\text{---}\text{CH}\text{---}\text{OCH})\text{---}$                                                                                                                                                                  |
| Ethyl cellulose                          | $\text{---}(\text{OCH}\text{---}\text{CH}\text{---}\text{OCH})\text{---}$                                                                                                                                                                  |

Fig. 6-8 (Continued).



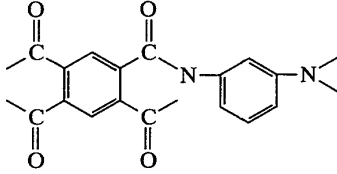
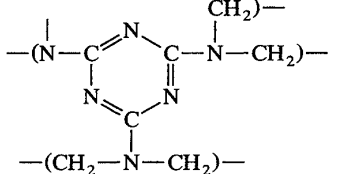
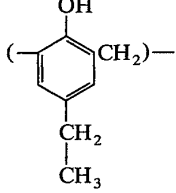
|                       |                                                                                          |
|-----------------------|------------------------------------------------------------------------------------------|
| Nylon 11              | $\text{---}[(\text{CH}_2)_{10}\text{C}(=\text{O})\text{NH}] \text{---}$                  |
| Nylon 12              | $\text{---}[(\text{CH}_2)_{11}\text{C}(=\text{O})\text{NH}] \text{---}$                  |
| Polyimide             |        |
| Urea-formaldehyde     | $\text{---}(\text{N}(\text{CH}_3)\text{C}(=\text{O})\text{N}(\text{CH}_2)_2) \text{---}$ |
| Melamine-formaldehyde |        |
| Phenol-formaldehyde   |        |
| Silicone              | $\text{---}(\text{Si}(\text{CH}_3)_2\text{O}) \text{---}$                                |

Fig. 6-8 (Continued).

and how they are arranged along the chain. There properties are usually intermediate between those of the homopolymers (single monomers); sometimes superior or inferior properties develop. A plastic such as polyethylene is formed from its monomer ethylene, polyvinyl chloride from its vinyl chloride monomer, and so on.

### Interpenetrating Networks

An interpenetrating polymer network (IPN) is a branch of blend technology,

wherein two plastics are combined into a stable interpenetrating network. There are all types of blends, such as synergistic types, to meet all types of performance requirements. In a true IPN, each polymer is cross-linked to itself, but not to the other, and two polymer networks interpenetrate each other; these become thermoset (TS) plastics. In semi-IPNs, only one polymer is cross-linked; the other is linear and by itself would be a thermoplastic (TP); these lend themselves to TP processing techniques. The rigidity of IPN structures increases mechanical and other properties such as chemical resistance. A polyurethane and

isocyanate system is an example of a full IPN. Polymerizing an elastomeric such as polysulfone within a cross-linked TS epoxy can make a semi-IPN.

Methods of preparing IPNs include the simplest approach of sequential preparation. A cross-linked polymer is produced, then put into a second monomer and cross-linker, and cross-linked and polymerized in situ. The result is a suspension-type plastic and a true IPN. Another method of preparing true IPNs involves simultaneous synthesis. Here the two components are polymerized more or less simultaneously but by different routes. For example, one could be produced by addition polymerization while the other by condensation polymerization. Many variations are used. Some latex IPNs may have a core shell structure, with two different networks on the same latex particle, or two latex materials may be bonded together, with two cross-linked networks. All these processing actions result in new engineering type plastics having special high performance properties.

### Graftings

Grafting is a deposition technique whereby plastics can be bonded to a wide variety of other materials. Grafting of two dissimilar plastics often involves a third plastic whose function is to improve the compatibility of the two principal components. The compatibilizer material is a grafted copolymer that consists of one of the principal components and is similar to the other component. The mechanism is similar to that of having soap improve the solubility of a greasy substance in water. The soap contains components that are compatible with both the grease and water.

### Reactive Polymers

Reactive alloying is simply a process to alloy different materials by changing their molecular structure inside a machine. True reactive alloying induces an interaction between different phases of an incompatible mixture and assures the stability of the mix-

ture's morphology. There are a variety of reactive alloying techniques available. Each typically requires a reactive agent and compatibilizer to bring about a molecular change in one or more of the blends components, thereby facilitating bonding. These techniques include the grafting process mentioned earlier and copolymerization interactions, whereby a functional material is built into the polymer chain of a blend component as a comonomer, with the resultant copolymer then used as a compatibilizer in ternary bonds, such as PP-acrylic acid copolymer, which bonds PP and AA. Another technique is solvent-based interactions, using material such as polycaprolactone, which is miscible in many materials and exhibits strong polarity, as well as hydrogen bonding, using the simple polarity of alloy components. This alloying concept produces thousands of new elastomeric to rigid compounds to meet specific product design requirements.

### Compounds

Compounds are an intimate composition of a plastic's alloys with all the additional materials necessary, such as additives, fillers, and/or reinforcements, required to fabricate a product (Fig. 6-9). In the United States yearly consumption of compound plastics is about  $11 \times 10^9$  lb ( $5 \times 10^9$  kg) with 35% PVC, 28% color compounds and concentrates, 19% reinforced or filled plastics, 9% TPE, and 9% other blends and alloys. The U.S. market is at least \$9 billion yearly. End-product uses are mainly automotive (26%), building and construction (24%), packaging (14%), and electrical and electronic (10%) (1, 7, 177, 616).

Unfortunately there is no one ideal additive, filler, or reinforcement since each of the infinite number of end uses will call for a particular set of characteristics, including diverging properties. Improvements in one property can sometimes lead to deterioration in others. Also, the effectiveness of compounding additives depends on the correct procedure of incorporation into the plastic matrix. The compatibility and diffusibility of

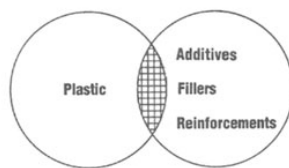
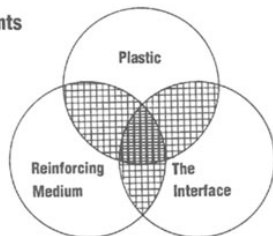
**Plastic Composition****Interplay Between Composite Constituents**

**Fig. 6-9** Composition of practically all molding compounds.

additives is normally assessed from experience or by trial and error. The basic theories and knowledge of solution thermodynamics may be used to determine potential compatibility and thus can be used in the preliminary stages to help design materials to meet specific performances (1).

Since production of the first plastic, cellulose nitrate, in the United States in 1868, there has been a growing demand for specially compounded plastics. By using a postreactor technique, resins can be compounded by alloying or blending polymers, using additives such as colorants, flame retardants, heat or light stabilizers, or lubricants, and adding fillers (Table 6-8) and reinforcements, or a combination thereof. The resulting reinforced compounds are usually referred to as reinforced plastics (RPs) or composites.

**Table 6-8** Typical conductivities of compounds with different additives and fillers

| Fillers                 | Conductivity $\sigma$ (S/cm) |
|-------------------------|------------------------------|
| Carbon black            | 0.01 to 0.1                  |
| Aluminum platelets      | 1 to 50                      |
| Steel fibers            | 1 to 50                      |
| Carbon fibers           | 0.1 to 10                    |
| Mica coated with nickel | 1 to 10                      |

Compounding or mixing is an important stage in the production of raw materials. The way it is performed can affect injection molding, especially if the compound is in the form of a powder and the ingredients (which have different weights) are not mixed together until shortly before molding.

Great significance has been attached to adding all kinds of masterbatches, for example. There are color masterbatches, reinforcing-fiber masterbatches, flame-retardant and antistatic masterbatches, and masterbatches containing foaming agents and other additives. The importance of plastic alloys, which widen the field of application of thermoplastics, has allowed experimentation with different pellets or powders.

Synergistic effects can be developed when certain plastics are combined. Some property improvements with alloying are shown in Fig. 6-10 and Tables 6-9 and 6-10.

A distinction based on the stirrer speed is drawn between gravity mixers and stirrers (slow and high-speed). The peripheral velocity in slow stirrers is 30 ft/sec, and in

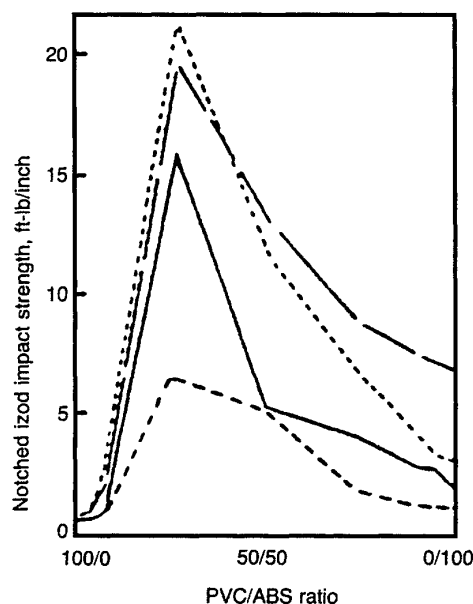


**Fig. 6-10** Example of how compounding affects plastic properties. The curves in this graph reflect four different polyblends.

**Table 6-9** Upgrading PVC by mixing and blending

| Upgraded Property           | Blending Polymer                                                                                                                                                     |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Impact resistance           | ABS, methacrylate-butadiene-styrene, acrylics, polycaprolactone, polyimide, polyurethanes, PVC-ethyl acrylate                                                        |
| Tensile strength            | ABS, methacrylate-butadiene-styrene, polyurethanes, ethylene-vinyl acetate                                                                                           |
| Low-temperature toughness   | Styrene-acrylonitrile, polyurethanes, polyethylene, chlorinated polyethylene, copolyester                                                                            |
| Dimensional stability       | Styrene-acrylonitrile, methacrylate-butadiene-styrene                                                                                                                |
| Heat-distortion temperature | ABS, methacrylate-butadiene-styrene, polyimide, polydimethyl siloxane                                                                                                |
| Processability              | Styrene-acrylonitrile, methacrylate-butadiene-styrene, chlorinated polyethylene, PVC-ethyl acrylate, ethylene-vinyl acetate, chlorinated polyoxymethylenes (acetals) |
| Moldability                 | Acrylics, polycaprolactone                                                                                                                                           |
| Plasticization              | Polycaprolactone, polyurethanes, nitrile rubber, ethylene-vinyl acetate, copolyester, chlorinated polyoxymethylenes (acetals)                                        |
| Transparency                | Acrylics, polyimide                                                                                                                                                  |
| Chemical and oil resistance | Acrylics                                                                                                                                                             |
| Toughness                   | Nitrile rubber, ethylene-vinyl acetate                                                                                                                               |
| Adhesion                    | Ethylene-vinyl acetate                                                                                                                                               |

high-speed stirrers it ranges from 30 to 150 ft/sec (10 to 50 m/sec).

In-plant blending of the molding compounds offers some advantages. It dispenses with some of the fabrication costs and potential problems due to heat history and greatly reduces inventories. Purchasing one type in bulk reduces the costs of raw materials. Production can be made very flexible to cope with small amounts and special wishes. Certainly, any know-how acquired during operation remains protected by these measures. (See Chap. 10.)

One of the most important mixing tasks in the injection molding factory is in-plant coloring. The advantages are obvious: saving costs incurred by the higher prices of colored grades, a wider selection of colors, adaptability, and reduced inventories. However, these advantages are balanced by the responsibility for selecting suitable colorants (e.g., types that are resistant to heat or ultraviolet radiation or are physiologically harmless). Moreover, the colorants must not impair the properties of the molding compound. In any case, the demands imposed on the quality of the

shades and their reproducibility from one machine to another and from one batch to another can never be so severe as those imposed on molding compounds supplied by the raw materials manufacturer. The cycle may become longer, and the shrinkage may change. Consequently, the workers entrusted with in-plant coloring are chiefly responsible for its quality.

Formerly, mixers were set aside in special rooms for in-plant coloring. They are now being supplemented by devices that allow coloring on the injection molding machine. They can proportion as many as three types of colorant, the molding compound in the natural color, and the regrind (i.e., a total of five ingredients) and are usually fitted with a mixer. The colorants are in the form of pellets, ground masterbatches, free-flowing and non-free-flowing pigment powders, pigment dispersions, and pumpable liquids. Great value must be attached to their dispersibility.

The quality of coloration obtained with in-plant techniques depends not only on the proportioning and mixing in the feeding device but also on plastification in the injection

**Table 6-10** Outstanding properties of some commercial compounds and alloys

| Alloy                                                  | Properties                                                       |
|--------------------------------------------------------|------------------------------------------------------------------|
| PVC, acrylic                                           | Flame, impact, and chemical resistance                           |
| PVC, ABS                                               | Flame resistance, impact resistance, processability              |
| Polycarbonate, ABS                                     | Notched impact resistance, hardness, heat-distortion temperature |
| ABS, polysulfone                                       | Lower cost                                                       |
| Polypropylene, ethylene-propylene-diene                | Low-temperature impact resistance and flexibility                |
| Polyphenylene oxide, polystyrene                       | Processability, lower cost                                       |
| Styrene acrylonitrile, olefin                          | Weatherability                                                   |
| Nylon, elastomer                                       | Notched Izod impact resistance                                   |
| Polybutylene terephthalate, polyethylene terephthalate | Lower cost                                                       |
| Polyphenylene sulfide, nylon                           | Lubricity                                                        |
| Acrylic, polybutylene rubber                           | Clarity, impact resistance                                       |

molding machine. Frequently, screws with mixing attachments in the metering section or static mixers connected in series behind the metering zone are indispensable.

In-plant blending of virgin plastics (plastics that have not been processed in the plant) with granulated or recycle plastics is important to proper control. If not controlled, performance of the part can be below requirements. (Details on granulating are given in Chap. 10.)

### Additives

An additive is a substance compounded into a plastic to modify its characteristics. They are physically dispersed in a plastic matrix usually without having a significant

effect on the molecular structure of the thermoplastic. In thermoset plastic, additives such as cross-linking catalyst and other agents do purposely affect structure. Additives are normally classified according to their specific functions rather than their chemical basis. While some additives have broad applications and are adaptable to many TPs and TS plastics, others are used exclusively with specific plastics. Of all the additives used the highest-volume additives used are modifiers. Property extenders and processing aids are also common. Of the plastics using additives, polyvinyl chloride (PVC) is the major outlet for additives, with polyolefins the next most widely used. The pace of developments in additives continues unabated.

Additives can be classified into various categories, the most important of which are: (1) process assistants (processing stabilizers, processing aids and flow promoters, internal and/or external lubricants, thixotropic agents); (2) bulk mechanical properties modifiers (plasticizers or flexibilizers, reinforcing agents, toughening agents); (3) formulation cost reducers (diluent and extenders, particle fillers); (4) surface properties modifiers (antistatic agents, slip additives, antiwear additives, antiblock additives, adhesion promoters); (5) optical properties modifiers (pigments and dyes, nucleating agents); and (6) antiaging additives (antioxidants, UV stabilizers, fungicides) and others such as blowing agents, flame retardants.

Examples of additives include carbon black, carnauba wax, coconut shell, coke dust, filler, macerate filler, inert pigment, ground rubber from used tires, reinforcement, shell flour, stabilizer, thermoplastic, thermoset plastic, vermiculite, and wax.

There are additive clarifiers to increase the transparency of a plastic. The liquid additives provide processors the best of both worlds with the high accuracy that liquid additives offer via pump dosing and in addition the ease of solid handling. Using liquid additives can have disadvantages such as spilling, screw slipping, longer equipment cleaning time, and separate dosing (resulting in capital investments for equipment). However, there are

porous bead carriers being used for liquid additives that provide easy dosing simulating solid additive actions. For example, nonhygroscopic beads act like sponges to absorb antistats, mold release agents, antioxidants, lubricants, fragrances, silanes, chain extenders, etc. Some additive modifiers act as internal lubricants, exuding to the surface of the plastic during and immediately after processing and thus providing the necessary lubricity to reduce or eliminate friction in molded parts. A number of additives are used to modify surface (or inter surface) properties in a desirable manner. Examples include external and internal mold release agents, slip agents, antistatic agents, and antifogging agents.

### *Fillers*

Fillers are also called extenders. They are usually low cost. Many different inert substances (organic and inorganic with low to high weights) are added to plastics to reduce costs. Fillers may also improve processing and physical and mechanical properties, particularly hardness, thermal insulation, stiffness, and impact strength. The particles are usually small, in contrast to those of reinforcements. Fillers include ash, calcium carbide, calcium carbonate, carbon filler, carborundum, alpha cellulose, channel black, coral, coke dust, diatomaceous earth, ferrite, milled fiber, flint, fuller's earth, glass filler, glass spheres, hemp, lampblack, leather dust, macerate filler, magnesium carbonate, mica, particulate filler, pumice, quartz, sawdust, talc, vermiculite, and wood flour.

*Filler versus unfilled compound cost* Although fillers can reduce the cost of plastic material, simply adding filler to a plastic does not automatically assure savings. The density and cost of both the filler and plastic play an important role in determining any savings. As an example, adding 30 wt% of a mineral filler such as talc to medium-impact polystyrene (s.g. 2.5 to 3.1) reduces the amount of plastic by only 15%. But if a low-density filler such as wood flour (s.g. 0.5; other types range from 0.2 to 1.5) is used in the same weight

percentage, the specific gravity of a part is reduced to 0.79. A plastic content savings of 47 wt% occurs compared to unfilled material.

### *Reinforcements*

Reinforcements are strong, inert materials bound into a plastic to improve properties such as strength, stiffness, impact resistance, resistance to dimensional shrinkage, etc. To be effective, the reinforcement must form a strong adhesive bond with the plastics; for certain reinforcements special cleaning, sizing, or finishing, treatments are used to improve the bond. Types of reinforcements include fibers of glass, graphite, boron, nylon, polypropylene, cotton, sisal, and asbestos. There are inorganic and organic fibers that have diameters ranging from about one to over 100 micrometers. Properties differ for the different types, diameters, shapes, and lengths. It is important for the designer to properly identify which reinforcement is used (as with the plastic). Other reinforcements include burlap, carbon black, metallic fiber, spider silk, and whiskers (1, 4, 7, 10, 11, 18, 453).

### *Summary*

Compounding to change and improve the physical and mechanical properties of plastics makes use of a wide variety of fillers (Tables 6-11 to 6-13). In general, mechanical properties are significantly increased by adding reinforcing fibers. Particulate fillers of various types usually increase the modulus; plasticizers generally decrease the modulus but enhance flexibility (Figs. 6-11 to 6-13).

Electrical properties may be affected by many additives, especially those that are conductive. Most plastics, which are poor conductors of current, build up a charge of static electricity. Antistatic agents can be used to attract moisture, reducing the likelihood of a spark or discharge.

In most cases, different additives are used to provide lower cost and different characteristics encompassing specific overall

**Table 6-11** Guide to the use of fillers and reinforcements

| Filler or<br>Reinforcement | Chemical<br>Resistance | Heat<br>Resistance | Electrical<br>Insulation | Impact<br>Strength | Tensile<br>Strength | Dimensional<br>Stability | Stiffness | Hardness | Lubricity | Electrical<br>Conductivity | Thermal<br>Conductivity | Moisture<br>Resistance | For Use<br>In | Recommended |
|----------------------------|------------------------|--------------------|--------------------------|--------------------|---------------------|--------------------------|-----------|----------|-----------|----------------------------|-------------------------|------------------------|---------------|-------------|
| Alumina, tabular           | •                      | •                  | •                        | •                  |                     | •                        | •         |          |           | •                          | •                       | •                      | •             | S, P        |
| Aluminum powder            |                        |                    |                          |                    |                     |                          |           |          |           |                            |                         |                        |               | S           |
| Aramid                     | •                      | •                  | •                        | •                  | •                   | •                        | •         | •        | •         | •                          | •                       | •                      | •             | S, P        |
| Bronze                     |                        |                    |                          |                    |                     |                          |           |          |           |                            |                         |                        |               | S           |
| Calcium carbonate          | •                      | •                  | •                        | •                  |                     | •                        | •         | •        |           |                            |                         |                        | •             | S, P        |
| Carbon black               | •                      | •                  |                          |                    |                     | •                        | •         | •        |           | •                          | •                       |                        |               | S, P        |
| Carbon fiber               |                        |                    |                          |                    |                     |                          |           |          |           | •                          | •                       |                        |               | S           |
| Cellulose                  |                        |                    |                          | •                  |                     | •                        | •         | •        |           |                            |                         |                        |               | S, P        |
| Alpha cellulose            |                        |                    | •                        |                    |                     | •                        |           |          |           |                            |                         | •                      |               | S           |
| Coal, powdered             | •                      |                    | •                        | •                  | •                   | •                        | •         | •        |           |                            |                         | •                      |               | S           |
| Cotton                     |                        |                    | •                        | •                  | •                   | •                        | •         | •        |           |                            |                         | •                      |               | S           |
| Fibrous glass              | •                      | •                  | •                        | •                  | •                   | •                        | •         | •        |           |                            | •                       | •                      |               | S, P        |
| Graphite                   | •                      |                    |                          |                    | •                   | •                        | •         | •        | •         | •                          |                         |                        |               | S, P        |
| Jute                       |                        |                    |                          | •                  |                     | •                        | •         | •        |           |                            |                         |                        |               | S           |
| Kaolin                     | •                      | •                  | •                        |                    |                     | •                        | •         | •        | •         |                            |                         | •                      | •             | S, P        |
| Mica                       | •                      | •                  | •                        |                    |                     | •                        | •         | •        | •         |                            |                         | •                      | •             | S, P        |
| Molybdenum<br>disulfide    |                        |                    |                          |                    |                     |                          | •         | •        | •         |                            |                         | •                      | •             | P           |
| Nylon                      | •                      | •                  | •                        | •                  | •                   | •                        | •         | •        | •         |                            |                         | •                      | •             | S, P        |
| Orlon                      | •                      | •                  | •                        | •                  | •                   | •                        | •         | •        |           |                            |                         | •                      | •             | S, P        |
| Rayon                      |                        |                    | •                        | •                  | •                   | •                        | •         | •        |           |                            |                         | •                      | •             | S           |
| Silica, amorphous          |                        |                    | •                        |                    |                     |                          |           |          |           |                            |                         | •                      | •             | S, P        |
| Sisal fibers               |                        |                    | •                        | •                  |                     | •                        | •         | •        |           |                            |                         | •                      | •             | S, P        |
| Fluorocarbon               | •                      |                    |                          |                    |                     | •                        | •         | •        | •         |                            |                         | •                      | •             | S, P        |
| Talc                       |                        |                    |                          |                    |                     | •                        | •         | •        | •         |                            |                         | •                      | •             | S, P        |
| Wood flour                 | •                      | •                  | •                        |                    |                     | •                        | •         | •        | •         |                            |                         | •                      | •             | S           |

P = thermoplastic.

S = thermoset.

**Table 6-12** Tradeoffs in thermoplastic composites

| Desired Modification                        | How Achieved                                                     | Sacrifice (from Base Resin)                     |                                                   | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|---------------------------------------------|------------------------------------------------------------------|-------------------------------------------------|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                             |                                                                  | Amorphous                                       | Crystalline                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Increased tensile strength                  | Glass fibers<br>Carbon fibers<br>Fibrous minerals                | Ductility, cost<br>Ductility, cost              | Ductility, cost<br>Ductility, cost<br>Ductility   | Glass fibers are the most cost-effective way of gaining tensile strength. Carbon fibers are more expensive; fibrous minerals are least expensive but only slightly reinforcing. Reinforcement makes brittle resins tougher and embrittles tough resins. Fibrous minerals are not commonly used in amorphous resins.                                                                                                                                      |
| Increased flexural modulus                  | Glass fibers<br>Carbon fibers<br>Rigid minerals                  | Ductility, cost<br>Ductility, cost<br>Ductility | Ductility, cost<br>Ductility, cost<br>Ductility   | Any additive more rigid than the base resin produces a more rigid composite. Particulate fillers severely degrade impact strength.                                                                                                                                                                                                                                                                                                                       |
| Flame resistance                            | FR additive                                                      | Ductility, tensile strength, cost               | Ductility, tensile strength, cost                 | FR additives interfere with the mechanical integrity of the polymer and often require reinforcement to salvage strength. They also narrow the molding latitude of the base resin. Some can cause mold corrosion.                                                                                                                                                                                                                                         |
| Increased heat-deflection temperature (HDT) | Glass fibers<br>Carbon fibers<br>Fibrous minerals                | Ductility, cost<br>Ductility, cost              | Ductility, cost<br>Ductility, cost<br>Ductility   | When reinforced, crystalline polymers yield much greater increases in HDT than amorphous resins. As with tensile strength, fibrous minerals increase the HDT only slightly. Fillers do not increase HDT.                                                                                                                                                                                                                                                 |
| Warpage resistance                          | 5–10% glass fibers<br>5–10% carbon fibers<br>Particulate fillers | Ductility, cost, tensile strength               | Cost<br>Cost<br>Ductility, cost, tensile strength | Amorphous polymers are inherently nonwarping molding resins. Only occasionally are fillers such as milled glass or glass beads added to amorphous materials, because they reduce shrinkage anisotropically. Addition of fibers tends to balance the difference between the inflow and crossflow shrinkage usually found in crystalline polymers. When a particulate is used to reduce and balance shrinkage, some fiber is needed to offset degradation. |

(Continues)

**Table 6-12** (Continued)

| Desired Modification                                       | How Achieved                                           | Sacrifice (from Base Resin)                                             |                                                                         | Comments                                                                                                                                                                                                                                                                                                     |
|------------------------------------------------------------|--------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                            |                                                        | Amorphous                                                               | Crystalline                                                             |                                                                                                                                                                                                                                                                                                              |
| Reduced mold shrinkage (increased mold-to-size capability) | Glass fibers<br>Carbon fibers<br>Fillers               | Ductility, cost<br>Ductility, cost<br>Tensile strength, ductility, cost | Ductility, cost<br>Ductility, cost<br>Tensile strength, ductility, cost | Reinforcement reduces shrinkage far more than fillers do. Fillers help balance shrinkage, however, because they replace shrinking polymer. The sharp shrinkage reduction in reinforced crystalline resins can often lead to warpage. The best "mold-to-size" composites are reinforced amorphous composites. |
| Reduced coefficient of friction                            | PTFE<br>Silicone<br>MoSe<br>Graphite                   | Cost                                                                    | Cost                                                                    | These fillers are soft and do not dramatically affect mechanical properties. PTFE loadings commonly range from 5–20%; the others are usually 5% or less. Higher loadings can cause mechanical degradation.                                                                                                   |
| Reduced wear                                               | Glass fibers<br>Carbon fibers<br>Lubricating additives | —<br>—<br>—                                                             | —<br>—<br>—                                                             | The subject of plastic wear is extremely complex and should be discussed with a composite supplier.                                                                                                                                                                                                          |
| Electrical conductivity                                    | Carbon fibers<br>Carbon powders                        | Ductility, cost<br>Tensile strength, ductility, cost                    | Ductility, cost<br>Tensile strength, ductility, cost                    | Resistivities of 1 to 100,000 $\Omega$ -cm can be achieved and are proportional to cost. Various carbon fibers and powders are available with wide variations in conductivity yields in composites.                                                                                                          |

properties. For example, coupling agents can be added to improve the bonding of a plastic to its inorganic filler materials, such as glass fibers. A variety of silanes and titanates are used for this purpose. Some extenders (i.e., fillers) permit a large volume of a given plastic to be produced with relatively little actual resin. Calcium carbonate, silica, and clay are frequently used extenders.

Many plastics, because they are organic, are flammable; thus, flame retardants are used in them. Additives that contain chlorine, bromine, phosphorous, and metallic salts reduce the likelihood that combustion will

occur or spread. Lubricants such as wax or calcium stearate reduce the viscosity of molten plastic and improve its forming characteristics. Plasticizers are low-molecular-weight materials that alter the properties and forming characteristics of plastics. An important application is the production of flexible grades of PVC.

Colorants must provide colorfastness under the required exposure conditions of light, temperature, humidity, chemical exposure, etc., but without reducing other desirable properties such as flow during processing, resistance to chalking and crazing,

**Table 6-13** Influence of fillers and reinforcements on thermoplastics

| Resin                 | Reinforcements                                  | Fillers                                                                          |
|-----------------------|-------------------------------------------------|----------------------------------------------------------------------------------|
| Amorphous             | +Can more than double tensile strength          | –Lower tensile strength                                                          |
| ABS                   |                                                 | +Can more than double flexural modulus                                           |
| SAN                   | +Can increase flexural modulus fourfold         | +Raise HDT slightly                                                              |
| Amorphous             |                                                 | –Embrittle resins                                                                |
| Nylon                 | +Raise HDT slightly                             |                                                                                  |
| Polycarbonate         | ±Toughen brittle resins, embrittle tough resins | +Can impart special properties such as lubricity, conductivity, flame retardance |
| Modified PPO          |                                                 |                                                                                  |
| Polystyrene           | +Can provide 1,000 Ω-cm resistivity             | +Reduce and balance shrinkage                                                    |
| Polysulfones          | +Reduce shrinkage                               | –Reduce melt flow                                                                |
|                       | –Reduce melt flow                               | +Can lower cost                                                                  |
|                       | –Raise cost                                     |                                                                                  |
| Crystalline           | +Can more than triple tensile strength          | –Lower tensile strength                                                          |
| Acetals               |                                                 | +Can more than triple flexural modulus                                           |
| Nylon 6, 6/6,         | +Can raise flexural modulus sevenfold           | +Raise HDT slightly                                                              |
| 6/10, 6/12, 11, 12    |                                                 | –Embrittle resins                                                                |
| Polypropylene         | +Can nearly triple HDT                          |                                                                                  |
| Polyphenylene sulfide | ±Toughen brittle resins, embrittle tough resins | +Can impart special properties such as lubricity, conductivity, magnetic         |
| Thermoplastic         |                                                 | properties, flame retardance                                                     |
| Polyesters            | +Can provide 1 Ω-cm resistivity                 | +Reduce shrinkage                                                                |
| Polyethylene          | +Reduce shrinkage                               | +Reduce distortion                                                               |
|                       | –Cause distortion                               | –Reduce melt flow                                                                |
|                       | –Reduce melt flow                               | +Can lower cost                                                                  |
|                       | –Raise cost                                     |                                                                                  |

and impact strength resolution. Colorants are usually classed as either pigments or dyes. Pigments are insoluble particles large enough to scatter light, but not soluble

enough to provide the high transparency of soluble dyes. However, dyes are usually poorer in light-fastness, heat stability, and tendency to bleed and migrate in the plastic

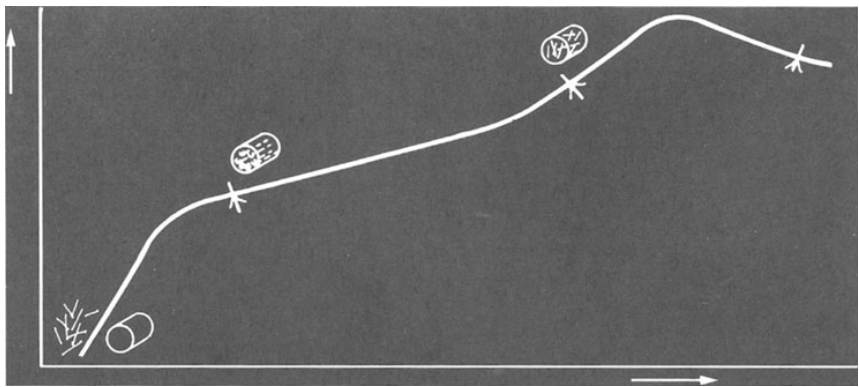


**Fig. 6-11** With more uniform compounding (horizontal direction) properties improve (vertical direction).

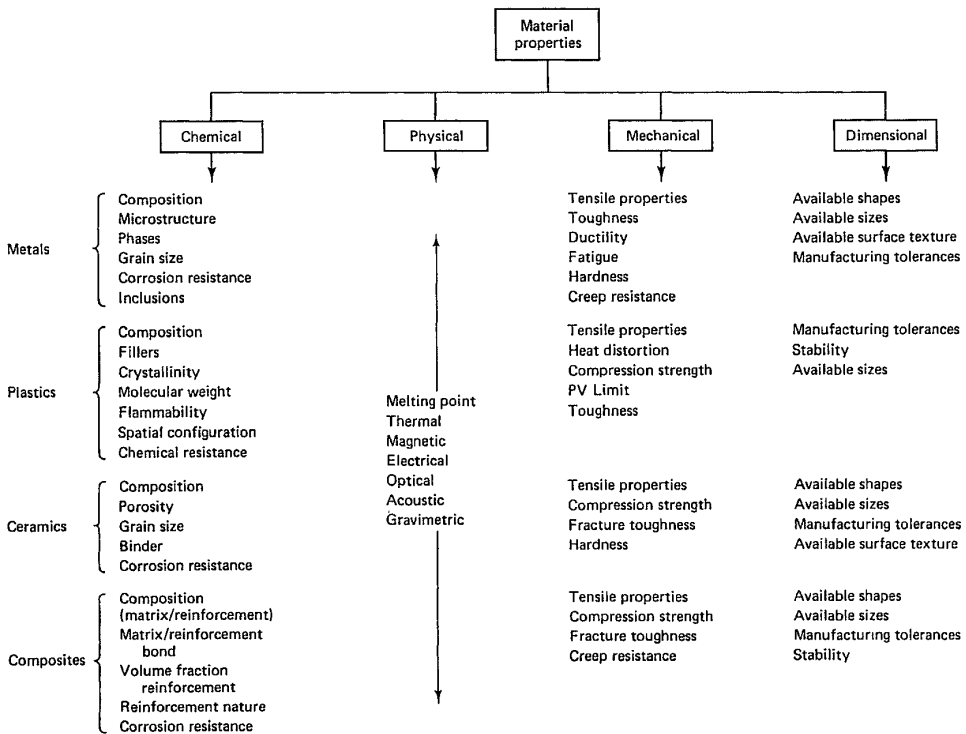


Fig. 6-12 Guide to various material properties.

system, so that they are much less used than pigments.

Pigments may be organic or inorganic. Organic ones usually provide stronger, more transparent colors, are higher-priced (although not necessarily more costly to use), and more soluble in plastic systems. Inorganics are denser and usually of a larger particle size. Common inorganic pigments include iron oxides in buff colors, titanium dioxide in white, lead and zinc chromates (in yellows, oranges, and reds), and other metal oxides and salts. Important organic pigments include monochromes and diazos (in yellow, orange, and red), phthalocyanine (in blues and greens), quinacridone (in gold, maroon, violet, etc.), and perylene. Carbon blacks are also widely used, both as a colorant and to protect polymers from thermal and UV degradation as well as a reinforcing filler. The various special colorants include metallics, fluorescent, phosphorescent, and pearlescent colorings.

### Alloys and Blends

Alloys are composite materials constructed by blending plastics or copolymers with other plastics or elastomers under selected conditions to retain the best characteristics of each constituent. There are many different basic materials that are made into alloys or blended. Alloys are mechanically blended. They do not depend on chemical bonds but often require special compatibilizers. Many alloys and blends are available with more always being developed to meet new performance requirements. Examples include ABS/nylon, in which the two substances are made compatible with additives; it offers improved chemical resistance, surface lubricity, etc.; ABS/PC which offers good processability, etc.; and ABS/TPU, with its improved flex fatigue, vibration clamping, cold temperature toughness, etc. The terms alloy and blend are often used interchangeably

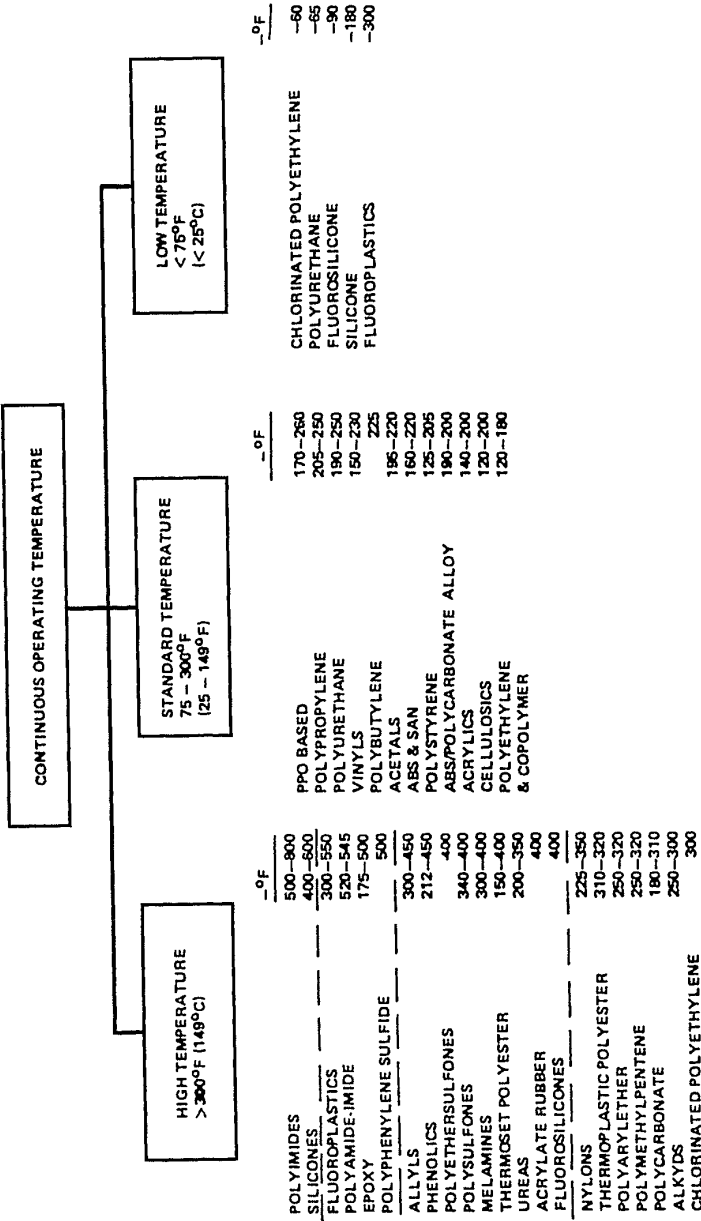


Fig. 6-13 Examples of continuous operating temperatures.

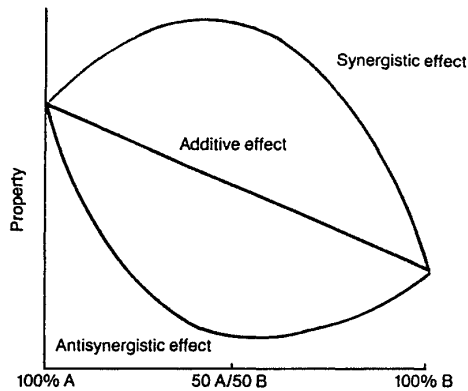


**Fig. 6-14** Developing synergistic effects is the desired objective of alloying plastics to significantly improve performance.

but generally an alloy is a subclass of plastic blends.

Alloys are usually designed to retain the best characteristics of each constituent. Most often, property improvements occur in such areas as impact strength, weather resistance, improved low-temperature performance, and flame retardation. (See Figs. 6-10, 6-14 to 6-16 and Tables 6-9, 6-10, and 6-14).

The classic objective of alloying and blending is to find two or more polymers whose

mixture will have synergistic property improvements beyond those that are purely additive in effect. Among the techniques used to combine dissimilar polymers are cross-linking, to form what are called interpenetrating polymer networks (IPNs), and grafting, to improve the compatibility of the resins.

Alloys can be classified as either homogeneous or heterogeneous. The former can be depicted as a solution with a single phase or single glass-transition temperature  $T_g$ . A heterogeneous alloy has both continuous and dispersed phases, each retaining its own distinctive  $T_g$ .

Until recently, blending and alloying were either restricted to polymers that had an inherent physical affinity for each other or else a third component, called a compatibilizer, was employed. These constraints severely limited the types of polymers that could be blended without sacrificing their good physical properties. As a rule, incompatible polymers produce a heterogeneous alloy with poor physical properties.

The advances in polymer blending and alloying technology have come about mainly through three routes: similar-rheology polymer pairs, miscible polymers such as polyphenylene oxide and polystyrene, or IPNs.

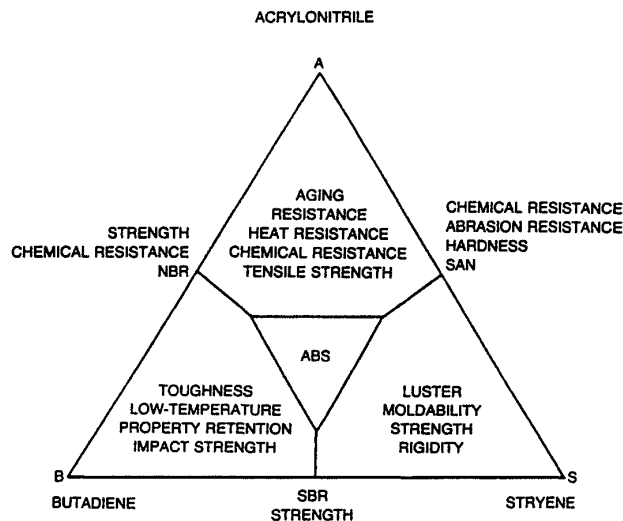


**Fig. 6-15** Diagram showing how ABS terpolymer properties are influenced by individual constituent plastic properties.

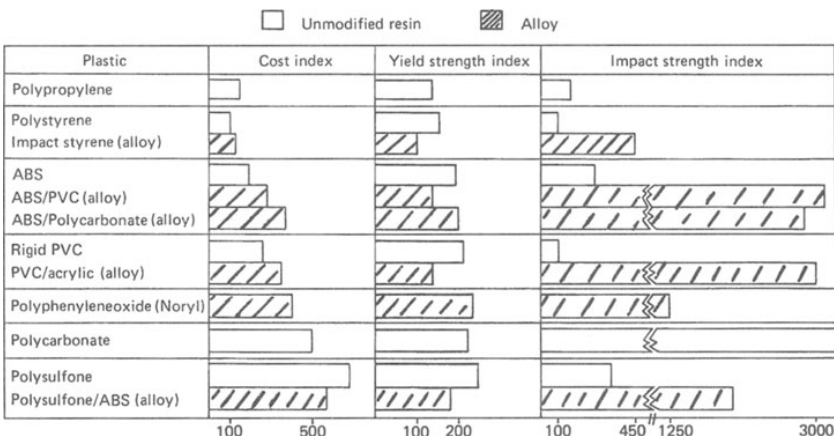


Fig. 6-16 Combining different plastics to provide cost-to-performance improvements.

All these systems are limited to specific polymer combinations that have an inherent physical affinity for each other. Recently, however, there has evolved another overall approach to producing blends via reactive polymers.

**Thermoplastic and Thermoset Plastics**

Plastics are classified as thermoplastic (TP) or thermoset (TS) where TPs represent at least 90 wt% of all plastics consumed. There are TP and TS elastomers (rubberlike). As

Table 6-14 Examples of plastic alloys using trade names

| Material       | Producers                                                        | Properties                                                                                                                                                                                      |
|----------------|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| PPO/PS         | GE (Noryl)                                                       | Polyphenylene oxide (PPO) has high strength and high heat resistance, but oxidizes at temperatures required for processing; adding polystyrene (PS) makes it possible to process.               |
| ABS/PC         | Mobay (Bayblend), Fiberite                                       | Acrylonitrile-butadiene-styrene (ABS) improves processability of polycarbonate; PC contributes toughness and heat resistance.                                                                   |
| PC/PET; PC/PBT | GE (Xonoy)                                                       | PC, though tough and able to withstand very high temperatures, lacks good resistance to chemicals; polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) make up for this lack. |
| PET/PBT        | GAF (Gafite), Hoechst Celanese (Celanex), GE (Valox)             | Alloying with PET lowers PBT's impact resistance but brings down its cost.                                                                                                                      |
| PVC/ABS        | General Tire & Rubber, GE, Cyclcoloy, Cycovin, various compounds | Polyvinyl chloride (PVC) adds flame retardance and rigidity to ABS, a more easily processed resin.                                                                                              |
| PP/elastomer   | Reichbold, Hoechst Celanese Montedison                           | Polypropylene (PP) contributes good heat resistance and processability; elastomers add impact resistance.                                                                                       |

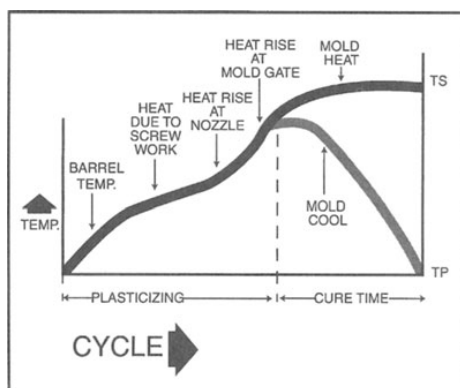


**Fig. 6-17** Processing thermal profiles of thermoplastic (TP) and thermoset (TS) plastic.

mentioned there are many different families of these plastics. Different processing conditions are used to mold products (Fig. 6-3). Injection molding processing temperatures in Fig. 6-17 provide examples of the thermal load profiles that occur with thermoplastic and thermoset plastic.

During the first part of the twentieth century in molding plastics (primarily compression molding), most of the plastics used were thermosets. The principal TSs used were phenolics. Since the 1940s, thermoplastics were predominantly molded (primarily injection molding). Even though only about 10 wt% of all plastics now molded worldwide are TSs, they remain important in certain applications. However, most injection molders and designers are not familiar with TSs.

There are designers that may be unfamiliar with advances in TS processing technology that make TSs a viable choice in material selection efforts; this is particularly true in terms of the manufacturing-cost bottom line. In general, TSs cost about 10 to 15% more in processing than do TPs. However, contemporary processing technology (including the use of cold runner manifolds, smaller runners and sprues, optimized cycle times, automated molding and deflashing, minimized scrap levels through the improved design of part and mold) has dramatically slashed TS manufacturing costs. The result has been the improvement of their utility and competitiveness.

Note that comparisons in the performance properties of TSs and TPs can be tough to make, owing to the current state of testing and evaluating materials. To offset this situation, a technical committee working on plastics in general and a subset of the International Standards Organization's (ISO) TC 61, referred to as the WG 10 group of international researchers, is working on developing more meaningful data for making comparisons on designing parts with TSs and engineering TPs. For example, the more real-world ISO standards for testing at elevated temperatures are being published that will make such comparisons more realistic.

### *Thermoplastics*

Thermoplastics are plastics or elastomers that after processing via heat and cooling into parts are capable of being repeatedly softened by reheating without many of them undergoing significant chemical or performance changes. TPs become soft on heating, and on cooling they harden. This cycle can be repeated.

### *Thermoset Plastics*

Thermoset plastics, also called thermoset resin, thermosetting resin, thermoset elastomer, or TS, are plastics that, after final processing into products, are substantially infusible and insoluble. They undergo a chemical reaction (cross-linking) by the action of heat and pressure, oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Curing actually occurs via polymerization and/or cross-linking. Cured TSs cannot be resoftened by heat. However, they can be granulated, with the material being useful as filler in TSs as well as TPs. The usual TS plastic, being very heat sensitive during processing compared to thermoplastic, usually uses a screw compression ratio (CR) of 1 with a water-cooled barrel to provide positive temperature control (Chap. 3). During plasticizing, if the temperature goes just

slightly too high, the melt solidifies in the barrel requiring screw pulling and clean up (1, 258).

*A-B-C-stages* These letters identify the various stages of cure when processing thermoset plastic that has been treated with a catalyst; basically A-stage is uncured, B-stage is partially cured, and C-stage is fully cured. Typical B-stage plastics are TS molding compounds and prepreps, which in turn are processed to produce C-stage fully cured plastic material products; they are relatively insoluble and infusible.

#### *Cross-Linking*

Cross-linking refers to the setting up of chemical links between the molecular chains of polymers. It is the principal distinction between TSs and TPs. During curing or hardening of TSs the cross-links are formed (using a chemical such as benzoyl peroxide) between adjacent molecules producing a complex, interconnected network that can be related to its viscosity and performance. These cross-bonds prevent the slippage of individual chains, thus preventing plastic flow under the addition of heat. If excessive heat is applied, degradation rather than melting will occur. There is no cross-linking when processing TPs (269).

#### *Cross-Linking Thermoplastics*

Certain TPs can be converted to TSs providing improved properties. They can be cross-linked by various processes including chemical ones and irradiation. Polyethylene is a popular plastic that is cross-linked; its abbreviation is XLPE. Cross-linking is an irreversible change that occurs through a chemical reaction, that is, by condensation, ring closure, or addition. Cure is usually accomplished by the addition of curing (cross-linking) agents, with or without heat and pressure.

#### *Thermoplastic Vulcanizates (TPVs)*

TPVs are a specific type of thermoplastic elastomer (TPE) made by alloying a TP with rubber, which is partially or fully vulcanized (cured) during the alloying process. Examples are PP and EPDM. These hygroscopic materials have been successful in replacing many thermoset rubber (TSR) parts. Processing TPVs offers numerous advantages over TS rubbers. They can be fully formulated without added compounding, they can be black or colored, they have faster cycle times, they are recyclable, they have tighter part tolerances and lower density parts, and they are more efficient and cost effective.

*Vulcanization* In the rubber industry (also with TS plastic elastomers) vulcanization refers to the process in which rubber or plastic undergoes a change in its chemical structure brought about by the irreversible process of reacting the materials with sulfur, benzoyl peroxide, and/or other suitable agents. These cross-linking actions (as described above) result in property changes such as decreased plastic flow, reduced surface tackiness, increased elasticity, much greater tensile strength, and considerably less solubility. Similar cross-linking action occurs with conventional thermoset plastics.

#### *Curing*

One can change the properties of a plastic material by chemical polycondensation or addition reactions through *curing*, the process of hardening a plastic. More specifically curing refers to the changing of the physical properties of a material by chemical reactions usually by the action of heat (includes dielectric heat, etc.) and/or catalyst with or without pressure. It is the process of hardening or solidification involving cross-linking, oxidizing, and/or polymerization (addition or condensation). The term curing, even though it is applied to thermoset and thermoplastic materials, is a term that refers to a chemical reaction (cross-linking) or change that occurs during the processing cycle. This reaction

occurs with TS plastics or TS elastomers as well as cross-linked TPs that become TSs.

TP materials go basically through a melting action. However, since the more popular plastics at the beginning of the twentieth century (with about 90 wt% of the market and principally the TS phenolic) were TSs the term “curing” was incorrectly used for TPs. Even with TPs coming aboard early in the twentieth century (now over 90 wt% of all plastics) the term continued to be used to indicate any plastic (TP or TS) that goes from a melt stage to a hardened stage.

### Heat Profiles

Heat-time profiles are important characteristics to control and understand (Figs. 6-7 and 6-17). For example, amorphous material usually requires a fairly low initial heat in the screw plasticator; its purpose is to preheat material but not melt it in the screw's feed section prior to entering the compression zone. Crystalline material requires higher initial heating to ensure that it melts prior to reaching the compression zone. Careful implementation of these procedures produces the best melts, which in turn produce the best products.

### Liquid Crystal Plastics (LCPs)

LCPs, also called liquid crystalline thermoplastics, liquid crystal polymers, or liquid crystalline polymers, form a unique class of

thermoplastics containing primarily benzene rings in its backbone with molecules that have stiff, rodlike structures organized in large parallel arrays. LCPs exhibit a crystalline phase in liquid; the melt state is due to the presence of highly ordered molecular fragments. It is melt processable and develops high orientation during molding (or extrusion) with resultant significant improvements in strength and modulus from low to high temperatures. LCPs can be used with or without fiber reinforcements.

LCPs are best thought of as being a separate, unique class of TPs. Their molecules are stiff, rodlike structures organized in large parallel arrays or domains in both the melted and solid states. These large, ordered domains provide LCPs with characteristics that are unique compared to those of the basic crystalline or amorphous plastics (see Table 6-15).

LCPs provide the designer with unparalleled combinations of properties, and many can resist most solvents and heat. Unlike many high-temperature plastics, LCPs have a low melt viscosity and are thus more easily processed, and in faster cycle times, than those with a high melt viscosity. They have the lowest warpage and shrinkage of all the TPs. When they are injection-molded, their molecules align into long, rigid chains that, in turn, align in the direction of flow and thus act like reinforcing fibers, giving LCPs both high strength and stiffness. As the melt solidifies during cooling, the molecular orientation freezes into place. The volume changes only minutely, with virtually no frozen-in stresses.

**Table 6-15** General properties of crystalline, amorphous, and liquid crystal polymers

| Property                  | Crystalline | Amorphous | Liquid<br>Crystalline |
|---------------------------|-------------|-----------|-----------------------|
| Specific gravity          | Higher      | Lower     | Higher                |
| Tensile strength          | Higher      | Lower     | Highest               |
| Tensile modulus           | Higher      | Lower     | Highest               |
| Ductility, elongation     | Lower       | Higher    | Lowest                |
| Resistance to creep       | Higher      | Lower     | High                  |
| Maximum usage temperature | Higher      | Lower     | High                  |
| Shrinkage and warpage     | Higher      | Lower     | Lowest                |
| Flow                      | Higher      | Lower     | Highest               |
| Chemical resistance       | Higher      | Lower     | Highest               |

In service, molded parts experience very little shrinkage or warpage. They have high resistance to creep. Their fiberlike molecular chains tend to concentrate near the surface, resulting in parts that are anisotropic, meaning that they have greater strength and modulus in the flow direction, typically on the order of three to six times those of the transverse direction. However, adding fillers or reinforcing fibers to LCPs significantly reduces their anisotropy, more evenly distributing strength and modulus and even boosting them. Most fillers and reinforcements also reduce overall cost and reduce mold shrinkage to near zero. Consequently, parts can be molded to tight tolerances. These low-melt-viscosity LCPs thus permit the design of parts with long or complex flow paths and thin sections.

#### Elastomers, Thermoplastic, and Thermoset

This class of plastics includes material referred to as elastomer, natural rubber, thermoset elastomer, thermoset rubber, synthetic rubber, and thermoplastic elastomer. At room temperature these rubberlike materials (natural or synthetic) generally stretch under low stress to at least twice their length and snap back to approximately their original length on release of the stress (pull) within a specified time period. The term elastomer is often used interchangeably with the term rubber. Although rubber identifies a thermoset elastomeric material obtained from a rubber tree, it also identifies a TS elastomer (TSE) or thermoplastic elastomer (TPE) material (256).

The various elastomers can be differentiated on the basis of how long the deformed material requires to return to its approximately original size after the deforming force is removed and by the extent of its recovery. Different properties also distinguish the elastomers, including strength and stiffness, abrasion resistance, solvent resistance, shock and vibration control, electrical and thermal insulation, waterproofing, tear resistance, and cost.

Plastic elastomers are generally lower-modulus flexible materials. Thermoset elastomeric or rubbery materials (the real rubber

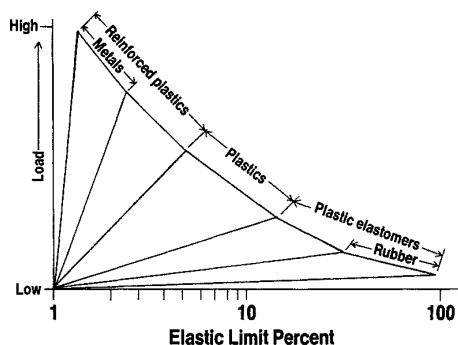


**Fig. 6-18** Strength and elasticity of different materials.

types) have been around for over a century. They will always be required to meet certain desired properties, but nowadays thermoplastic elastomers (TPEs) are replacing traditional TS natural and synthetic rubbers. TPEs are also widely used to modify the properties of rigid TPs, usually by improving their impact strength.

TPEs offer a combination of strength and elasticity, as well as exceptional processing versatility. They present creative designers with endless new and unusual product opportunities. More than 100 major different groups of TPEs are produced worldwide, with new grades continually being introduced to meet different electrical, chemical, radiation, wear, swell, and other requirements (Fig. 6-18).

Quite large elastic strains are possible with minimal stress in TPEs. TPEs have two specific characteristics: Their glass transition temperature ( $T_g$ ) is below that at which they are commonly used, and their molecules are highly kinked, as in natural TS rubber (polyisoprene). When a stress is applied, the molecular chain uncoils and the end-to-end length can be extended several hundred percent, with minimum stresses. Some TPEs have an initial modulus of elasticity of less than 10 MPa (1,500 psi); once the molecules are extended, the modulus increases.

The modulus of metals decreases with an increase in temperature. However, in stretched TPEs the opposite is true, because at higher temperatures, they exhibit increasingly vigorous thermal agitation in their molecules. Therefore, the molecules resist

more strongly the tension forces attempting to uncoil them. To resist requires greater stress per unit of strain, so that the modulus increases with temperature. When stretched into molecular alignment, many rubbers can form crystals, an impossibility when they are relaxed and “kinked” (7).

### *Thermoplastic Elastomers*

Thermoplastic elastomers, also called thermoplastic rubber, TPE, TPEL, or TPV, are plastics or plastic blends that resemble vulcanized rubbers in that they can be deformed significantly at room temperature (to say twice their original length) and return to their original shape after the stress is removed. Properties of TPEs vary widely. For example, there are low durometer, low modulus TPEs. They include styrenic block copolymers, polyolefin blends, and elastomeric alloys. Soft TPEs are used in ergonomic product designs incorporating soft-touch elements. They compete with thermoset rubbers.

### *Thermoset Elastomers*

Thermoset elastomers, also called thermoset resin, thermosetting resin, or TS, provide the characteristics of an elastomer such as natural rubber, which is a TS material. After final processing into products, they are substantially infusible and insoluble. They undergo a chemical reaction (cross-linking) by the action of heat and pressure, oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Curing actually occurs via polymerization and/or cross-linking. Cured TSs cannot be resoftened by heat. However, they can be granulated, with the material being used as filler in both TSs and TPs.

### *Natural Rubbers*

Natural rubbers are thermoset cross-linked plastics having glass transition temperatures below room temperature and exhibiting highly elastic deformation and high elongation. These materials are capable of recovering from large deformations quickly

and forcibly. A rubber in its modified state, free of diluent, is identified by different tests. For example, it can retract within one minute to less than 1.5 times its original length after being stretched at room temperature to twice its length and held for one minute before release. It can be, or already is, modified to a state in which it is essentially insoluble (but can swell) in a boiling solvent such as benzene or methyl ethyl ketone.

### *Rubber Elasticity*

The elastic behavior of these plastics are well above their glass transition temperature (the rubbery region of viscoelasticity behavior) where they show elasticity at high strains of up to several hundred percent. If the material is perfectly elastic then all the work done will be stored as strain energy. A highly successful statistical molecular theory of rubber elasticity that closely describes many of the experimentally determined features of elastomer behavior has been developed.

### *Rubber Market*

Worldwide demand for rubber, which includes injection molded products, will grow at a faster rate than their major tire market supply because of the large gains expected in nontire rubber demand, especially in newly industrialized countries. Of the total market 66 wt% is synthetic and 34 wt% natural. Marketwise 40 wt% are in tires. The United States alone consumes 19 wt% of the world supply.

### **Commodity and Engineering Plastics**

The more than 17,000 compounds commercially available worldwide are used in various processes to meet specific melt-flow characteristics and/or provide cost-to-product performance advantages. They are classified as commodity plastics or engineering plastics.

Commodities such as PEs, PVCs, PPs, and PSs account for at least two-thirds of plastic sales. The improved performance

characteristics of engineering plastics include such things as heat resistance, impact strength, and the ability to be molded to high-precision standards. Examples of engineering plastics are PAs, PCs, ABS, POM, PSU, and PEEK. Many of the TS plastics are of the engineering type. Historically, as more competition and/or production occur for certain engineering plastics, their costs go down and they become commodity plastics. Half a century ago the dividing line costwise was about \$0.15/lb; now it stands at about \$1.00/lb. A general description sometimes used throughout all industries (plastic, metal, etc.) is summarized in Fig. 6-19. Note that listed under polymer (plastics) are those that are usually commodity plastics; however, these are also compounded and alloyed to create the higher performing engineering plastics.

**Injection Molding Thermoplastics and Thermosets**

With thermoplastics the mold is kept at a temperature below the solidification point of the plastic, causing the injected melt to “freeze,” thus forming the part. After cooling, the mold opens and the part is ejected. From 85 to 90% of all injection-molded plastics are thermoplastic.

When processing thermosets, the melt is kept below the temperature where it would cause solidification due to its exothermic reaction until it enters the cavity. In turn, the cavity temperature is kept high to cause the melt to solidify.

The basic difference between an injection molding machine processing thermoplastic and one processing thermoset is in the barrel, screw, and nozzle. TS barrels generally use water jackets for temperature control of melt. Screws are shorter (in the range of 13/1 and 16/1 L/D), the compression ratio is usually 1, and they do not have a nonreturn valve at the tip. Nozzles may or may not be temperature-controlled, depending on size and other design details.

**High Performance Reinforced Moldings**

Reinforced plastics are also called composites. The term reinforced plastic (RP) refers to combinations of plastic (matrix) and reinforcing materials that predominantly come in fiber forms such as chopped, continuous, woven and nonwoven fabrics, etc. and also in other forms such as powder or flake (Figs. 6-9 and 6-20). By far the most common reinforcements are short glass fibers (Fig. 6-21); however, other fibers are also used (Table 6-16 and Figs. 6-22 and 6-23). Both thermoset

**Table 6-16** Tabulated properties of high performance fibers

| Type of Fiber Reinforcement | Specific Gravity | Density (lb/in. <sup>3</sup> ) | Tensile Strength (10 <sup>3</sup> psi) | Specific Strength (10 <sup>6</sup> in.) | Tensile Elastic Modulus (10 <sup>6</sup> in.) | Specific Elastic Modulus (10 <sup>8</sup> in.) |
|-----------------------------|------------------|--------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------------|------------------------------------------------|
| Glass                       |                  |                                |                                        |                                         |                                               |                                                |
| E Monofilament              | 2.54             | 0.092                          | 500                                    | 5.43                                    | 10.5                                          | 1.14                                           |
| 12-end roving               | 2.54             | 0.092                          | 372                                    | 4.04                                    | 10.5                                          | 1.14                                           |
| S Monofilament              | 2.48             | 0.090                          | 665                                    | 7.39                                    | 12.4                                          | 1.38                                           |
| 12-end roving               | 2.48             | 0.090                          | 550                                    | 6.17                                    | 12.4                                          | 1.38                                           |
| Boron (tungsten substrate)  |                  |                                |                                        |                                         |                                               |                                                |
| 4 mil or 5.6 mil            | 2.63             | 0.095                          | 450                                    | 4.74                                    | 58                                            | 6.11                                           |
| Graphite                    |                  |                                |                                        |                                         |                                               |                                                |
| High strength               | 1.80             | 0.065                          | 400                                    | 6.15                                    | 38                                            | 5.85                                           |
| High modulus                | 1.94             | 0.070                          | 300                                    | 4.29                                    | 55                                            | 7.86                                           |
| Intermediate                | 1.74             | 0.063                          | 360                                    | 5.71                                    | 27                                            | 4.29                                           |
| Organic                     |                  |                                |                                        |                                         |                                               |                                                |
| Aramid                      | 1.44             | 0.052                          | 400                                    | 7.69                                    | 18                                            | 3.46                                           |

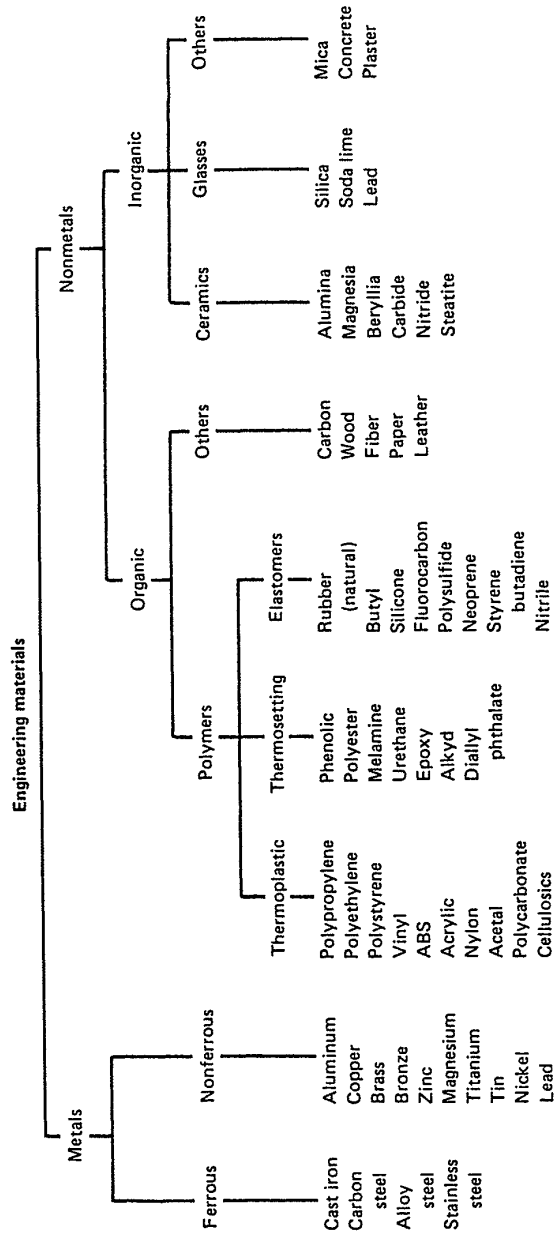


**Fig. 6-19** General classification of engineering materials.

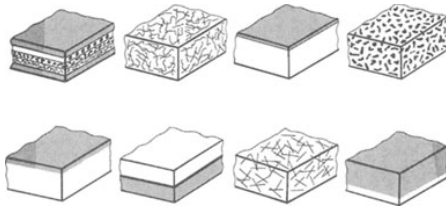


**Fig. 6-20** Different layouts used to mold products.

and thermoplastic can be reinforced. Reinforcement provides significant property and/or cost improvements over the individual components; primary benefits include high strength and modulus, high strength-to-weight ratio, oriented/directional strength, lowerweight, lower shrinkage during processing and in service (Fig. 6-24), high dielectric strength and corrosion resistance, and long-term durability (Figs. 6-25 to 6-28). The term composite denotes the thousands of different combinations of two or more materials. The more descriptive and popularly used worldwide term is reinforced plastic (1, 18).

The RP industry is a mature industry. Improved understanding and control of processes continue to increase performance and reduce variability. Fiber strengths have risen to the degree that the 2-D and 3-D RPs used can produce very high strength and stiff products having long service lives. Thermoplastic RPs (RTPs), even with their relatively poorer properties when compared to thermoset RPs (RTSs), are used in about 55 wt% of all RP parts. Current U.S. annual consumption of all forms of RPs exceeds 3.5 billion lb (1.6 billion kg). Included in these RTPs are stampable

reinforced thermoplastics (Chap. 16, Reinforced Plastics).

Advanced RP (ARP) typically refers to a plastic matrix reinforced with very high strength, high modulus fibers and/or other properties. Examples of these type fibers include carbon, graphite, aramid, boron, S-glass, and ZenTron-glass. ARPs can provide the designer with specific properties or characteristics such as strength, stiffness, and lower density used in different environments. They can be at least 50 times stronger and 25 to 150 times stiffer than the matrix. A typical ARP might possess the desirable properties of low density ( $1.4\text{--}2.7\text{ g/cm}^3$ ), high strength (3–5 GPa), and high modulus (60–550 GPa). With proper processing these ARPs provide certain properties equal to or exceeding those of most other materials.

### Injection Moldings

The RTPs (reinforced thermoplastics) are practically all injection molded with very fast cycles and use short glass fibers that produce highly automated and high performance parts (Fig. 6-21). Fiber lengths can be 13 mm (0.5 in.) and up to at least 38 mm (1.5 in.). The TPs include principally nylons and polypropylenes, as well as polycarbonates, acetals, and polyesters. TSs include predominantly polyesters as well as epoxies, phenolics, and urethanes.

Different IM techniques are used. One method uses injection-compression molding or coining (Chap. 15). In this technique glass fiber fabrics or long fibers are located in a mold. In turn plastic melt is injected into the cavity to produce extra strength products. This is a variation of in-molding as reviewed in Chap. 15.

### Bulk Molding Compounds (BMCs)

Bulk molding compounds are mixtures of short 3 mm to 3 cm ( $1/8$  to  $1\frac{1}{4}$  in.) glass fibers, thermoset plastic (usually polyester), and additives (1, 4, 7, 18). This mixture, with the consistency of modeling clay, can be produced in bulk form or extruded in ropelike form

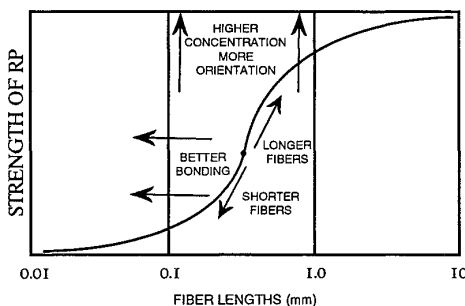


**Fig. 6-21** Effect of fiber length on strength.

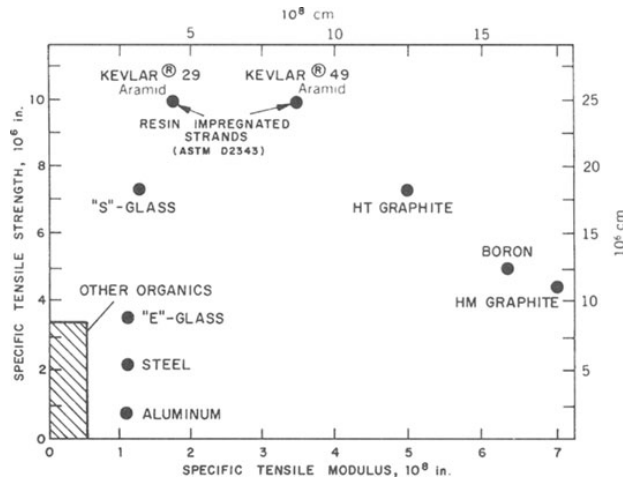


Fig. 6-22 Comparing fiber properties.

and cut (to produce “log”) for easy handling. BMC is injection molded using a ram alone or the usual ram-screw. The difference between conventional injection molding and that of BMC is the presence of a stuffing unit instead of the more common feeder hopper. This stuffing pressure control unit, which usually preheats the BMC, permits loading of extremely flexible BMC into a screw. This action exposes the reinforced fibers to little shear during feeding.

Since the 1950s BMC products have been used principally as insulators in the electrical industry. More recently the most

important application has been in the automotive industry. To meet their demands IMM builders have perfected proportional hydraulic, servohydraulic, or servoelectric systems with reproducible process control. Extensive quality assurance devices ensure economy in the manufacture of high-grade BMC moldings of consistently high quality.

#### Characterizations

RPs can be characterized in a variety of ways (e.g., by type and construction of

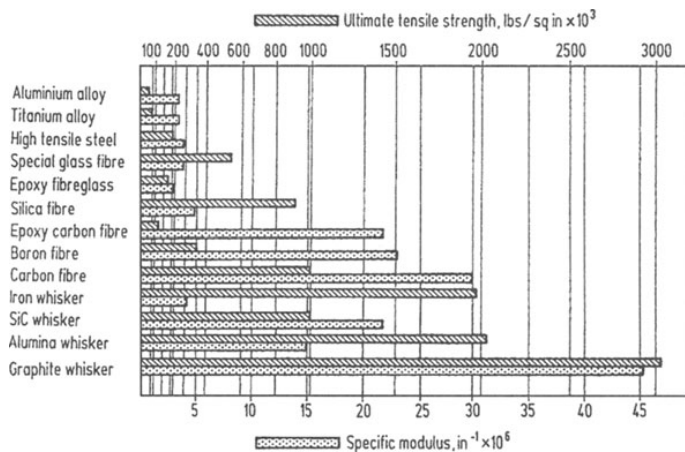


Fig. 6-23 Strength and specific density ( $E/\text{density}$ ) for various materials.

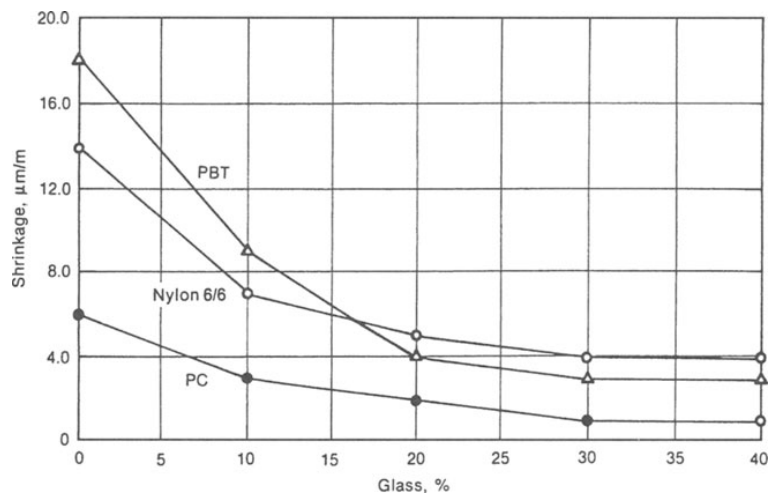


Fig. 6-24 Example of glass reinforcement on molded product shrinkages.

reinforcement used, by impact and fatigue strength properties, etc). Testing for tensile stress-strain ( $S$ - $S$ ) properties over a range of test rates offers a potential method for estimating relative toughness (Chap. 12). Comparing fatigue strength for notched and

unnotched conditions at various ratios of minimum to maximum stress is useful in structural design. Depending on construction and the orientation of stress relative to reinforcement, it may not be necessary to provide extensive

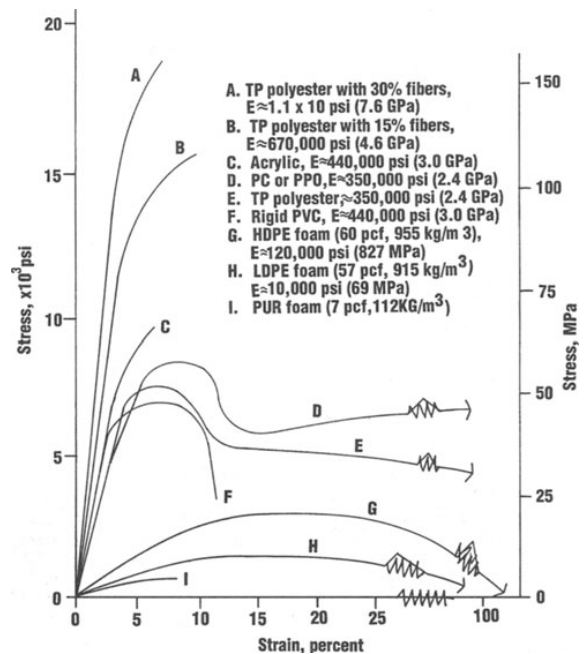


Fig. 6-25 Range in strength with and without chopped glass fibers.

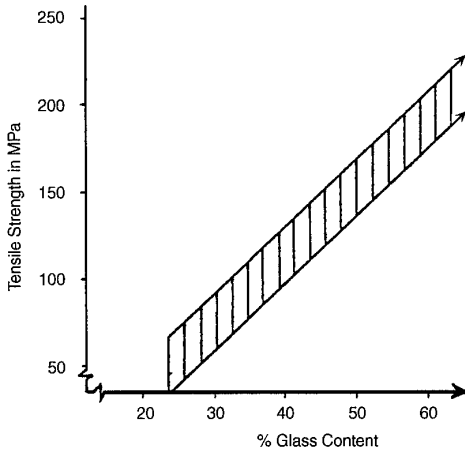


**Fig. 6-26** Effect of strength versus glass content for glass TS polyester compound.

data on time-dependent stiffness properties since their effects may be small and can frequently be considered by rule of thumb using established practical design approaches. When time-dependent strength properties are required, creep and other data are used most effectively. Many RP products have had life spans of many decades, including products that have been subjected to various dynamic loads in many different environments from very low temperatures to very high corrosive conditions, etc.

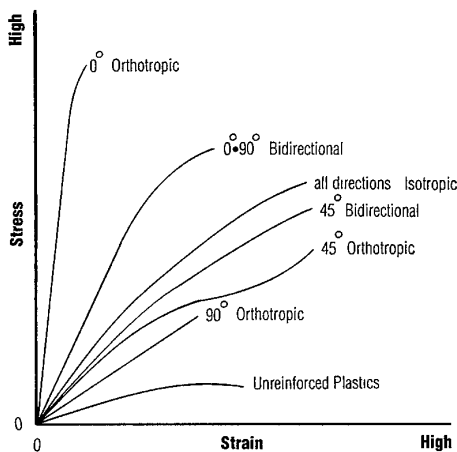


**Fig. 6-27** Stress versus strain diagrams at various angles.

### Directional Properties

RPs provide an opportunity to optimize design by focusing on a material's composition, part geometry, orientation, and melt-flow direction (Fig. 6-28). However, this involves "making" the RP material. The arrangement and the interaction of the usual stiff, strong fibers dominate the behavior of RPs with the less stiff, weaker plastic matrix (TS or TP). A major advantage is that directional properties can be maximized. Basic design theories of combining actions of plastic and reinforcement have been developed and used successfully since the 1940s. As mentioned different injection molding techniques such as in-molding can be used to incorporate high-performance directional properties.

When compared to unreinforced plastics, the analysis and design of reinforced plastics is simpler in some respects and perhaps more complicated in others. Simplifications are possible since the stress-strain behavior of RPs is frequently fairly linear to failure and RPs are less time dependent. For high-performance applications, they suffer their first damage at stresses just below ultimate strength. They are also much less temperature dependent, particularly the RTSs (reinforced TSs). The potential complications that arise relate principally to the directional effects resulting from the fiber construction.

When constructed from any number and arrangement of RP plies, the stiffness and strength property variations may overwhelm the novice. But like other materials, there are similarities that can be used to advantage. The view that these complications cause unsolvable problems is incorrect because an RP can be properly designed, fabricated, and evaluated to take into account any possible variation. The variations may be insignificant or significant. In either case, the designer will use the required values and apply to them a safety factor; a similar approach is used with other materials (4, 10, 18).

### Viscosities

Viscosity is the property of the resistance to flow exhibited within a body of material.

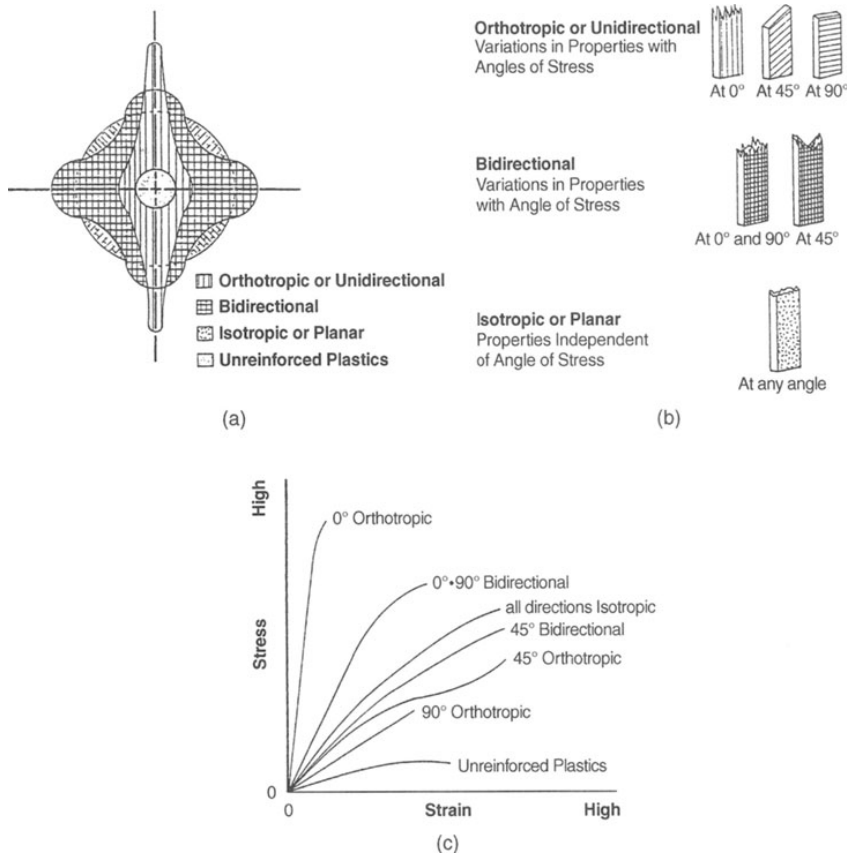


**Fig. 6-28** Fiber orientation effect on performance.

Ordinary viscosity is the internal friction or resistance of a plastic to flow. It is the constant ratio of shearing stress to the rate of shear. Shearing is the motion of a fluid, layer by layer, like a deck of cards. When plastics flow through straight tubes or channels they are sheared and the viscosity expresses their resistance. The melt index (MI) or melt flow index (MFI) is an inverse measure of viscosity. High MI implies low viscosity and low MI means high viscosity (see Chap. 12, Melt Tests). Plastics are shear thinning, which means that their resistance to flow decreases as the shear rate increases. This is due to molecular alignments in the direction of flow and disentanglements (see Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems).

Viscosity is usually understood to mean Newtonian viscosity, in which case the ratio of shearing stress to the shearing strain is constant. In non-Newtonian behavior, which is the usual case for plastics, the ratio varies with the shearing stress (Fig. 6-36). Such ratios are often called the apparent viscosities at the corresponding shearing stresses. Viscosity is measured in terms of flow in Pa.s, with water as the base standard (value of 1.0). The higher the number, the less flow.

#### *Newtonian Flow*

If a material (liquid, etc.) flows immediately on application of force and the rate of flow is directly proportional to the force

applied then the flow is Newtonian. It is a flow characteristic evidenced by viscosity that is independent of shear rate. Water and thin mineral oils are examples of fluids that undergo Newtonian flow.

### *Non-Newtonian Flow*

There are some plastic melts or liquids that exhibit non-Newtonian flow response when force is applied. That is, their viscosity depends on the rate of shear. Deviations from ideal Newtonian behavior may be of several different types.

One type is attributed to apparent viscosity, which may increase with shear rate (shear thickening or shear dilatancy) or decrease with rate of shear (shear thinning or pseudoplasticity). The latter behavior is usually found with plastic melts and solutions. In general such a dependency of shear stress on shear rate can be expressed as a power law. Another type of non-Newtonian flow results from a time-dependent viscosity, as for materials exhibiting thixotropy or rheopexy. Some plastic melts and solutions may be elasticoviscous, in which the fluid may exhibit elastic effects. Basically flow of a plastic melt is characterized by nonproportionality between shear rate and shear stress.

### **Viscoelasticities**

Viscoelasticity is a combination of viscous and elastic properties in a plastic with the relative contribution of each being dependent on time, temperature, stress, and strain rate. A material having this property is considered to combine the features of a perfectly elastic solid and a perfect fluid. The response to stress of all plastic structures is viscoelastic, meaning that it takes time for the strain to accommodate the applied stress field. The time constants for this response will vary with the specific characteristics of the plastic and processing techniques. In the rigid section of a block polymer the response time is usually on the order of microseconds to milliseconds. With resilient, rubber sections of the struc-

ture the response time can be as long as tenths of a second to seconds. This difference in response time is the cause of failure under rapid loading for certain plastics.

To understand why brittle failure can, in fact, occur when the response under high-speed stressing is transferred from resilient regions of a block polymer, an analysis of the response of the two types of materials in the structure is necessary. The elastomeric regions, which stay soft and rubbery at room temperature, will have a very low elastomeric modulus and a very large extension to failure. The rigid, virtually cross-linked regions, which harden together into a crystalline region on cooling, will be brittle and have very high moduli and very low extension to failure, usually from 1 to 10%. If the stress rate is a small fraction of the normal response time for the rubbery regions, they will not be able to strain quickly enough to accommodate the applied stress. As a consequence the brittle, virtually cross-linked regions take a large amount of the stress, and since they support limited elongation, they fail. The apparent effect is that of a high stretch, rubbery material undergoing brittle failure at an elongation that is a small fraction of the possible values.

### **Plastic Structures and Morphology**

In addition to the size of the plastic molecules and their distribution, the shapes or structures of individual polymer molecules also play an important role in determining the properties and processability of plastics. There are those that are formed by aligning themselves into long chains of molecules and others with branches or lateral connections that form complex structures. All these forms exist in either two or three dimensions. Because of the geometry, or morphology, of these molecules, some can come closer together than others. These forms are identified as crystalline; all others as amorphous. Morphology influences such properties as mechanical and thermal swelling and solubility, specific gravity, and chemical and electric properties.

This behavior of morphology is essentially limited to TP, not TS, plastics. When TSs are processed, their individual chain segments are strongly bonded together during a chemical reaction that is irreversible.

*Chemical and Physical Characteristics*

The variety of chemical and physical characteristics of plastics derives from the four factors of chemical structure, form, arrangement, and size of the polymer. For example, the chemical structure, that is, the types of atoms and the way in which they are joined to one another, influences density. The form of the molecules as well as their size and disposition within the material influence its mechanical behavior. It is possible deliberately to vary the crystal state to alter the hardness or softness, toughness or brittleness, and resistance to temperature.

*Crystalline and Amorphous Plastics*

Plastic molecules that can be packed closer together can more easily form crystalline structures in which the molecules align themselves in some orderly pattern. During processing, they tend to develop higher strength in the direction of the molecules. Since commercially perfect crystalline polymers are not produced, they are identified technically as semicrystalline TPs, but in this book are called crystalline (as is conventional in the plastics industry).

Amorphous TPs, which have molecules going in all different directions, are normally transparent. Compared to crystalline types, they undergo only small volumetric changes when melting or solidifying during processing. Tables 6-17 to 6-21 and Fig. 4-60 compare the basic performance of crystalline and amorphous plastics. Exceptions exist, particularly with respect to the plastic compounds that include additives and reinforcements.

As symmetrical molecules approach within a critical distance, crystals begin to form in the areas where they are the most densely packed. A crystallized area is stiffer and

**Table 6-17** General morphology of thermoplastics

| Crystalline |                     | Amorphous        |
|-------------|---------------------|------------------|
| No          | Transparent         | Yes              |
| Excellent   | Chemical resistance | Poor             |
| No          | Stress-craze        | Yes              |
| High        | Shrinkage           | Low              |
| High        | Strength            | Low <sup>a</sup> |
| Low         | Viscosity           | High             |
| Yes         | Melt temperature    | No               |
| Yes         | Critical $T/T^b$    | No               |

<sup>a</sup> Major exception is PC.

<sup>b</sup>  $T/T$  = Temperature/time.

stronger; a noncrystallized (amorphous) area is tougher and more flexible. With increased crystallinity, other effects occur. For example, with polyethylene there is increased resistance to creep, heat, and stress cracking, as well as increased mold shrinkage.

In general, crystalline types of plastics are more difficult to process, requiring more precise control during fabrication, have higher melting temperatures and melt viscosities, and tend to shrink and warp more than amorphous types. They have a relatively sharp melting point. That is, they do not soften gradually with increasing temperature but remain hard until a given quantity of heat has been absorbed, and then change rapidly into a low-viscosity liquid. If the amount of heat is not applied properly during processing, product performance can be drastically reduced or an increase in processing cost occurs. This is not necessarily a problem, because the qualified processor will know what to do. Amorphous plastics soften gradually as they are heated, but they do not flow as easily during molding as crystalline materials.

Processing conditions influence the performance of plastics. For example, heating a

**Table 6-18** Distinctive characteristics of plastics

| Crystalline            | Amorphous             |
|------------------------|-----------------------|
| Sharp melting point    | Broad softening range |
| Usually opaque         | Usually transparent   |
| High shrinkage         | Low shrinkage         |
| Solvent-resistant      | Solvent-sensitive     |
| Fatigue-wear-resistant | Poor fatigue/wear     |

**Table 6-19** Examples of crystalline (semicrystalline) and amorphous TPs

| Crystalline                | Amorphous                             |
|----------------------------|---------------------------------------|
| Acetal (POM)               | Acrylonitrile-butadiene-styrene (ABS) |
| Polyester (PET, PBT)       | Acrylic (PMMA)                        |
| Polyamide (nylon) (PA)     | Polycarbonate (PC)                    |
| Fluorocarbons (PTFE, etc.) | Modified polyphenylene oxide (PPO)    |
| Polyethylene (PE)          | Polystyrene (PS)                      |
| Polypropylene (PP)         | Polyvinyl chloride (PVC)              |

crystalline material above its melting point, followed by quenching, can produce a polymer that has a far more amorphous structure. Its properties can be significantly dif-

**Table 6-20** Examples of key properties for engineering TPs

| Crystalline                         | Amorphous                  |
|-------------------------------------|----------------------------|
| <i>Acetal</i>                       | <i>Polycarbonate</i>       |
| Best property balance               | Good impact resistance     |
| Stiffest unreinforced thermoplastic | Transparent                |
| Low friction                        | Good electrical properties |
| <i>Nylon</i>                        | <i>Modified PPO</i>        |
| High melting point                  | Hydrolytic stability       |
| High elongation                     | Good impact resistance     |
| Toughest thermoplastic              | Good electrical properties |
| Absorbs moisture                    |                            |
| <i>Glass-reinforced</i>             |                            |
| High strength                       |                            |
| Stiffness at elevated temperatures  |                            |
| <i>Mineral-reinforced</i>           |                            |
| Most economical                     |                            |
| Low warpage                         |                            |
| <i>Polyester (glass-reinforced)</i> |                            |
| High stiffness                      |                            |
| Lowest creep                        |                            |
| Excellent electrical properties     |                            |

ferent from those of materials cooled properly (slowly) and allowed to recrystallize. The effects of time are similar to those of temperature in the sense that any given plastic has a preferred or equilibrium structure in which it would prefer to arrange itself. However, it is prevented from doing so instantaneously or at least on "short notice." If given enough time, the molecules will rearrange themselves into their preferred pattern. Heating causes this action to occur sooner. During this action, severe shrinkage and property changes could occur in all directions in the processed plastics.

This characteristic morphology of plastics can be identified by tests. (See Chap. 12.) It provides excellent control as soon as material is received in the plant, during processing, and after fabrication.

Amorphous is a term that means formless. It describes a thermoplastic having no crystalline plastic structure. These TPs have no sharp melting point and are usually glassy and transparent. Examples include polystyrene (PS) and acrylic (PMMA). If they are rigid, they may be brittle. During processing all thermoplastics are normally in the amorphous state with no definite order of molecule chains. If TPs that normally crystallize (crystalline plastics) are not properly quenched (the process of cooling the hot melt to solidify the plastic) the result is an amorphous or partially amorphous solid state, usually with inferior properties.

There are amorphous plastic regions. These are regions in a crystalline plastic that have not crystallized and therefore the polymer chains there exist in a random configuration. Since crystallization is limited in a crystalline plastic, amorphous regions are always present, typically accounting for up to about 20% of the plastic. Thus, plastic acts as a composite of amorphous and crystalline polymers. Both regions contribute their characteristic properties to the overall behavior, with amorphous regions exhibiting a glass transition temperature ( $T_g$ ).

The crystalline plastics are the thermoplastic types that tend to have their molecules arranged in a relatively regular repeating structure. They are usually translucent or opaque

**Table 6-21** General properties of TPs during and after processing

| Property                        | Crystalline <sup>a</sup>             | Amorphous <sup>b</sup>              |
|---------------------------------|--------------------------------------|-------------------------------------|
| Melting or softening            | Fairly sharp melting point           | Softens over a range of temperature |
| Density (for the same material) | Increases as crystallinity increases | Lower than for crystalline material |
| Heat content                    | Greater                              | Lower                               |
| Volume change on heating        | Greater                              | Lower                               |
| After-molding shrinkage         | Greater                              | Lower                               |
| Effect of orientation           | Greater                              | Lower                               |
| Compressibility                 | Often greater                        | Sometimes lower                     |

<sup>a</sup> Typical crystalline plastics are: polyethylene, polypropylene, nylon, acetals, and thermoplastic polyesters. <sup>b</sup> Typical amorphous plastics are: polystyrene, acrylics, PVC, SAN, and ABS.

and generally have higher softening points than the corresponding amorphous plastics. They can be made transparent with chemical modification. Partly crystalline plastics are often less brittle than amorphous plastics. Technically they are called semicrystalline since typically less than 80% of their content is crystalline; the remainder is amorphous. They tend to pack into neat orderly 3-D geometric symmetry providing a plastic with an assortment of high density, sharp melting point ( $T_m$ ), and directional properties. When molecules crystallize, their high degree of organization becomes a major factor in the plastic's overall structure. Thus properties depend upon the percent of crystallinity and the size of the crystals present.

Crystalline plastic relaxation is (with thermoplastics) a relaxation, with its accompanying transition associated with the crystalline regions. The most important relaxation or the primary relaxation is melting. Certain secondary transitions such as premelting, are also sometimes observed.

*Polarized light* It is easy to determine whether the plastic is amorphous or crystalline by observing the sample using polarized light. Amorphous areas appear black, while crystalline areas are clear and have multicolored patterns. This difference occurs because crystalline plastics have molecules that crystallize and fold together in a uniformly orderly manner, whereas the amorphous plastics do not.

*Catalysts and Metallocenes*

A catalyst is a substance that can initiate a chemical reaction or augment the rate of reaction without itself being consumed. It is recovered unaltered in form and amount at the end of the reaction. It generally accelerates the chemical change such as in thermoset plastics. Although the materials ordinarily used to aid the polymerization of most plastics are not catalysts in the strict sense of the word (they are consumed), common usage during the past century has resulted in this name being applied to them.

The metallocene catalyst is also called single site, Me, or m. Metallocene catalysts achieve exceptional control in polymerization and product design permitting creative uses in both old and new markets. Using metallocene catalysts, chemists can model and predict plastics structural products in a matter of days rather than years. Emphasis has been on the polyolefins (mPOs); others include PS, PE/PS, TPO, and EPDM. Uniformity of molecular weight effectively eliminates molecular extremes. This results in a range of property improvements that include improved mechanical, physical, and chemical properties; various processing advantages; and lower costs.

Uniquely synergistic combinations of complementary abilities are available. For example, mPE becomes an economical material competing with the properties of nylon and thermoplastic polyester plastics. Also, one can produce mLLDPE film with the same

strength at a lower gauge than conventional LLDPE because of its narrow molecular weight range. These Me catalysts are more accurate in characterizing plastics than today's quality control instruments can verify.

The long established Ziegler-Natta catalysts (Z-N catalysts) as well as the more recently discovered metallocene catalysts (m or ME catalysts) are used to synthesize polyolefins and other plastics. One difference is that polyolefins produced with Z-N exhibit randomly arranged, comparatively short side chains whereas MEs give rise to polyolefins with a tailor-made side chain length (up to entire polymer chains) and a defined side chain distribution (1, 97).

### Plastic Green Strength

Plastic green strength refers to a processed material such as unvulcanized rubber, elastomer, or plastic in which the solidification or cure is not complete. Certain plastics have mechanical strength that allows its removal from the mold and handling in an unvulcanized state without tearing or permanent distortion. A high green strength is desirable in those processing operations in which the integrity of a shaped piece of the material needs to be maintained prior to vulcanization.

### Molecular Weight (MW)

The molecular weight, or formula weight, is the sum of the atomic weights of all the atoms in a molecule. It represents a measure of the chain length for the molecules that make up the polymer (1). Plastics require very large molecules to provide the cohesion necessary for most end-use properties; but these large molecules disentangle and flow only with difficulty during melt processing. Thus, thermoplastic injection molding requires a compromise molecular weight: low enough for reasonably easy processing but high enough for reasonably good end-use properties (7).

For simplicity, we speak of a polymer as if it had a certain molecular weight; but in reality, any polymer is a mixture of large

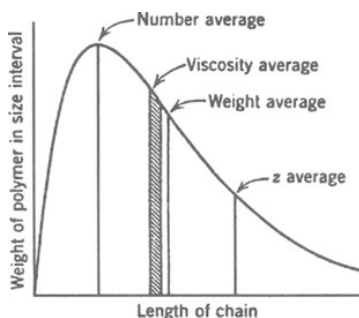


**Fig. 6-29** Typical molecular weight distribution and averages.

molecules of different sizes, which we call the molecular weight distribution (Fig. 6-29). The polymerization mechanism and conditions, and to some extent the compounding and molding conditions, determine whether the distribution is narrow or broad, normal, or skewed, or occasionally even bimodal or multimodal. Both (1) average molecular weight and (2) molecular weight distribution will have specific effects on both injection moldability and end-use properties. Two related considerations are (3) branching of the polymer molecule and (4) plasticizers added in compounding. Each of these four effects can be considered separately.

### Average Molecular Weight

The average molecular weight is the sum of the atomic masses of the elements forming the molecule, indicating the relative size of a typical chain length of the polymer molecule. Many techniques are available for its determination. The choice of method is often complicated by limitations of the technique as well as by the nature of the polymer because most techniques require a sample in solution.

**Melt viscosity** Ask any polymer chemist or engineer about the relationship between polymer structure and injection moldability, and his or her first answer will most likely be: "Increasing molecular weight produces increasing melt viscosity and more difficult injection molding." Countless studies have documented this relationship, many of them quantitatively.

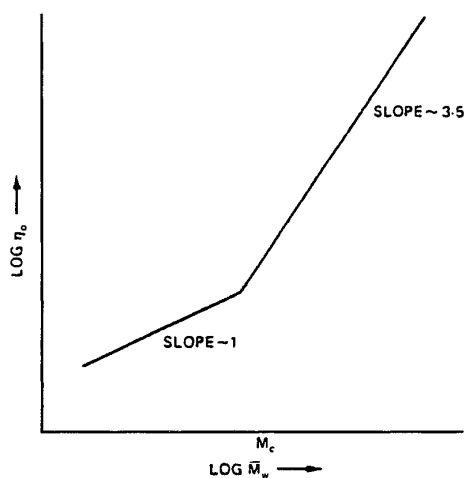


Fig. 6-30 Log-log plot of melt viscosity versus molecular weight.

Quantitatively, the relationship takes the form

$$\eta = KM_w^a$$

meaning that melt viscosity  $\eta$  is proportional to some exponential function of weight-average molecular weight  $M_w$ . The proportionality constant  $K$  depends on the flexibility and intermolecular attraction of the polymer molecules, and on processing conditions: temperature, pressure, and shear rate. The exponent  $a$ , the slope of the log-log plot (Fig. 6-30), is equal to one at low molecular weights, meaning that the melt viscosity is simply proportional to the size of the molecules. At high molecular weights, however, the exponent rises to 3.4 to 3.5, meaning that increasing molecular weight will have a much more severe effect on melt viscosity and injection moldability because of the difficulty of disentangling large polymer molecules to permit melt flow. The transition from  $a = 1$  to  $a = 3.4$  to  $3.5$  occurs at some critical molecular weight  $M_c$  that is generally between 5,000 and 15,000, depending on molecular flexibility, and may even be predictable from basic theoretical considerations.

Since melt viscosity is a linear function of both molecular weight and temperature, graphical and mathematical analysis using the superposition principle can be applied to produce simple master curves and shift fac-

tors, permitting the use of limited experimental data to make broad predictions about processing conditions and processability.

Increasing molecular weight not only increases melt viscosity but also rubbery melt flow. This is the inability of molecules to disentangle completely within the limited temperature, pressure, shear rate, and time span of the process, which produces an elastic melt that can result in a variety of injection molding problems, such as die swell, melt fracture, and postmolding shrinkage, warping, and cracking. The injection molder can compensate for these problems by increasing temperature and time, decreasing shear rate, or changing to a lower-molecular-weight grade of resin.

Although the effect of molecular weight on melt viscosity is the most important relationship in injection molding, molecular weight may also affect other properties important in injection molding, such as thermal stability, thermal conductivity, coefficient of thermal expansion, and melting and crystallization phenomena.

**Thermal stability** It is occasionally observed that increasing molecular weight produces increased thermal stability, which in turn gives the injection molder increased latitude in processing. There are two reasons why stability increases with molecular weight: (1) Most polymerization mechanisms leave unstable structures on the ends of the polymer molecules, so the concentration of these unstable structures is inversely related to molecular weight; (2) most chemical reactions, including degradation reactions, require molecular mobility, which is inversely related to molecular weight. Thus, increasing molecular weight reduces both (1) the concentration of unstable groups that would initiate degradation and (2) the molecular mobility that controls the kinetics of the degradation reaction.

**Thermal conductivity** Once the polymer melt has filled the mold, the injection molder wants to cool it as rapidly as possible to shorten the molding cycle. Here thermal conductivity of the polymer is of prime concern. In a molten polymer, conduction is

primarily due to convection, which depends on molecular mobility and is therefore inversely related to molecular weight. However, as the cold wall of the mold solidifies the outer layer of polymer, further conduction through this solid polymer is required to complete the cooling of the hot interior. Conduction through this layer of solid polymer is no longer by convection, but by atomic vibration. These vibrations are transmitted much more efficiently down the length of a polymer molecule than they are through the spaces between polymer molecules. Thus, in the solid polymer, conduction is directly related to molecular weight. Basic research on these effects remains to be done, but it should illustrate clearly how the two successive phenomena contribute to overall cooling in the injection mold.

#### *Coefficient of linear thermal expansion*

Once the mold has been filled and the polymer proceeds to cool, decreasing thermal vibration produces decreasing free volume, and the practical result is mold shrinkage, which must be compensated by foresight in mold design. Since the ends of the polymer molecules have the greatest mobility, they play the major role in free volume and therefore shrinkage. Increasing molecular weight decreases the concentration of end groups and, therefore, shrinkage during cooling (Table 5-8 and Fig. 5-20).

#### *Molecular Weight Distribution*

Up to this point, we have considered the effects of *average* molecular weight. Any real polymer is composed of a range of molecules from low to high molecular weight; many polymer scientists believe that the shape of this molecular-weight-distribution curve—narrow or wide, normal or skewed, or even multimodal—may have critical effects on injection moldability. A typical sampling from the research literature indicates that the subject is too complex and obscure for complete understanding at the present time. In some cases, there is fairly general agreement; in others, there are mysterious conflicts between theories in their present state. A few

examples will illustrate the present state of our knowledge.

*Melt viscosity* Broadening the molecular weight distribution (MWD) decreases the melt viscosity of polyethylene and impact styrene, but it increases the melt viscosity of ABS and PVC. Confusion may result from different ways of expressing molecular weight averages and distributions and/or the complicating effects of branching.

#### *Additives*

Aside from the structure of the polymer itself, most injection molding compounds contain many additives that have important effects on injection moldability. These additives may be grouped according to whether they improve or hinder melt flow or have other effects on processability (Fig. 6-9 and Tables 6-11 to 6-13).

The use of fillers, and particularly reinforcing fibers, also introduces or accentuates a number of processing problems. Several of these may be noted as follows: (1) Polymer melt flow is generally non-Newtonian, often pseudoplastic. The addition of glass fibers generally accentuates this behavior. The mechanism here is reasonably straightforward; the practical effects are qualitatively similar to those in pure polymers. (2) When a suspension of solid particles in a liquid flows through a channel, the solid particles tend to concentrate at the front of the flow. (3) Short fibers in a polymer melt tend to orient in the direction of flow during injection molding, but this depends on the specific flow patterns. In convergent flow (e.g., in a capillary), they align parallel to the axial flow. In divergent flow (e.g., the entrance from a gate into a mold cavity), they align perpendicular to the major flow direction, as the melt moves transversely to fill the sides of the mold. In shear flow, particularly at low flow rates, they tend to lose alignment and distribute more randomly. The effects of fiber orientation on end-use properties generally resemble those of molecular orientation. (4) Although molten polymer can be injection-molded without a serious change in

structure and properties, short-glass-fiber reinforcement can suffer serious degradation during the injection molding process, and its reinforcing ability suffers accordingly. (5) Since inorganic fillers and reinforcing fibers are almost as hard as steel, they cause severe abrasive wear as they flow through screws, nozzles, gates, and molds in general, particularly around pins and projecting edges. Certain coupling agents can reduce wear. Generally, soft fillers and glass spheres cause less wear, whereas the sharp ends of glass fibers are particularly harmful. While short fibers have more ends, long fibers cause higher viscosity and therefore even more severe wear. (6) Aside from additives used purposely to improve properties, accidental impurities also often affect injection moldability. Most often, absorption of water from the atmosphere causes hydrolytic degradation of polyesters, polyurethanes, and polyamides, lowering molecular weight, increasing melt flow, and degrading end-use properties.

#### *Molecular Weight and Melt Flow*

Having adequate molecular weight (MW) is a fundamental requirement to meet desired properties of plastics. With MW differences of incoming material, the molded part performance can be altered; the more the difference, the more dramatic the change in the part. Melt flow rate (MFR) tests are used to detect degradation in molded parts where comparisons, as an example, are made of the MFR of pellets to the MFR of parts. MFR has a reciprocal relationship to melt viscosity. This relationship of MW to MFR is an inverse one; as the MFR increases, the MW drops. MW and melt viscosity are also related; as one increases the other increases.

#### *Molecular Weight and Aging*

MW and aging may each act as cause and/or effect on plastics. Reactivity with oxygen, ozone, or moisture and UV light sensitization via outdoor weathering and/or high temperature all become important with

aging particularly the neat plastics. Different additives are used with different plastics to provide long-time aging. Based on actual service tests and extensive creep tests, certain plastics have been shown to improve with aging. However, other plastics have limited endurance. This action is somewhat related to MW: Low MW materials tend to degrade while the higher MWs become stronger through cross-linking.

#### **Rheology and Melt Flow**

Rheology is the science of the deformation and flow of matter under force. It is concerned with the response of plastics to mechanical force. The response may be either irreversible flow or reversible flow. An understanding of rheology and the ability to measure rheological properties are necessary before viscous behavior can be controlled during processing. Such control is essential for the manufacture and fabrication of numerous plastic materials and products (1, 169, 534, 584).

For linear elastic materials or Newtonian fluids, simple observations are sufficient to establish a general equation that describes how any material will respond to any type of deformation. However, for the more complex materials such as non-Newtonian molten plastics, the development of an equation is very complex and more difficult to evaluate, requiring many different test and evaluation studies. Relationships are developed and put to practical use. Present knowledge of rheological behavior of non-Newtonian plastics is largely empirical and most useful for these viscoelastic plastics.

Measuring melt flow is important for two reasons. First, it provides a means for determining whether a plastic can be formed into a useful product such as a usable extrudate, completely fill a mold cavity, provide mixing action in a screw, meet product thickness requirements, etc. Second, the flow is an indication of whether the plastic's final properties will be consistent with those required. The target is to provide the necessary homogeneous, stable melt during processing

while working in equilibrium. In practice, despite the major developments that continue to occur this perfect stable situation is never achieved and there are variables that affect the output. If we analyze the process, two types of variables affecting the quality and output rate can be identified: (1) the variables of the machine's design and manufacture and (2) the operating or dynamic variables that control how the machine is run (see Chap. 12, Thermal Property Tests).

The rheology of plastics, particularly TPs, is complex but manageable. These materials exhibit properties that combine those of an ideal viscous liquid (i.e., exhibiting pure shear deformation) with those of an ideal elastic solid (exhibiting pure elastic deformation). Thus, plastics are said to be viscoelastic. The mechanical behavior of plastics is dominated by such viscoelastic phenomena as tensile strength, elongation at break, and rupture energy, which are often the controlling factors. The viscous attributes of polymer melt flow are also important considerations in plastics processing and fabrication.

### Flow

The rheological properties of a melt govern the way it deforms and flows in response to applied forces, as well as the decay of stresses when the flow is halted. These properties therefore play a central role in the injection molding process. In mold filling, it is viscosity, along with thermal properties, that governs the ability of the melt to fill the mold, that is, the pressure required to force the melt through the runner and gate and into the cavity. After filling, it is the relaxation of stresses in the melt that determines residual orientation in the finished part, and this can have an important effect on its mechanical properties. For these reasons, it is important to the molder, as well as the manufacturer of molding resins, to know something about melt rheology and to be able to perform rheological tests on melts (see Chap. 4 on the flow of plastic melt) (7).

It is convenient to discuss shear flows by referring to the simplest type of shear flow.

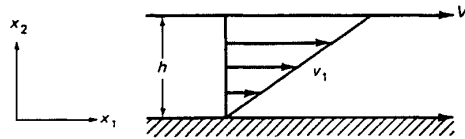


**Fig. 6-31** Simple shear flow between parallel plates.

Simple shear is defined as the flow between two parallel plates, one of which is stationary, while the other moves in a straight line with a velocity  $V$ . Referring to Fig. 6-31 we see that the velocity distribution is given by

$$v_1 = \frac{V}{h} \cdot x_2$$

The shear rate at each point in the fluid is

$$\dot{\gamma} = \frac{dv_1}{dx_2} = \frac{V}{h}$$

Thus, the shear rate is uniform throughout the fluid. If  $V$  does not change with time, we have a steady simple shear flow.

If  $F$  is the total force required to move the upper plate (equal to the force required to hold the lower plate stationary), and  $A$  is the surface area of the plate that is in contact with the liquid, then the shear stress  $\sigma$  is given by

$$\sigma = F/A$$

This is the tangential force per unit area required to produce the shear rate  $\dot{\gamma}$ .

### Viscosity

Viscosity  $\eta$ , the resistance to liquid flow, can be more precisely defined as the ratio of shear stress  $\tau$  to shear rate  $\dot{\gamma}$  in laminar flow:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{\text{shear stress}}{\text{shear rate}}$$

Shear stress is the tangential force per unit area applied to a liquid layer. Shear rate is the ratio of the resulting velocity of layer no. 1 in Fig. 6-32 to the distance from reference layer no. 2. Shear rate is more precisely defined as the rate of change of velocity with distance in the system of laminae,  $dv/dr$ .

In simple systems, viscosity is independent of shear rate (see the Newtonian example in

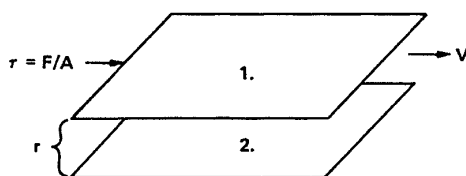


Fig. 6-32 Schematic illustrating laminar flow.

Figs. 6-33 and 6-34). Few plastisols exhibit this type of flow behavior and it is necessary to consider the application of shear rate when compounding for flow properties and to approximate it in some way when measuring the viscosity of the compounded dispersion. Most dispersions show shear rate thinning, thickening, or display the mixed dependencies of Fig. 6-33.

The particles in vinyl dispersions interact to form temporary structures and the dispersion viscosity reacts to the time necessary to break down and rebuild this structure. Time dependency, as well as shear rate dependency, must therefore be considered in selecting instruments and test methods for viscosity measurement. Common terms for shear rate and time dependencies are:

*Shear rate thinning* (pseudoplastic): decreasing viscosity at increasing shear rate

*Shear rate thickening* (dilatant): increasing viscosity at increasing shear rate

*Mixed*: shear rate thinning and thickening at different shear rate ranges

*Rheoplectic*: increasing viscosity with time of agitation at constant shear rate

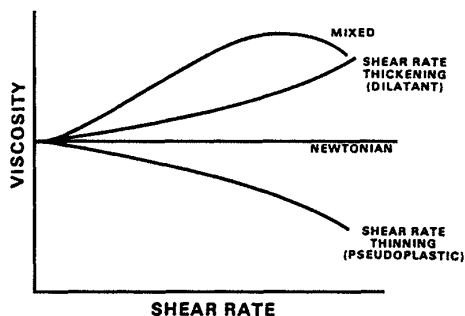


Fig. 6-33 Types of flow illustrating shear rate dependence.

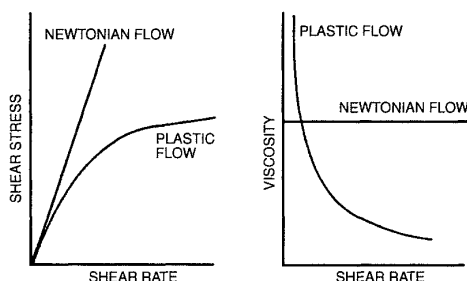


Fig. 6-34 Arithmetic plots of shear stress versus shear rate and viscosity versus shear rate for Newtonian and plastic non-Newtonian materials.

*Thixotropic*: decreasing viscosity with time of agitation at constant shear rate

For low-molecular-weight, single-phase liquids such as water, glycerine, and syrup, viscosity depends on temperature and pressure, but not the shear rate. Such liquids are said to be Newtonian. The viscosity of a Newtonian liquid decreases sharply as the temperature rises and increases (less sharply) as the pressure rises (Fig. 6-35).

### Viscoelasticity

The flow of plastics is compared to that of water in Fig. 6-36 to show their different behaviors. With plastics there are two types of deformation or flow: viscous, in which the

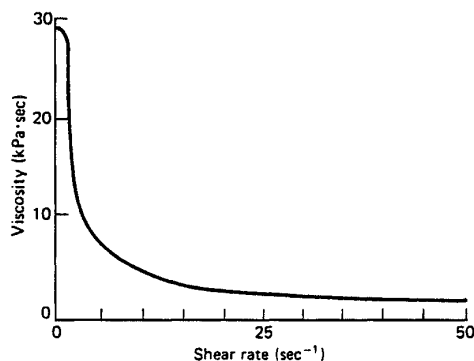


Fig. 6-35 Viscosity can depend not only on temperature and pressure but also on shear rate. These materials are said to be shear-thinning or pseudoplastic.

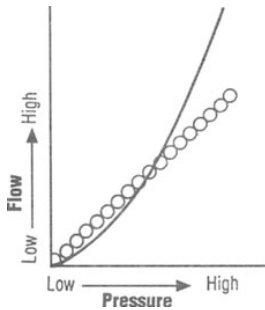


**Fig. 6-36** Rheology and flow properties of plastic (curve) and water (circles).

energy causing the deformation is dissipated, and elastic, in which that energy is stored. The combination produces viscoelastic plastics.

Rheology and flow properties of plastics differ. The volume of a so-called Newtonian fluid, such as water, when pushed through an opening is directly proportional to the pressure applied. The flow rate of a non-Newtonian fluid such as a plastic when pushed through an opening increases more rapidly than the applied pressure (the solid curved line in Fig. 6-36). Different plastics generally have their own flow and rheological rates so that their non-Newtonian curves are different.

Viscosity is a material's resistance to viscous deformation (flow). Its unit of measure is Pascals-second (Pa-sec) or pounds-second/sq in. (lb-sec/sq in.). Plastic melt viscosities range from 2 to 3,000 Pa-sec (glass  $10^{20}$ , water  $10^{-1}$ ). The resistance to elastic deformation is the modulus of elasticity  $E$ , which is measured in Pascals (Pa) or pounds per square inch (psi). Its range for a plastic melt is 1,000 to 7,000 kPa (145 to 1,015 psi), which is called the rubbery range (Figs. 6-37 and 6-38).

Not only are there two classes of deformation, there are also two modes in which deformation can be produced: simple shear and simple tension. The actual action during melting, as in a screw plasticator, is extremely complex, with all types of shear-tension combinations. Together with engineering design, deformation determines the pumping efficiency of a screw plasticator and controls the relationship between output rate and pressure drop through a die system or into a mold.

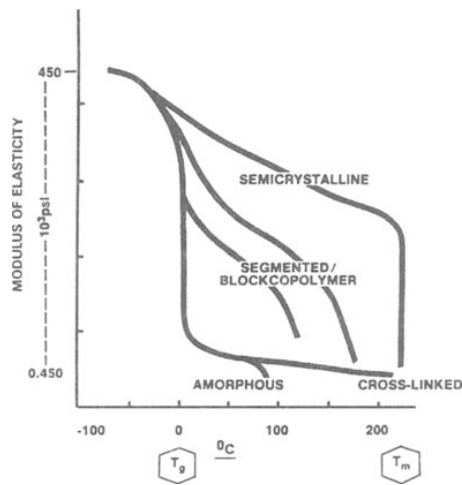


**Fig. 6-37** Example of the dynamic and mechanical properties of TPs and TSs in relation to their glass transition temperature ( $T_g$ ) and melt temperature ( $T_m$ ).

#### Intrinsic Viscosity

Intrinsic viscosity (IV) is a measure of the capability of a plastic in solution to enhance the viscosity of the solution. IV increases with increasing polymer molecular weight (Fig. 6-39).

#### Shear Rate

When a melt moves in a direction parallel to a fixed surface, such as with a screw barrel, mold runner, or die wall, it is subject to a shearing force. As the screw speed increases,

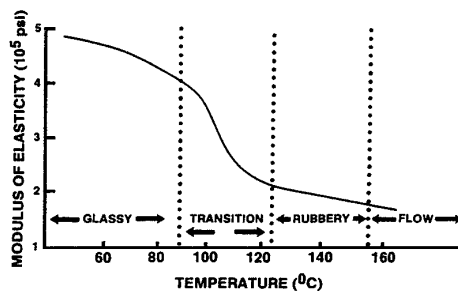


**Fig. 6-38** Example of modulus of elasticity versus temperature of plastics.

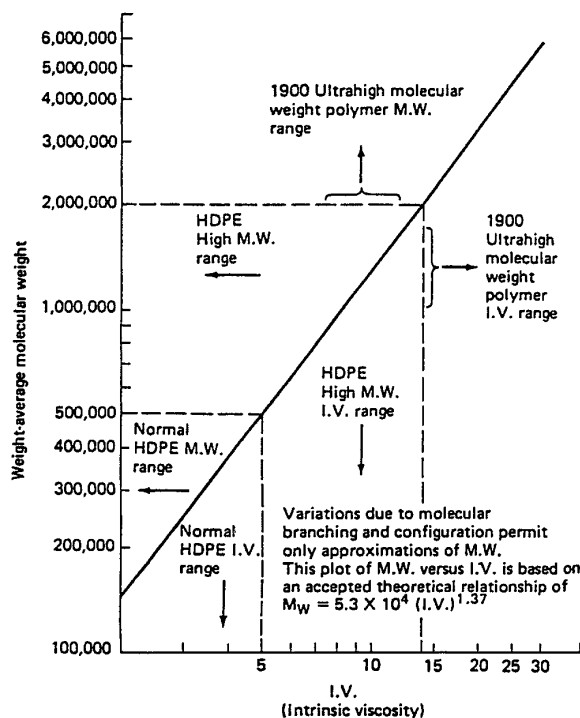


Fig. 6-39 Relationship between intrinsic viscosity and molecular weight of UHMWPE.

so does the shear rate, with potential advantages and disadvantages (see Fig. 6-40). The advantages of an increased shear rate are a less viscous melt and easier flow. This shear-

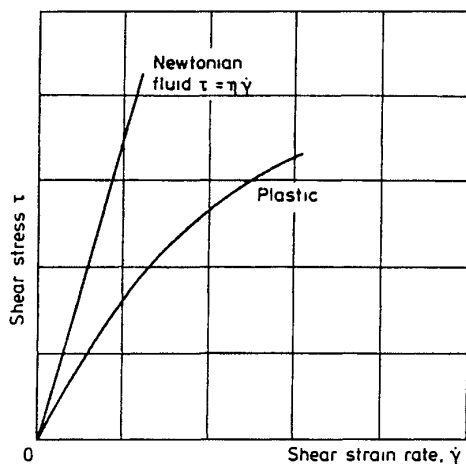


Fig. 6-40 Example of relationship between shear stress and shear rate.

thinning action is required to “move” plastic. (See Chap. 7.) When water (a Newtonian liquid) is in an open-ended pipe, pressure can be applied to move it; doubling the water pressure doubles the flow rate of the water. Water does not have a shear-thinning action. However, in a similar situation but using a plastic melt (a non-Newtonian liquid), if the pressure is doubled, the melt flow may increase from 2 to 15 times, depending on the plastic used. For example, linear low-density polyethylene (LLDPE), with a low shear-thinning action, experiences a low rate increase, which explains why it can cause more processing problems than other PEs in certain equipment. The higher-flow melts include polyvinyl chloride (PVC) and polystyrene (PS).

A disadvantage observed with higher shear rates is that too high a heat increase may occur, potentially causing problems in cooling, as well as degradation and discoloration. A high shear rate can lead to a rough product surface from melt fracture and other causes.

For each plastic and every processing condition, there is a maximum shear rate beyond which such problems can develop.

Shear in the channel of the screw is equal to

$$\frac{\pi DN}{60h}$$

where  $D$  = average barrel inside diameter

$N$  = screw rpm

$h$  = average screw channel depth

This formula does not include the melt slippage between the barrel wall and screw surfaces, but the shear rate obtained is still useful for purposes of comparison. A  $2\frac{1}{2}$ -in. screw with a 0.140-in. channel rotating at 100 rpm results in a shear rate of 93.5 reciprocal seconds (rsec). This value is approximately the desired value in most extrusion processes, with 100 rsec generally being the target.

The same formula can be used to determine the shear rate of slippage between the barrel and screw. With a new barrel, which usually has a small clearance of 0.005 in., a high shear rate of about 2,618 rsec can exist. With this small clearance, only a small amount of melt is subject to the higher heat, so that any overheating is overcome by the melt mass it encounters (i.e., mixes with). As the screw wears, more melt flows through enlarged clearances, but the shear rate is lower. The effect of wear on overheating is usually small and not the main reason why the complete melt overheats.

Shear rates can also be determined in melt flow through mold cavities and particularly in extrusion dies. The formulas applicable to the different-shaped dies usually do not account for the slippage of melt on die surfaces, but they can be used to compare the processability of melts and control melt flow. The formula for a die extruding a rod is

$$\frac{4Q}{\pi R^3},$$

for a long slit

$$\frac{6Q}{wh^2},$$

and for an annulus die

$$\frac{6Q}{\pi Rh^2}$$

where  $Q$  = volumetric flow rate

$R$  = radius

$w$  = width

$h$  = die gap

### *Laminar and Nonlaminar Melt Flows*

It is desirable to have melt that moves in even "layers" that do not interfere with each other during processing. This laminar flow makes it easier to control the melt's behavior in fabricating products. With nonlaminar flows distortion occurs causing potential problems on fabricated products such as poor surface finish. (see Chap. 4, Mold Cooling, Reynolds Number).

### *Melt Flow Analyses*

Software can simulate the desired process for comparison with reality. The purpose of flow analysis is to gain a comprehensive understanding of the melt flow filling process based on process controls. The most sophisticated computer models provide detailed information concerning the influence of filling conditions on the distribution of flow patterns as well as flow vectors, shear stresses, frozen skin, temperatures and pressures, and other variables. Less sophisticated programs that model fewer variables are also available.

From these data, conclusions regarding tolerances, as well as part quality in terms of factors such as strength and appearance, can be drawn. Location of weld lines and weld line integrity can be predicted. The likelihood of warping surfaces, blemishes, and strength reductions due to high-shear stress can be anticipated. On this basis, the best filling conditions can be selected. A program from Spirex Corp. called The Molder's Technician is a typical example of such software. (Chap. 9).

### *Melt Flow Analysis Programs*

Computer flow analysis programs used throughout the plastics industry worldwide utilize 2-D and 3-D models of parts in conjunction with rheology equations. Models

range all the way from a simple Poiseuille's equation for fluid flow to much more complex mathematical models involving differential calculus. It is important for the user of this technology to recognize that, from the simplest to the most complex of these models, all provide only approximations. The user must also understand that their relational techniques, coupled with the user's assumptions, determine whether or not the findings of the flow analysis have any real validity. What actually happens is determined after processing the plastic (1, Chap. 9).

#### *Analyzing Melt Flow Results*

When analyzing the results, it is important to determine the type and location of error, for instance determine if the pressure loss error is in the thin, thick, or virtually all sections. If the error appears in all, it may mean that there is simply an offset caused by a difference between viscosity data used in the flow analysis and the actual viscosity during processing. If this is true, changing the processing speed should allow the flow analysis data to be duplicated with a different fill or exit time. If, however, the flow analysis overstated thick sections and understated thin sections, there could be a serious problem with the mathematics used.

#### *Melt Flow Defects*

Flow defects affect the appearance of a product; sometimes they are desirable, such as in producing a matte finish. Typical defects involve nonlaminar flow, nonplastication, volatiles, sharkskin, and shrinkage.

#### *Hindering Melt Flow with Additives*

Different additives, such as particulate fillers and especially fibrous reinforcements, generally increase viscosity and impede melt flow.

#### *Melt Fractures*

Melt fractures result from elastic turbulence, which is an instability or an elastic strain in the melt flow usually through a mold. The resulting surface irregularities on the finished part look like a regular helix or irregularly spaced ripples. Plastic's rheology influences its melt fracture behavior. Higher molecular weight plastic (with narrow MWD) tends to have less sensitivity to fracture onset.

#### *Cavity Filling*

The objective in filling the cavity is to achieve complete filling without short shots while avoiding sink marks, warpage, sticking in the mold, flash, and poor mechanical properties. This is accomplished by delivering the correct amount of resin to the cavity while avoiding overpressurization, high thermal stresses, and high residual orientation. Some of the factors that favor complete filling, however, also promote overpressurization and residual stresses, so care must be taken in selecting operating conditions for a given mold and resin.

As melt flows into the cavity, the situation cannot be described in terms of pressure flow between parallel plates with a gap equal to the mold clearance, because a frozen layer forms immediately at the cavity wall. Moreover, the melt in the center has a lower viscosity owing to its higher temperature, and as a result, the maximum shear rate occurs not at the surface of the frozen layer but closer to the center. The shear rate in the cavity generally falls in the range of 8,000 to 15,000  $\text{sec}^{-1}$ .

Another important phenomenon that causes the flow to deviate from two-dimensional flow between parallel plates is termed the "fountain effect" (Fig. 6-41). Here the melt does not reach the wall or surface of the frozen wall layer by simple forward advance, but rather it tends to flow down the center of the cavity to the melt front and then flow out toward the wall. This can have an important effect on the direction of

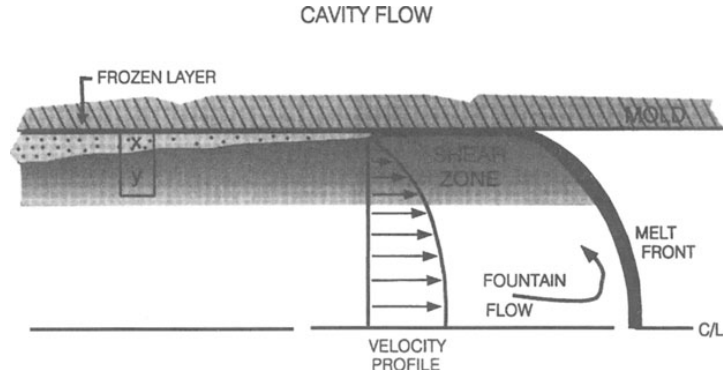


**Fig. 6-41** Fountain flow melt flow pattern.

the flow-induced orientation of the polymer molecules.

If the melt must flow around an obstacle of any kind in the cavity, a weld line will result. A phenomenon that can lead to a complex pattern of weld lines is "jetting." This term refers to the tendency of the melt to spurt into the cavity without wetting the walls near the gate, and the result is that the cavity fills by a piling up of the jet at the end of the cavity rather than the smooth advancement of a melt front starting at the gate.

### Plastic Raw Materials

Plastics are usually obtained in the form of granules, powders, flakes, or pellets, or sometimes in liquid form or tapes. Each has certain advantages, such as providing specific molded part performances, ease in compounding, ease of processing, and/or reduced cost. They can be delivered in small to large amounts from all kinds of material suppliers worldwide. Usually delivery is in 55 lb (25 kg) sacks, gaylords of 1,000 lb (455 kg), semibulk containers (half to a full ton), or in truck or rail car tanks of up to 25 tons.

### Plastic Advantages and Disadvantages

As a material of construction for all types of products, plastics provide practically unlimited benefits. Unfortunately for plastics, as well as other materials (steel, aluminum,

wood, etc.), no one specific plastic has all the benefits. The successful applications of their benefits and an understanding of a particular plastic's individual advantages and weaknesses (as reviewed throughout this book) allow useful and successful products to be produced.

### Plastic Properties and Characteristics

Materials are identifiable by different property characteristics. They include mechanical, physical, electrical, thermal (Table 6-22), and chemical properties (Table 6-23), as well as transparency and many other characteristics to meet product requirements. Extensive amounts of mechanical data such as those presented in Table 6-24 are available. When examining and comparing data it is important to recognize the potential difficulties in making comparisons, for data from different sources may have been conducted under different conditions of testing (Chap. 12).

### Melt Shear Behaviors

Melt shear rate in the gate can be very high. The melt pressure flow that establishes the shear rate can produce a rate in a pin gate in excess of  $100,000 \text{ sec}^{-1}$  in extreme cases. Typically it ranges from  $1,000$  to  $10,000 \text{ sec}^{-1}$ ; in runner's from  $10$  to  $1,000 \text{ sec}^{-1}$ ; and in

**Table 6-22** Examples of thermal properties of plastics and other materials

| Plastics<br>(morphology) <sup>a</sup> | Density,<br>g/cm <sup>3</sup><br>(lb./ft. <sup>3</sup> ) | Melt<br>Temperature<br>T <sub>m</sub> , °C (°F) | Glass<br>Transition<br>Temperature<br>T <sub>g</sub> , °C (°F) | Thermal                                                          |                                        | Heat<br>Capacity,<br>cal/g °C<br>(BTU/lb. °F) | Thermal<br>Diffusivity,<br>10 <sup>-4</sup> cm <sup>2</sup> /s,<br>(10 <sup>-3</sup> ft <sup>2</sup> /hr) | Thermal<br>Expansion,<br>10 <sup>-6</sup> cm/cm °C<br>(10 <sup>-6</sup> in./in. °F) |
|---------------------------------------|----------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------|----------------------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                                       |                                                          |                                                 |                                                                | Conductivity,<br>10 <sup>-4</sup> cal/s<br>cm °C<br>(BTU/lb. °F) | Conductivity,<br>cm °C<br>(BTU/lb. °F) |                                               |                                                                                                           |                                                                                     |
| PP                                    | (C) 0.9 (56)                                             | 168 (334)                                       | 5 (41)                                                         | 2.8 (0.068)                                                      | 0.9 (0.004)                            | 3.5 (1.36)                                    | 81 (45)                                                                                                   |                                                                                     |
| HDPE                                  | (C) 0.96 (60)                                            | 134 (273)                                       | -110 (-166)                                                    | 12 (0.290)                                                       | 0.9 (0.004)                            | 13.9 (5.4)                                    | 59 (33)                                                                                                   |                                                                                     |
| PTFE                                  | (C) 2.2 (137)                                            | 330 (626)                                       | -115 (-175)                                                    | 6 (0.145)                                                        | 0.3 (0.001)                            | 9.1 (3.53)                                    | 70 (39)                                                                                                   |                                                                                     |
| PA                                    | (C) 1.13 (71)                                            | 260 (500)                                       | 50 (122)                                                       | 5.8 (0.140)                                                      | 0.075 (0.003)                          | 6.8 (2.64)                                    | 80 (44)                                                                                                   |                                                                                     |
| PET                                   | (C) 1.35 (84)                                            | 250 (490)                                       | 70 (158)                                                       | 3.6 (0.087)                                                      | 0.45 (0.002)                           | 5.9 (2.29)                                    | 65 (36)                                                                                                   |                                                                                     |
| ABS                                   | (A) 1.05 (66)                                            | 105 (221)                                       | 102 (215)                                                      | 3 (0.073)                                                        | 0.5 (0.002)                            | 3.8 (1.47)                                    | 60 (33)                                                                                                   |                                                                                     |
| PS                                    | (A) 1.05 (66)                                            | 100 (212)                                       | 90 (194)                                                       | 3 (0.073)                                                        | 0.5 (0.002)                            | 5.7 (2.2)                                     | 50 (28)                                                                                                   |                                                                                     |
| PMMA                                  | (A) 1.20 (75)                                            | 95 (203)                                        | 100 (212)                                                      | 6 (0.145)                                                        | 0.56 (0.002)                           | 8.9 (3.45)                                    | 50 (28)                                                                                                   |                                                                                     |
| PC                                    | (A) 1.20 (75)                                            | 266 (510)                                       | 150 (300)                                                      | 4.7 (0.114)                                                      | 0.5 (0.002)                            | 7.8 (3.0)                                     | 68 (38)                                                                                                   |                                                                                     |
| PVC                                   | (A) 1.35 (84)                                            | 199 (390)                                       | 90 (194)                                                       | 5 (0.121)                                                        | 0.6 (0.002)                            | 6.2 (2.4)                                     | 50 (128)                                                                                                  |                                                                                     |
| Aluminum                              | 2.68 (167)                                               | 1,000                                           |                                                                | 3000 (72.5)                                                      | 0.23                                   | 4900 (1900)                                   | 19 (10.6)                                                                                                 |                                                                                     |
| Copper/bronze                         | 8.8 (549)                                                | 1,800                                           |                                                                | 4500 (109)                                                       | 0.09                                   | 5700 (2200)                                   | 18 (10)                                                                                                   |                                                                                     |
| Steel                                 | 7.9 (493)                                                | 2,750                                           |                                                                | 800 (21.3)                                                       | 0.11                                   | 1000 (338)                                    | 11 (6.1)                                                                                                  |                                                                                     |
| Maple wood                            | 0.45 (28.1)                                              | 400 (burns)                                     |                                                                | 3 (0.073)                                                        | 0.25                                   | 27 (10.5)                                     | 60 (33)                                                                                                   |                                                                                     |
| Zinc alloy                            | 6.7 (418)                                                | 800                                             |                                                                | 2500 (60.4)                                                      | 0.10                                   | 3700 (1430)                                   | 27 (15)                                                                                                   |                                                                                     |

<sup>a</sup> C = crystalline resin; A = amorphous resin.

**Table 6-23** Effects on plastics of elevated temperature versus chemical agents

| Plastic Material                       | Temperature (°F): |     |    |     |     |     |     |     |     |     |     |     |     |     |     |     |
|----------------------------------------|-------------------|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                                        | 77                | 200 | 77 | 200 | 77  | 200 | 77  | 200 | 77  | 200 | 77  | 200 | 77  | 200 | 77  | 200 |
| Acetals                                | 1-4               | 2-4 | 1  | 2   | 1-2 | 4   | 1-3 | 2-5 | 1-5 | 2-5 | 5   | 5   | 5   | 5   | 1   | 2-3 |
| Acrylics                               | 5                 | 5   | 2  | 3   | 5   | 5   | 1   | 3   | 2   | 5   | 4   | 4-5 | 5   | 5   | 5   | 5   |
| Acrylonitrile-Butadiene-Styrenes (ABS) | 4                 | 5   | 2  | 3-5 | 3-5 | 5   | 1   | 2-4 | 1   | 2-4 | 1-4 | 5   | 1-5 | 5   | 3-5 | 5   |
| Aramids (aromatic polyamide)           | 1                 | 1   | 1  | 1   | 1   | 1   | 2   | 3   | 4   | 5   | 3   | 4   | 2   | 5   | 1   | 2   |
| Cellulose Acetates (CA)                | 2                 | 3   | 2  | 3   | 3   | 4   | 2   | 3   | 3   | 5   | 3   | 5   | 3   | 5   | 5   | 5   |
| Cellulose Acetate Butyrates (CAB)      | 4                 | 5   | 1  | 3   | 3   | 4   | 2   | 4   | 3   | 5   | 3   | 5   | 3   | 5   | 5   | 5   |
| Cellulose Acetate Propionates (CAP)    | 4                 | 5   | 1  | 3   | 3   | 4   | 1   | 2   | 3   | 5   | 3   | 5   | 3   | 5   | 5   | 5   |
| Diallyl Phthalates (DAP, filled)       | 1-2               | 2-4 | 2  | 3   | 2   | 4   | 2   | 3   | 2   | 4   | 1-2 | 2-3 | 2   | 4   | 3-4 | 4-5 |
| Epoxies                                | 1                 | 2   | 1  | 2   | 1-2 | 3-4 | 1   | 1-2 | 1   | 2   | 2-3 | 3-4 | 4   | 4-5 | 2   | 3-4 |

<sup>a</sup>Rating of 1 equals greatest stability.

**Table 6-24** Examples of ASTM mechanical property data of glass fiber reinforced thermoplastic compounds

| Plastic                           | Glass-Fiber Content, wt% | Specific Gravity, D 792 | Tensile Strength, MPa, <sup>a</sup> D 638 | Tensile Elongation, %, D 638 | Tensile Modulus, GPa, <sup>a</sup> D 638 | Flexural Strength, MPa, <sup>a</sup> D 790 | Flexural Modulus, GPa, <sup>a</sup> D 790 | Compressive Strength, MPa, <sup>a</sup> D 695 | Impact Strength, Izod Notched, J/m, <sup>b</sup> D 256 |
|-----------------------------------|--------------------------|-------------------------|-------------------------------------------|------------------------------|------------------------------------------|--------------------------------------------|-------------------------------------------|-----------------------------------------------|--------------------------------------------------------|
| ABS                               | 10                       | 1.10                    | 65                                        | 3.0                          | 4.6                                      | 102                                        | 4.5                                       | 83                                            | 64                                                     |
|                                   | 20                       | 1.22                    | 76                                        | 2.0                          | 5.1                                      | 107                                        | 4.9                                       | 97                                            | 59                                                     |
|                                   | 30                       | 1.28                    | 90                                        | 1.4                          | 6.3                                      | 116                                        | 6.4                                       | 104                                           | 53                                                     |
| acetal                            | 10                       | 1.54                    | 72                                        | 2.4                          | 6.6                                      | 107                                        | 6.1                                       | 69                                            | 53                                                     |
|                                   | 30                       | 1.63                    | 83                                        | 2.0                          | 7.7                                      | 114                                        | 7.2                                       | 81                                            | 43                                                     |
| nylon-6                           | 15                       | 1.25                    | 104                                       | 4.0                          | 5.9                                      | 159                                        | 5.4                                       | 97                                            | 80                                                     |
|                                   | 30                       | 1.37                    | 166                                       | 3.0                          | 7.2                                      | 200                                        | 6.9                                       | 166                                           | 117                                                    |
| nylon-6,6                         | 13                       | 1.23                    | 97                                        | 4.0                          | 6.2                                      | 173                                        | 4.5                                       | 93                                            | 53                                                     |
|                                   | 30                       | 1.37                    | 173                                       | 3.0                          | 9.0                                      | 235                                        | 9.0                                       | 186                                           | 107                                                    |
| nylon-6,12                        | 30                       | 1.30                    | 135                                       | 4.0                          | 8.3                                      | 193                                        | 7.6                                       | 138                                           | 117                                                    |
| polycarbonate                     | 10                       | 1.26                    | 83                                        | 9.0                          | 5.2                                      | 110                                        | 4.1                                       | 97                                            | 107                                                    |
|                                   | 30                       | 1.43                    | 121                                       | 2.0                          | 8.6                                      | 141                                        | 6.9                                       | 117                                           | 128                                                    |
| polyester, thermoplastic          | 30                       | 1.52                    | 131                                       | 4.0                          | 8.3                                      | 193                                        | 7.9                                       | 124                                           | 96                                                     |
| polyethylene                      | 10                       | 1.04                    | 36                                        | 4.0                          | 2.5                                      | 46                                         | 2.5                                       | 35                                            | 75                                                     |
|                                   | 30                       | 1.18                    | 59                                        | 3.0                          | 5.0                                      | 89                                         | 4.9                                       | 41                                            | 91                                                     |
| poly(phenylene oxide), modified   | 20                       | 1.21                    | 100                                       | 5.0                          | 6.4                                      | 128                                        | 5.2                                       | 121                                           | 96                                                     |
| poly(phenylene sulfide)           | 40                       | 1.64                    | 152                                       | 3.0                          | 14.1                                     | 255                                        | 13.0                                      | 145                                           | 80                                                     |
| polypropylene                     | 10                       | 0.98                    | 43                                        | 4.0                          | 2.5                                      | 54                                         | 2.4                                       | 41                                            | 43                                                     |
|                                   | 20                       | 1.04                    | 45                                        | 3.0                          | 3.7                                      | 57                                         | 3.6                                       | 45                                            | 59                                                     |
|                                   | 30                       | 1.12                    | 47                                        | 2.0                          | 4.4                                      | 63                                         | 4.3                                       | 47                                            | 69                                                     |
| polypropylene, chemically coupled | 10                       | 0.98                    | 50-59                                     | 4.0                          | 3.7                                      | 72-94                                      | 3.5                                       | 43-44                                         | 64-75                                                  |
|                                   | 20                       | 1.04                    | 57-68                                     | 3.0                          | 3.9                                      | 81-106                                     | 3.7                                       | 44-47                                         | 69-80                                                  |
|                                   | 30                       | 1.12                    | 68-83                                     | 2.0                          | 4.6                                      | 90-131                                     | 4.6                                       | 45-48                                         | 69-91                                                  |
| polystyrene                       | 20                       | 1.22                    | 90                                        | 1.2                          | 8.3                                      | 131                                        | 7.9                                       | 110                                           | 59                                                     |
| high heat copolymer               | 30                       | 1.35                    | 83                                        | 1.8                          | 6.5                                      | 123                                        | 5.7                                       | 76                                            | 80                                                     |
| high heat terpolymer              | 20                       | 1.38                    | 97                                        | 2.5                          | 6.0                                      | 138                                        | 5.9                                       | 124                                           | 64                                                     |
| polysulfone                       | 40                       | 1.55                    | 124                                       | 1.5                          | 11.6                                     | 173                                        | 10.7                                      | 138                                           | 80                                                     |
| polyurethane                      | 10                       | 1.22                    | 33                                        | 48.0                         | 0.7                                      | 43                                         | 0.6                                       | 35                                            | 747                                                    |
| PVC                               | 20                       | 1.58                    | 97                                        | 3.0                          | 0.8                                      | 145                                        | 6.9                                       | 83                                            | 80                                                     |
| SAN                               | 20                       | 1.22                    | 100                                       | 1.8                          | 8.6                                      | 131                                        | 7.6                                       | 121                                           | 64                                                     |
|                                   | 35                       | 1.35                    | 110                                       | 1.4                          | 10.4                                     | 155                                        | 9.3                                       | 45                                            | 53                                                     |

<sup>a</sup> To convert MPa to psi, multiply by 145; to convert GPa to psi, multiply by 145,000.<sup>b</sup> To convert J/m to ft-lbf/in., divide by 53.38.

cavities from 0.001 to 100 sec<sup>-1</sup>. Local flow rates and shear rates are constantly changing during filling and vary in direct relationship to the channel depths and the cross sectional area for flow. Added to this variation is the highly transient nature of the process: The melt pool is at rest in the barrel prior to injection but between “rest” periods the melt is rapidly accelerated or decelerated (see Chap. 4, Correcting Mold Filling Imbalances in Geometrically Balanced Runner Systems).

### Weld Line Strengths and Materials

Weld lines can develop during molding, particularly if improper design of the part occurred. Different plastics can cause the problem. This section concerns tests conducted on specific materials by Monsanto Polymer Products Co. Complex polymer (plastics) systems were used and evaluated.

This work involves the investigation of weld line strength of several rubber modified flame-retardant polymers including two styrene maleic anhydride (SMA) materials (one natural and one pigmented), three modified polyphenylene oxide (PPO) polymers, and a flame-retardant (FR) ABS (Table 6-25). Many other complex polymer systems that contain relatively high levels of plasticizers or inert solids such as pigments and fillers may display weld line performance like that described here.

In all but the simplest injection molding configurations, two or more melt streams will combine to form what is known as weld or knit lines. A weak line theory suggests that strength in the weld line region is more important than bulk material properties. A good deal has been written on how to adjust molding conditions to optimize weld line strength. It has also been shown that materials selection is very important if good weld line strength is desired.

Previous work emphasized the need to mold at high stock temperature to obtain good molecular entanglements across the weld line. Most of the previous work was done on relatively pure polymer systems. The presence of large concentrations of solid and liquid additives can greatly influence the formation of entanglements across the weld line interface and therefore affect weld line strength.

The objective of this study was to define variation in weld line strength with stock temperature for several complex polymer systems and identify a possible cause of the variation.

Tensile and tensile impact strength were used to study weld lines. The two tests measure different characteristics of weld lines. The tensile impact test was used to identify possible product weakness that cannot be seen from a routine tensile test run on samples containing weld lines. Dimensions of test specimens are shown in Fig. 6-42.

**Table 6-25** Plastics used for weld line evaluations

| Material     | Measured Heat Distortion at 264 psi, °C | Sidewinder Flow at Maximum Recommended Stock Temperature |     | Flammability ul 94 at 1.5 mm |
|--------------|-----------------------------------------|----------------------------------------------------------|-----|------------------------------|
|              |                                         | cm                                                       | °C  |                              |
| FRABS        |                                         |                                                          |     |                              |
| Natural      | 86                                      | 33                                                       | 238 | V-0                          |
| Modified SMA |                                         |                                                          |     |                              |
| Natural      | 101                                     | 34                                                       | 249 | V-0                          |
| Grey         | 102                                     | 33                                                       | 249 | V-0                          |
| Modified PPO |                                         |                                                          |     |                              |
| A            | 89                                      | 43                                                       | 288 | V-0                          |
| B            | 99                                      | 36                                                       | 288 | V-1                          |
| C            | 103                                     | 26                                                       | 288 | V-0                          |

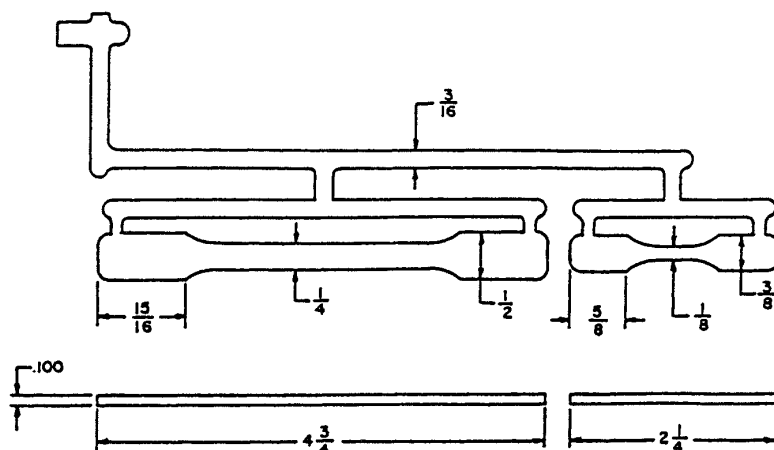


**Fig. 6-42** Mold configuration used for producing tensile-impact (right) tensile specimens with weld lines.

Electron micrographs were taken of a number of weld line profiles. These micrographs show that weld line depth can vary considerably with small stock temperature changes.

Information on strength versus rate of testing is given in Table 6-26.

Figure 6-43 illustrates how the percentage of weld line breaks change as the molding

temperature is changed. Dashed lines show where samples were molded above their recommended temperature limit. In all cases where impact weld line breaks occurred with a 5 cu cm/sec injection rate, better results were seen with a 2.5 cu cm/sec injection rate if the sample filled the mold at the lower rate.

Figure 6-44 shows absolute weld line strength as a function of molding tempera-

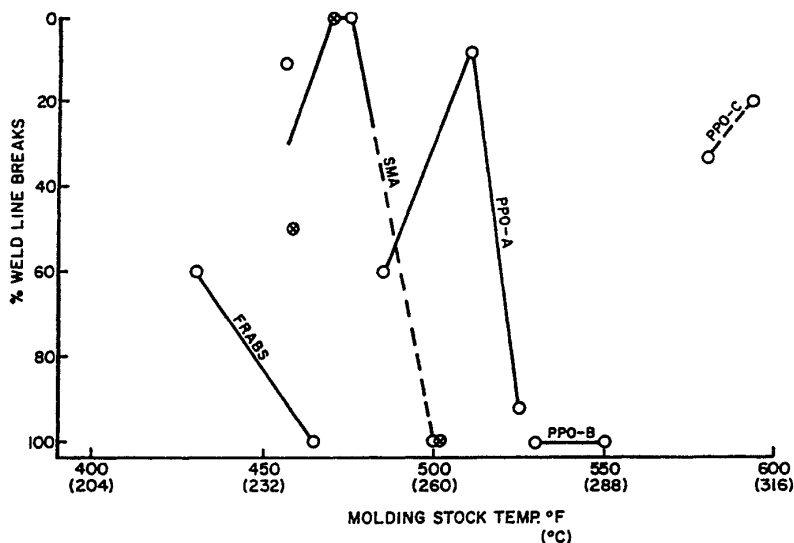


**Fig. 6-43** Tensile impact with percent breaks at weld line versus stock temperature, for 5 cm<sup>3</sup>/s injection rate.

**Table 6-26** Weld line strength of FR plastics

| Material    | Sample No. | Stock Temperature (°C) | Injection Rate (cu cm/s) | Tensile Strength (MPa) |
|-------------|------------|------------------------|--------------------------|------------------------|
| FRABS       | 1          | 221                    | 5                        | 33.9                   |
|             | 1A         | 221                    | 2.5                      | 33.1                   |
|             | 2          | 241                    | 5                        | 32.4                   |
|             | 2A         | 241                    | 2.5                      | 33.9                   |
| SMA natural | 6          | 236                    | 5                        | 26.8                   |
|             | 6A         | 236                    | 2.5                      | 26.8                   |
|             | 5          | 246                    | 5                        | 26.8                   |
|             | 5A         | 246                    | 2.5                      | 26.8                   |
|             | 9          | 260                    | 5                        | 28.9                   |
| SMA grey    | 7          | 237                    | 5                        | 26.5                   |
|             | 7A         | 237                    | 2.5                      | 26.5                   |
|             | 8          | 243                    | 5                        | 27.8                   |
|             | 8A         | 243                    | 2.5                      | 27.8                   |
|             | 10         | 260                    | 5                        | 29.6                   |
|             | 10A        | 260                    | 2.5                      | 30.3                   |
| PPO-A       | 11A        | 252                    | 2.5                      |                        |
|             | 13         | 266                    | 5                        | 35.0                   |
|             | 13A        | 266                    | 2.5                      | 35.2                   |
|             | 15         | 274                    | 5                        | 35.0                   |
|             | 15A        | 274                    | 2.5                      | 35.2                   |
|             | 18         | 287                    | 5                        |                        |
| PPO-B       | 16         | 277                    | 5                        | 32.0                   |
|             | 16A        | 277                    | 2.5                      |                        |
|             | 19         | 289                    | 5                        | 32.1                   |
|             | 19A        | 289                    | 2.5                      | 32.1                   |
| PPO-C       | 20         | 290                    | 5                        | —                      |
|             | 21         | 304                    | 5                        | 46.6                   |
|             | 21A        | 304                    | 2.5                      | 44.0                   |
|             | 22         | 312                    | 5                        | 46.8                   |
|             | 22A        | 312                    | 2.5                      | 46.8                   |

ture. Except for the PPO-C sample, all materials have a similar average weld line strength. However, when parts fail, it is usually the “weak link” that fails. Figure 6-45 shows weld line impact strength as a percentage of nonweld line impact strength versus molding temperature. The FRABS, PPO-A, and PPO-B samples show weld line impact strength to be only 10 to 30% of nonweld line impact strength. This means that for these three materials, some parts may be produced with very weak weld lines.

The SMA samples show very good weld line strength at molding temperatures at or below the recommended maximum, whereas the PPO-C samples show good weld line

strength at the two temperatures studied. It should be kept in mind that the PPO-C sample would not fill the mold until the stock temperature was increased well above the manufacturer’s recommended stock temperature. Apparently, the high molding temperature did not adversely affect weld line strength for the PPO-C sample. However, some other property outside of this study may suffer because the material was molded above its recommended temperature limit.

The FRABS, SMA, and PPO-A samples show a relatively low percentage of weld line breaks at low molding temperature and high percentage of breaks at or above the upper molding limit. This is the opposite of tensile

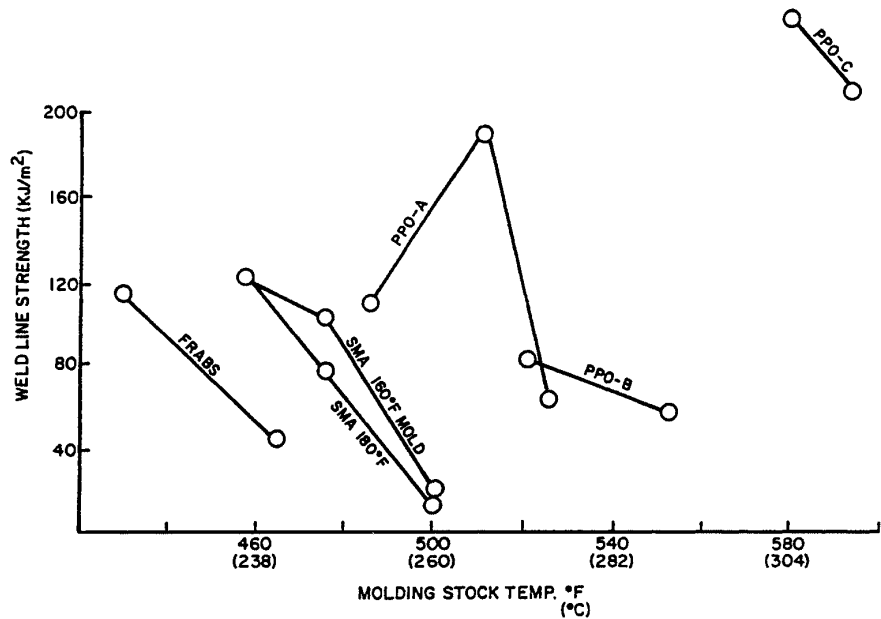


Fig. 6-44 Effect of stock temperature on tensile-impact strength for all breaks, for 5 cm³/s injection rate.

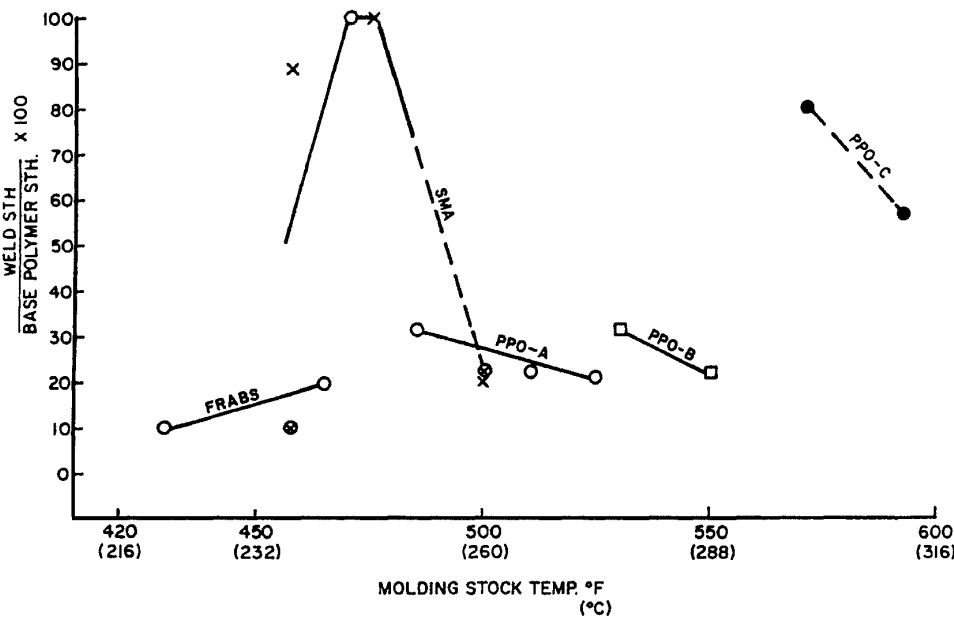


Fig. 6-45 Effect of stock temperature on tensile-impact weld line strength as percent base plastic strength, for 5 cm³/s injection rate.

**Table 6-27** Depth of weld line of various SMA samples

| Sample | Molding Temperature (°C) | Depth of Notch ( $\mu\text{m}$ ) |
|--------|--------------------------|----------------------------------|
| 7      | 237                      | 240                              |
| 8      | 243                      | 5                                |
| 10     | 260                      | 0                                |

strength data, which show weld line strength to improve the molding temperature. For SMA and PPO-A samples, it appears that weld line breaks decrease at a low molding temperature (Fig. 6-27). This seems probable based on previous studies. To identify the cause of this phenomenon, transmission electron micrographs were taken of a cross section of SMA samples 7, 8, and 10. Some very large differences were seen (Table 6-27 and Figs. 6-46 and 6-47). The notch depth value is approximate because some weld lines are

irregular. The deep 240- $\mu\text{m}$  crack seen at the lowest molding temperature (sample 7) seems to explain why that sample had poor weld line strength.

Several electron micrographs (Fig. 6-46 SMA and Fig. 6-48 PPO samples) show that rubber particles are severely elongated in a direction parallel to the weld line. This effect will reduce impact resistance to fracture propagation parallel to and near the weld line.

The PPO-B sample showed 100% weld line breaks at both molding temperatures, whereas the higher melt viscosity sample PPO-C showed only 20 to 30% breaks (Fig. 6-43). Since notch depth correlates with high melt viscosity, poor weld line strength seen with the PPO-B sample at all molding temperatures and the FRABS, SMA, and PPO-A samples molded at or above the upper temperature limit must be due to something



**Fig. 6-46** A 5- $\mu$ -deep SMA weld line from a sample molded at 470°F (243°C). Rubber particles are elongated parallel to the weld line.

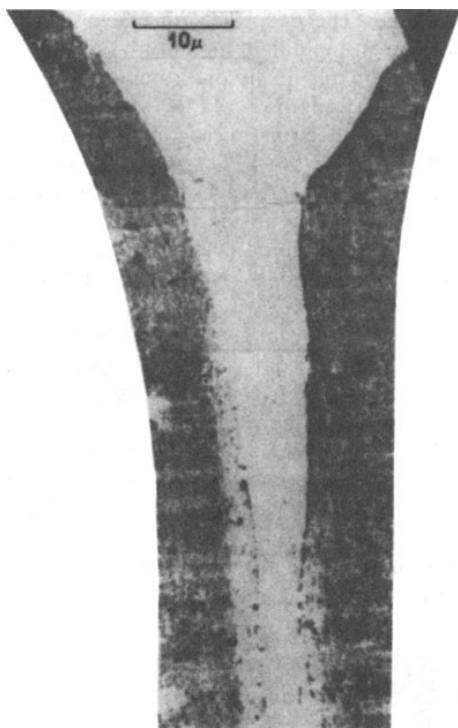


**Fig. 6-47** Portion of a 240- $\mu$ -deep SMA weld line molded at 460°F (237°C).

other than notch depth. Even chain entanglement and morphological differences should be changing in a direction that gives better weld line strength at a high molding temperature.

Some complex polymer systems are known to change composition when processed under certain conditions. Deposits of additives on molded part surface (bloom) and in molds (plate-out) are indications of this phenomenon. Samples displaying strong and weak weld line strength were analyzed under a scanning electron microscope to determine whether differences could be observed. Figure 6-49 is a scanning electron micrograph (SEM) taken of sample 7A (Table 6-26), which had a strong weld line.

The reason for poor weld line strength can be seen from Fig. 6-50. At the high molding temperature, additives concentrate at the part surface and the weld line interface because of fountain flow.

The presence of particles at the weld line will block the movement of polymer molecules across the interface by what has been called *repetition*. The lack of chain entanglements across the interface will lead to reduced strength.

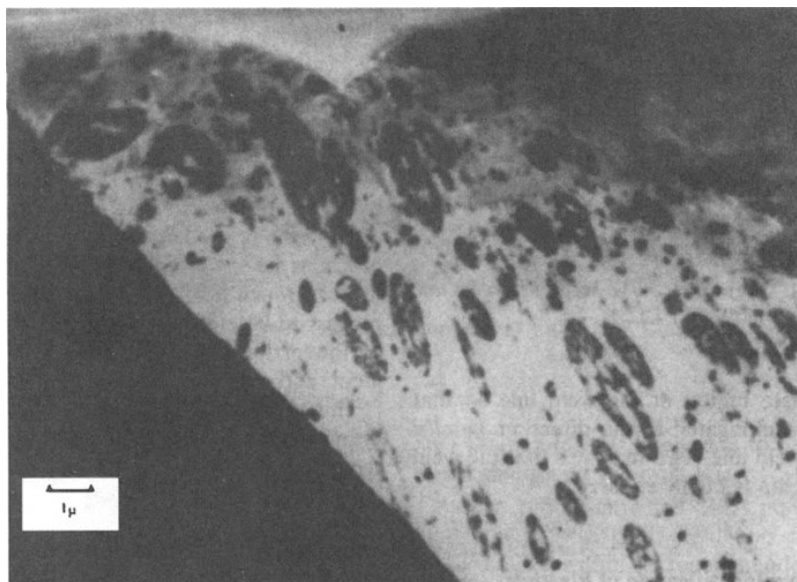


**Fig. 6-48** PPO weld line showing oriented rubber particles at the weld surface.

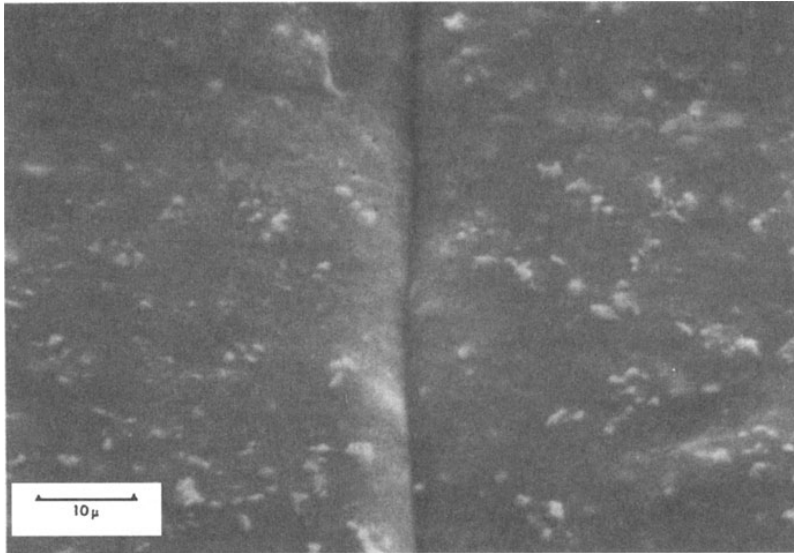


**Fig. 6-49** Scanning electron micrograph of strong FR SMA weld line, relatively free of particles.

Thermoplastics need to be molded at a high enough temperature so that molecules can replicate across weld lines giving good strength. For polymers such as flame-retardant materials that contain significant amounts of solid additives, weld strength

increases with melt temperature only to a point. Then particles concentrate at the interface, blocking chain movement and resulting in poor weld strength.

Based on this review, the following conclusions were made:

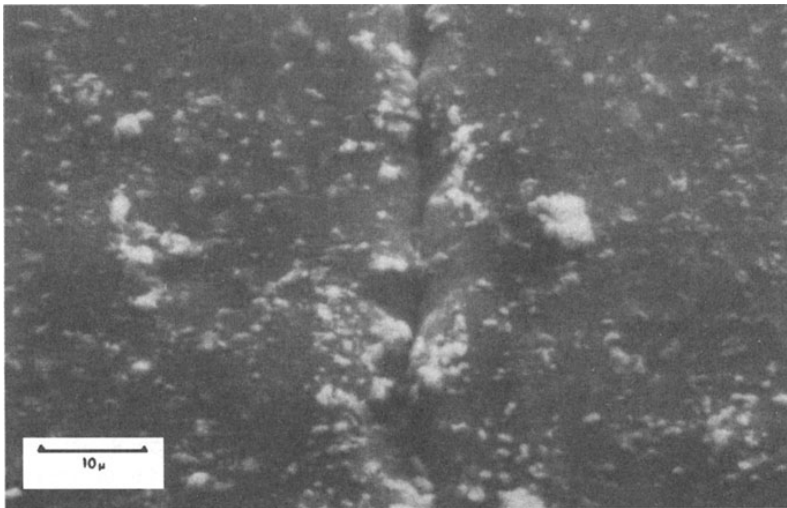


**Fig. 6-50** SEM showing weak FR SMA weld line molded above the recommended stock temperature. A large amount of particles can be seen on the product's surface and in the weld notch.

1. For complex polymer systems such as the ones studied here, impact strength at the weld line usually decreases when they are molded at a temperature near or above the recommended maximum temperature.

2. Material characteristics other than melt viscosity can have a great influence on weld line strength. Poor weld line impact strength seen during molding, especially at high temperature, is likely due to compositional changes at the weld line.

3. The rubber-modified SMA polymer is more apt to give good weld line strength when molded within its recommended temperature range than the PPO and FRABS polymer samples studied.

4. An increased injection rate above some limit is apt to reduce impact strength at the weld line for high-heat FR polymers.

5. The weld line strength of rubber-modified polymers is better characterized with impact testing than tensile testing.

6. The weld line notch depth varies greatly with mold temperature for a given polymer. A very deep notch will significantly reduce strength at the weld line.

7. In impact-modified polymers, rubber particles are apt to be compressed in the immediate region of the weld line so that they are elongated in the direction parallel to the weld line. This indicates that the weld line region is highly stressed.

can be helpful (Chap. 17, Process and Material Selections).

To arrive at the optimum material for a given use with some degree of efficiency and reliability, a systematic approach (obviously) has to be used that identifies and lists the product requirements. This is easier said than followed by some (possibly many). The requirements include factors such as aesthetics, tolerances, fabricating process to be used, surface finish, rough service conditions, sunlight, life cycle, and so on. Establishing these requirements can be complex, and if one is just starting to work with plastics the results can be incomplete. Examples of a method that can be used in material selection are provided in Tables 5-2 to 5-4.

The very limited plastics material properties information and data presented in this book are provided as comparative guides; readers can obtain the latest information from suppliers and/or software, recognizing that a specific plastic usually has many modifications to meet different properties and/or processing requirements. Also, new developments in plastic materials are always on the horizon. In addition to selecting the plastic material, one must also select the form the material is received (e.g., pellets, flakes, powder, or liquids). A number of different considerations must be taken into account. For instance certain equipment (particularly type of screw design) requires certain forms to operate efficiently at the lowest costs (1, 10, 18, 119).

## **Material Selections**

For many materials (plastics, metals, etc.) selection can be a highly complex process if not properly approached, particularly when using granulated or recycled plastics. Material selection methodology ranges from a high degree of subjective intuition in some areas to a high degree of sophistication in other areas. It runs the gamut from highly systematic value engineering or failure analysis in aerospace to a telephone call for advice from a material supplier in the decorative houseware business. Available are different publications, seminars, and software programs that

## *Colorants*

As already mentioned colorants are generally divided into dyes or pigments. The dyes are synthetic or natural compounds of submicroscopic or molecular size, soluble in most common solvents, yielding perfectly transparent colors. The pigments are organic or inorganic substances with larger particle sizes and usually insoluble in the common solvents. They are used to provide conditions such as coloring plastics for aesthetic qualities, color matching, UV stability, strength, electrical properties, resistance to migration

(bleeding), and/or other requirements. They may be naturally present in a material, admixed with it mechanically, or applied in solution.

A valid distinction between dyes and pigments is almost impossible to draw. Some have established it on the basis of solubility or on physical form and method of application. Dyes are fairly soluble in plastics whereas pigments, being insoluble, are dispersed throughout the mass. The choice depends on plastic compatibility or the need for solubility. Important is color stability, which means that the color is stable at processing temperature and on exposure to light, moisture, etc. when in use. Certain colorants, such as heavy metals (lead, cadmium, mercury, etc.), can present a problem in waste disposal. They can constitute a toxic residue following incineration if they are not properly handled and disposed. Safer alternatives are being used based on environmental requirements.

Various instruments are available for matching colors, with results about the same as those of visual inspection but more consistent. An example is the colorimeter, also called the color comparator or photoelectric color comparator. Basically the sample is illuminated by light from the three primary color filters and scanned by an electronic detecting system. A colorimeter is sometimes used in conjunction with a spectrophotometer, which is used for close control of color in production.

Color matching includes the use of the Kubelka-Munk theory, which provides a basis for computer-color-matching calculations. It is a phenomenological turbid-medium theory relating the reflectance and transmission of scattering and absorbing materials to constants and the concentrations of their colorants. Although it may be difficult to imagine doing professional color work without access to a spectrophotometer, it is also difficult to imagine letting any instrument be the final judge. Continued efforts to improve the hardware and software have greatly improved the usefulness of the spectrophotometers. Despite all these advances, such instruments have yet to replace people who have substantial color matching experience.

Color selection for a plastic product may be important for reasons other than aesthetics. For example, it is well known that the surface temperature of a product exposed to sunlight depends on its color. Developing color stability during processing is important. Generally the most significant single and controlling factor contributing to color shift is melt temperature. Other processing parameters or controlling factors having a lesser degree of significance on both the mean and variance are rate of melt flow and melt pressure.

### *Concentrates*

Concentrates are a mixture of a measured amount of additives (colorants, lubricants, antistats, antifogs, antioxidants, biocides, blowing agents, UV stabilizers, etc.) and a specific plastic, usually prepared in pellet form. Other forms include tablets, biscuits, and microporous carriers. This approach can provide a very accurate mixture for mixing with the base plastics during processing. Care should be taken to verify that the concentrate plastic is compatible with the base plastic being processed. Usually the amount of concentrate used is about 1 to 4 wt%.

The concentrate letdown ratio is the ratio of a plastic concentrate material, such as a color additive, to the basic plastic material. This ratio is usually identified as a percent by weight of both materials.

### *Barrier Plastics*

Barrier plastics are materials with low or no permeability to different environments or products. Barrier technology is not only becoming more complex but more precise. Various factors influence performance, including being pinhole-free; chemical composition, cross-linking, modification, molecular orientation, density, and thickness. The coinjection molding process is used to reduce permeability while retaining other desirable properties. Total protection against vapor transmission by a single-barrier material increases linearly with increasing thickness, but thick materials are not economical. Thus

extensive use is made of multiple layer constructions. These composites would include low cost as well as recycled plastics to provide mechanical support, etc.

With crystalline plastics, the crystallites can be considered impermeable. Thus, the higher the degree of crystallinity, the lower the permeability to gases and vapors. The permeability in an amorphous plastic below or not too far above its glass transition temperature ( $T_g$ ) is dependent on the degree of molecular orientation. It is normally lower than the permeability at higher temperatures, although small strains sometimes increase the permeability of certain plastics. The orientation of elastomers well above their  $T_g$  has relatively less effect on the overall transport property. Cross-linking thermoplastics will decrease permeability by decreasing their diffusion coefficient. The effect of cross-linking is more pronounced for large molecule size vapors. The addition of a plasticizer usually increases the rates of vapor diffusion and permeation.

Permeation of vapors occurs via two basic processes: sorption and diffusion. For example, in the packaging industry, moisture resistance is essential for the preservation of many products. The loss of moisture, flavor, etc. through packaging materials may damage foodstuff. The prevention of the ingress of moisture by a barrier is essential for the storage of dry foods and other products. In other applications, the degree of resistance to water and oxygen is important for the

development of corrosion resistance coatings, electrical and electronic parts, etc.

**ASTM 4000 Standard Guide for Plastic Classifications**

A classifying plastic materials standard that serves many of the industry needs has been issued by ASTM. This standard is designated as D 4000 and entitled "Standard Guide for Identification of Plastic Materials." It provides an easy means of identifying plastic materials used in the fabrication of parts.

Ever since classification systems were adopted many years ago for materials such as 1030 steel and elastomers, there had been an effort to issue this guide. The approach used follows the steel and elastomer unified classification systems of ASTM.

The guide provides tabulated properties for unfilled, filled, and reinforced plastic materials suitable for processing into parts. This standard is required to reduce the growing number of material specifications, paperwork, and man-hours used to ensure that parts of known quality are being produced from commercially available materials. The D 4000 standard will eliminate the many certifications required for the same material that a processor may have to obtain from several vendors for a customer or different customers.

Table 6-28 provides the basic outline that identifies the D 4000 line call-out.

**Table 6-28** ASTM D 4000 line call-out

| 0     | 1                  | 2                                  | 3             | 4               | 5     | 6                                                              | 7      |
|-------|--------------------|------------------------------------|---------------|-----------------|-------|----------------------------------------------------------------|--------|
| Group | Broad generic type | Specific<br> <br>Group class grade | Reinforcement | % Reinforcement | Table | Cell Requirements<br> <br>[ x x x x x ]<br>Physical properties | Suffix |

- 0 = One digit for expanded group, as needed.
- 1 = Two or more letters identify the generic family based on abbreviations D 1600.
- 2 = Three digits identify the specific chemical group, the modification or use class, and the grade by viscosity or level of modification. A basic property table will provide property values.
- 3 = One letter indicates reinforcement type.
- 4 = Two digits indicate percent of reinforcement.
- 5 = One letter refers to a cell table listing of physical specifications and test methods.
- 6 = Five digits refer to the specific physical parameters listed in the cell table.
- 7 = Suffix code indicates special requirements based on the application and identifies special tests.

The classification system and subsequent line call-out (specification) are intended to provide a means of identifying plastic materials used in the fabrication of end items or parts. It is not intended for the selection of materials. Material selection should be made by those having expertise in the plastics field after careful consideration of the design and performance required of the part, environment to which it will be exposed, fabrication process to be employed, inherent properties of the material not covered in this document, and economic factors.

This classification system is based on the premise that plastic materials can be arranged into broad generic families using basic properties to arrange the materials into groups, classes, and grades. A system is thus established that, together with values describing additional requirements, permits as complete a description as desired of the selected material. Note that Tables 6-29 to 6-32 provide only sections of the complete information contained in D 4000.

The format for this system (Table 6-28) was prepared to permit the addition of

**Table 6-29** Standard symbols for generic families with referenced standards and cell tables

| Standard Symbol | Plastic Family Name                      | ASTM Standard | Suggested Reference Cell Tables for Materials without an ASTM Standard |        |
|-----------------|------------------------------------------|---------------|------------------------------------------------------------------------|--------|
|                 |                                          |               | Unfilled                                                               | Filled |
| ABS             | Acrylonitrile/butadiene/styrene          | D_            |                                                                        |        |
| AMMA            | Acrylonitrile/methylmethacrylate         |               | E                                                                      |        |
| ASA             | Acrylonitrile/styrene/acrylate           |               | E                                                                      |        |
| CA              | Cellulose acetate                        | D 706         |                                                                        |        |
| CAB             | Cellulose acetate butyrate               | D 707         |                                                                        |        |
| CAP             | Cellulose acetate propionate             |               | E                                                                      | D      |
| CE              | Cellulose plastics, general              |               | E                                                                      | D      |
| CF              | Cresol formaldehyde                      |               | H                                                                      | H      |
| CMC             | Carboxymethyl cellulose                  |               | E                                                                      |        |
| CN              | Cellulose nitrate                        |               | E                                                                      | D      |
| CP              | Cellulose propionate                     | D 1562        |                                                                        |        |
| CPE             | Chlorinated polyethylene                 |               | F                                                                      |        |
| CS              | Casein                                   |               | H                                                                      | H      |
| CTA             | Cellulose triacetate                     |               | E                                                                      | D      |
| CTFE            | Polymonochlorotrifluoroethylene          |               |                                                                        |        |
| DAP             | Poly(diallyl phthalate)                  |               | H                                                                      | H      |
| EC              | Ethyl cellulose                          |               | E                                                                      | D      |
| EEA             | Ethylene/ethyl acrylate                  |               | F                                                                      |        |
| EMA             | Ethylene/methacrylic acid                |               | F                                                                      |        |
| EP              | Epoxy, epoxide                           |               | H                                                                      | H      |
| EPD             | Ethylene/propylene/diene                 |               |                                                                        |        |
| EPM             | Ethylene/propylene polymer               |               | F                                                                      | D      |
| ETFE            | Ethylene-tetrafluoroethylene copolymer   |               |                                                                        |        |
| EVA             | Ethylene/vinyl acetate                   |               | F                                                                      |        |
| FEP             | Perfluoro (ethylene-propylene) copolymer |               |                                                                        |        |
| FF              | Furan formaldehyde                       |               | H                                                                      | H      |
| IPS             | Impact styrene                           | (see PS)      |                                                                        |        |
| MF              | Melamine-formaldehyde                    |               | H                                                                      | H      |
| PA              | Polyamide (nylon)                        | D 4066        |                                                                        |        |
| PAI             | Polyamide-imide                          |               | G                                                                      | G      |
| PARA            | Polyaryl amide                           |               |                                                                        |        |

**Table 6-30** Reinforcement-filler symbols and tolerances

| Symbol | Material                                                                             | Tolerance                                               |
|--------|--------------------------------------------------------------------------------------|---------------------------------------------------------|
| C      | Carbon and graphite fiber-reinforced                                                 | ±2 percentage points                                    |
| G      | Glass-reinforced                                                                     | ±2 percentage points                                    |
| L      | Lubricants (i.e., TFE, graphite, silicone, and molybdenum disulfide)                 | by agreement between the supplier and user              |
| M      | Mineral-reinforced                                                                   | ±2 percentage points                                    |
| R      | Reinforced-combinations, mixtures of reinforcements or other fillers, reinforcements | ±3 percentage points (based on the total reinforcement) |

**Table 6-31** Suffix symbols and requirements

| Symbol | Characteristic                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A      | Color (unless otherwise shown by suffix, color is understood to be natural)<br>Second letter: A = does not have to match a standard;<br>B = must match standard<br>Three-digit number: 001 = color and standard number on drawing;<br>002 = color on drawing                                                                                                                                                                                                                                                                                                                                           |
| B      | Not assigned                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| C      | Melting point, softening point<br>Second letter: A = ASTM D 789 (Fisher-Johns);<br>B = ASTM D 1525 Rate A (Vicat);<br>C = ASTM D 1525 Rate B (Vicat);<br>D = ASTM D 3418 (transition temperature DSC/DTA);<br>E = ASTM D 2116 (Fisher-Johns high temperature)<br>Three-digit number = minimum value °C                                                                                                                                                                                                                                                                                                 |
| D      | Deformation under load<br>Second letter: A = ASTM D 621, Method A; B = ASTM D 621, Method B<br>First digit: 1 = total deformation; 2 = recovery<br>Second and third digit × factor of 0.1 (deformation) = % minimum 1 (recovery)                                                                                                                                                                                                                                                                                                                                                                       |
| E      | Electrical<br>Second letter: A = dielectric strength (short-time), ASTM D 149;<br>Three-digit number × factor of 0.1 = kV/mm, minimum<br>B = dielectric strength (step by step), ASTM D 149;<br>Three-digit number × factor of 0.1 = kV/mm, minimum<br>D = dielectric constant at 1 MHz, ASTM D 150, maximum;<br>Three-digit number × factor of 0.1 = value<br>E = dissipation factor at 1 MHz, ASTM D 150, maximum;<br>Three-digit number × factor of 0.0001 = value<br>F = arc resistance, ASTM D 495, minimum;<br>Three-digit number = value<br>[Other methods under review, ASTM D 257 and D 1531] |
| F      | Flammability (Note 1)<br>Second letter: A = ASTM D 635 (burning rate),<br>000 = to be specified by user,<br>B = ASTM D 2863 (oxygen index)<br>Three-digit number = value %, maximum                                                                                                                                                                                                                                                                                                                                                                                                                    |

**Table 6-32** Cell table G detail requirements<sup>a</sup>

| Designation<br>Order Number | Property                                                       | Cell Limits |     |       |       |        |        |        |        |        |               |
|-----------------------------|----------------------------------------------------------------|-------------|-----|-------|-------|--------|--------|--------|--------|--------|---------------|
|                             |                                                                | 0           | 1   | 2     | 3     | 4      | 5      | 6      | 7      | 8      | 9             |
| 1                           | Tensile strength, ASTM D 638,<br>MPa, minimum <sup>b</sup>     | Unspecified | 15  | 40    | 65    | 85     | 110    | 135    | 160    | 185    | Specify value |
| 2                           | Flexural modulus, ASTM D 790,<br>MPa, minimum <sup>b</sup>     | Unspecified | 600 | 3,500 | 6,500 | 10,000 | 13,000 | 16,000 | 19,000 | 22,000 | Specify value |
| 3                           | Izod impact, ASTM D 256,<br>J/m, minimum <sup>c</sup>          | Unspecified | 15  | 30    | 50    | 135    | 270    | 425    | 670    | 950    | Specify value |
| 4                           | Deflection temperature, ASTM<br>D 648 (1,820 kPa), °C, minimum | Unspecified | 130 | 160   | 200   | 230    | 260    | 300    | 330    | 360    | Specify value |
| 5                           | To be determined                                               | Unspecified | —   | —     | —     | —      | —      | —      | —      | —      | —             |

<sup>a</sup> Other cell tables are in D 4000.<sup>b</sup> MPa × 145 = psi.<sup>c</sup> J/m × 18.73 × 10<sup>-3</sup> = ft · lbf/in.

property values for future plastics. Plastic materials will be classified on the basis of their broad generic family. The generic family is identified by letter designations to be found in Table 6-29. These letters represent the standard abbreviations for plastics in accordance with abbreviations D 1600. For example, PA = polyamide (nylon).

The generic family is based on the broad chemical makeup of the base polymer. By its designation, certain inherent properties are specified. The generic family is classified into groups according, in general, to the chemical composition. These groups are further subdivided into classes and grades, as shown in the basic property table that applies. The letter designation applicable is followed by a three-digit number indicating group, class, and grade.

The basic property tables have been developed to differentiate the commercially available unreinforced plastics into groups, classes, and grades. These tables are found in the standards listed in Table 6-29. When a standard does not exist for this classification system, the letter designation for the generic family will be followed by three Os and the use of the cell table that applies. For example, P1000 would indicate a polyimide plastic (PI) from Table 6-29, with 000 indicating no basic property table and G12360 requirements from Cell Table G (Table 6-32).

To facilitate the incorporation of future materials or when the present families require expansion of a basic property table, a number preceding the symbol for the generic family is used to indicate that additional groups have been added to the table. This digit coupled with the first digit after the generic family will indicate the group to be found in the basic property table.

Reinforced versions of the basic material are identified by a single letter that indicates the reinforcement used and by two digits that indicate the quantity in percent by mass. Thus, the letter designation G for glass-reinforced and 33 for percent of reinforcement, G33, specifies a 33% glass-filled material. The reinforcement letter designations, with tolerance levels, are shown in Table 6-30.

To facilitate the identification of new, special, and reinforced materials for which basic

property tables are not provided in a material specification, cell tables have been incorporated in this document. These tables should be used in the same manner as the cell tables that appear on the material specifications. Although the values listed in the cell tables include the range of properties available on existing materials, users should not infer that every possible combination of properties exists or can be obtained.

The requirements for special or reinforced materials will use the classification system as described by the addition of a single letter that indicates the proper cell table in which the properties are listed. A specific value is designated by the cell number for each property in the order in which it is listed in the table. When a property is not to be specified, a zero is entered as the cell number.

### Thermal Properties and Processability

To select materials that will maintain acceptable mechanical characteristics and dimensional stability processors and designers must be aware of both the normal and extreme operating environments to which the product will be subjected. The properties of plastics are influenced by their thermal characteristics, such as those reviewed in Table 6-22. All these thermal properties factor into how to determine the best useful processing conditions to meet product performance requirements. There is a maximum temperature or, to be more precise, a maximum temperature-to-time relationship for all materials preceding loss of performance or decomposition.

#### Melt Temperatures

The melt temperature ( $T_m$ ) occurs at a relatively sharp point for crystalline plastics. Amorphous plastics do not have a distinct  $T_m$ ; they simply start melting as soon as the heat cycle begins. In reality there is no single melt point but rather a range that is often taken as the peak of a differential scanning calorimeter curve (Chap. 12, Characterizing Properties and Tests, Thermal Analysis Tests). The melt temperature is dependent

**Table 6-33** Examples of decomposition temperatures

| Material <sup>a</sup> | °F       | (°C)      |
|-----------------------|----------|-----------|
| PP                    | 610–750  | (321–399) |
| PC                    | 645–825  | (341–441) |
| PVC                   | 390–570  | (199–299) |
| PS                    | 570–750  | (299–399) |
| PMMA                  | 355–535  | (180–280) |
| ABS                   | 480–750  | (249–399) |
| PA                    | 570–750  | (299–399) |
| PET                   | 535–610  | (280–322) |
| Fluoropolymer         | 930–1020 | (499–549) |

<sup>a</sup> Note that adding certain fillers and reinforcements can raise decomposition temperatures.

on the processing pressure and the time subjected to heat, particularly during a slow temperature change for relatively thick melts. Also, if the  $T_m$  is too low, the melt's viscosity will be high and more power will be required to process it. If the viscosity is too high, degradation will occur (Table 6-33) (1, 478, 549).

### Glass Transition Temperatures

The glass transition temperature ( $T_g$ ), also called the glass–rubber transition temperature, is the reversible change in phase of a plastic from a viscous or rubbery state to a brittle glassy state.  $T_g$  is the point below which plastic behaves like glass, being very strong and rigid (Figs. 6-51 and 6-52). Above this temperature it is not as strong or rigid as glass, but neither is it brittle. At  $T_g$  the plastic's volume or length increases; above it, desirable properties degrade. The amorphous TPs have a more definite  $T_g$  when compared to their crystalline counterparts. It is usually reported as a single value. However, it occurs over a temperature range and is kinetic in nature. Examples of  $T_g$  range from  $-125^\circ\text{C}$  for PE to  $+105^\circ\text{C}$  for PMMA.

**Mechanical properties and  $T_g$**  As can be seen from Table 6-22, the value of  $T_g$  for a particular plastic is not necessarily a low temperature, which immediately helps explain some of the differences we observe in plastics. For example, because at room temperature polystyrene and acrylic are below their

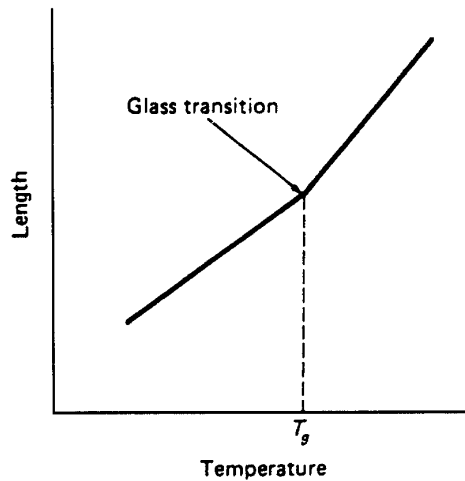


**Fig. 6-51** At the glass transition temperature ( $T_g$ ) various properties change including product length, volume, and elasticity.

respective  $T_g$  values, we observe these plastics to be in their glassy stage. In contrast, at room temperature natural rubber is above its  $T_g$  [ $T_g = -75^\circ\text{C}$  ( $-103^\circ\text{F}$ );  $T_m = 30^\circ\text{C}$  ( $86^\circ\text{F}$ )] with the result that it is very flexible. When cooled below its  $T_g$  natural rubber becomes hard and brittle.

### Dimensional Stabilities

Dimensional stability is an important thermal property for the majority of plastics. For most plastics the main determinant is the glass transition temperature. Only with highly crystalline plastics is  $T_g$  not the

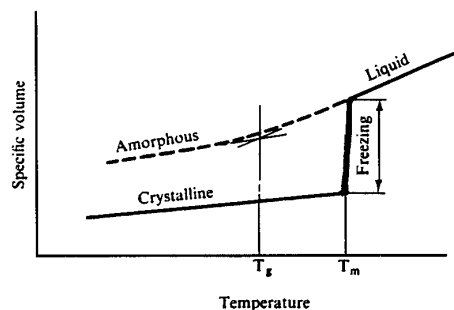


**Fig. 6-52** The specific volumes of amorphous and crystalline plastics versus temperature. Note the difference at  $T_g$  and  $T_m$  (melt temperature).

limitation. Substantially crystalline plastics in the range between  $T_g$  and  $T_m$  are referred to as leathery, because they are made up of a combination of rubbery noncrystalline regions and stiff crystalline areas. Thus plastics such as polystyrene and polypropylene maintain their usefulness at moderately elevated temperatures even though those temperatures lie above their respective  $T_g$ s.

#### *Thermal Conductivities and Thermal Insulation*

Thermal conductivity is an important factor since plastics are often used as an effective heat insulation in heat-generating applications and in structures requiring heat dissipation. The high degree of molecular order for crystalline TPs tends to make their values twice those of amorphous plastics. In general, thermal conductivity is low for plastics. To increase conductivity fillers such as metals, glass, or electrically insulating fillers such as alumina can be incorporated. Conductivity is decreased by using foamed plastics (Chap. 15).

#### *Heat Capacities*

The specific heat of amorphous plastics increases with temperature in an approximately linear fashion below and above  $T_g$ , but a significant shift or step occurs near the  $T_g$ . No such stepping occurs with crystalline types.

#### *Thermal Diffusivities*

Thermal diffusivity determines a plastic's rate of heat change with time. Although a function of thermal conductivity and specific heats at constant pressure and density, all of which vary with temperature, thermal diffusivity is relatively constant.

#### *Coefficients of Thermal Expansion*

Like metals, plastics generally expand when heated and contract when cooled. For a

given temperature change many TPs experience a greater change than metals. Expansion and contraction can be controlled in plastics by orientation, cross-linking, adding fillers or reinforcements, etc. With certain additives the values could be zero or near zero. For example, graphite powder contracts rather than expands during a temperature rise. The TS plastics are much more resistant to thermal changes. The degree of cross-linking has a direct effect, with some TSs exhibiting no change at all.

#### *Thermal Stresses*

If a plastic part is free to expand and contract, its thermal expansion/contraction property will usually be of little significance. However, if it is restricted or attached to another material having a different thermal characteristic, then its movement will be restricted and the potential to develop thermal stresses exists, which can cause product destruction.

#### **Shrinkages**

An important shrinkage characteristic is the usual relative change in dimensions from those measured on a molded part after it is first removed from a mold cavity to those of the molded part left to stabilize, usually after 24 h out of the mold. Material behavior and processing conditions influence shrinkage. Fillers and/or reinforcements in materials are used to reduce shrinkage. With thermoset plastics usually little or no shrinkage occurs. Many thermoplastics do shrink and require an understanding of their shrinkage behaviors; some exhibit very little shrinkage while others have shrinkage behaviors that are controllable or repeatable.

Excessive postmold shrinkage can occur after a part is removed from the mold. Non-uniform material shrinkage in a part can also occur, possibly owing to incomplete shrinkage before complete hardening is attained. A reduction in size of a material occurs during its hardening and/or curing solidification process with no external forces applied that can inhibit such reduction. If necessary shrinkage

block jigs made of metal, wood, plastic, etc. can be used. A shaped jig can aid in retaining part shape by applying light or no pressure while cooling to reduce warpage and distortion.

### Drying

Plastic materials, particularly thermoplastics (TPs), either in virgin forms (pellets, granules, powder, etc.) or regrind, are subject to contamination by moisture, which manifests itself in various ways. When moisture is present during molding, it tends to cause defects in the molded part. These include irregular moldings, splay marks, brittleness, lower physical and mechanical properties, nozzle drool between molding shots, foamy melt, bubbles in parts, poor shot control, and sink marks (1, 7, 578).

Thermoplastics that pick up moisture and those that are moisture sensitive will have to be dried before molding. The drying temperature used must permit the removal of moisture without causing the materials to adhere to each other, behavior that could cause bridging over the IMM throat where the screw receives the material. It is also useful to set the water valve (where available) which cools the IMM throat so that its temperature will not be too low, which could cause condensation on the plastic, or too high, which could cause bridging of the plastic at the throat entrance. Attention to the correct setting of the water valve can yield savings in both water and heat of plastication in the chamber. The preferred method of drying plastics is the dehumidification process, whereby the humidity is removed and dry air is supplied at the specific conditions required for each material.

Many past and present fabricating problems are usually directly related to the moisture content in the plastic materials being processed. This situation should not be a problem since well-established procedures and equipment are available to properly dry hygroscopic or nonhygroscopic plastics (Chap. 10, Drying).

Of the various TPs available, nylon, PC, PMMA, PUR, PET, and ABS are among

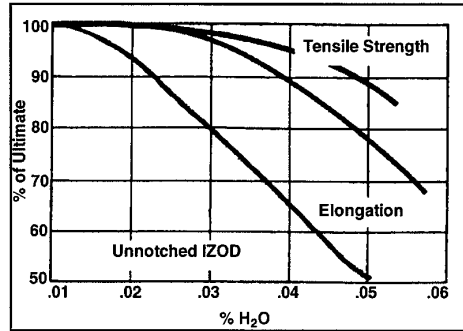


**Fig. 6-53** Example of the effects of moisture on the mechanical properties of a hygroscopic PET IM product.

those categorized as hygroscopic. These absorb moisture, which then has to be removed before the plastics can be converted into acceptable products. Low concentrations, as specified by the plastic's supplier, can be achieved through efficient drying systems and properly handling the dried resin prior to and during molding or extrusion.

Drying hygroscopic resins should not be undertaken casually. The simple tray dryers or mechanical convection hot-air dryers that may be adequate for nonhygroscopic resins are simply not capable of removing water to the degree necessary for the proper processing of hygroscopic resins or their compounds, particularly during periods of high humidity.

The effect of having excess moisture manifests itself in various ways, depending on the process being employed. The common result is a loss in both mechanical (Fig. 6-53) and physical properties, with splays, nozzle drool between shot-size control, sinks, and other losses that may occur during processing. The effects during extrusion can also include gels, trails of gas bubbles in the extrudate, arrowheads, wave forms, surging, lack of size control, and poor appearance.

### Material Handling

A very important area that must be considered is one's material handling capability. With proper feeding and/or blending of plastic materials, one can achieve superior process control of equipment, resulting in

quality molded products. Details on material handling are in Chap. 10 and information on quality control can be found in Chaps. 12 and 13.

### **Annealing**

Annealing—also called hardening, tempering, physical aging, and heat treatment—can be defined as a heat-treatment process directed at improving performance by removal of stresses or strains set up in the material during its fabrication. The plastic is first brought up to the required temperature for a definite time period, and then liquid (usually water; but also oils and waxes) and/or air is introduced to cool (quench) the material to room temperature at a controlled rate.

Annealing is done at a temperature close to but below the melting point. At the specified temperature the molecules have enough mobility to orient in a configuration that removes or reduces residual stress. The objective is to permit stress relaxation without distortion of shape and obtain maximum performance and/or dimensional control.

Annealing is generally restricted to thermoplastics, either amorphous or crystalline. Annealing results in increased density, thereby improving the plastic's heat resistance and dimensional stability when exposed to elevated temperatures. It frequently improves the impact strength and prevents crazing and cracking of excessively stressed products. The magnitude of these changes depends on the nature of the plastic, the annealing conditions, and the part's geometry.

The most desirable annealing temperatures for amorphous plastics, certain blends, and block copolymers lie above their glass transition temperature ( $T_g$ ) where the relaxation of stress and orientation can occur rapidly. However, the required temperatures may cause excessive distortion and warping. The plastic is heated to the highest temperature at which dimensional changes owing to strain are released. This temperature can be determined by placing the plastic part in an air oven or liquid water bath and gradually raising the temperature by intervals of 3 to 5°C until the maximum allowable change in

shape or dimension occurs. This distortion temperature is dictated by the thermomechanical processing history, geometry, thickness, and size. Usually the annealing temperature is set about 5°C lower using careful quality control procedures.

Rigid, amorphous plastics such as polystyrene (PS) and acrylic (PMMA) are frequently annealed for stress relief. Annealing crystalline plastics, in addition to the usual stress relief, may also bring about significant changes in the nature of their crystalline state, depending on the crystal structure, degree of crystallinity, size and number of spherulites, and orientation. In cases where proper temperature and pressure are maintained during processing, the induced internal stresses may be insignificant, and annealing is not required.

Plastic blends and block copolymers typically contain other low and intermediate molecular weight additives such as plasticizers, flame-retardants, and UV or thermal stabilizers. During annealing, phase and microphase separation may be enhanced and bleeding of the additives may be observed. The morphologies of blends and block copolymers can be affected by processing and quenching conditions. If their melt viscosities are not matched, compositional layering perpendicular to the direction of flow may occur. As in the case of crystalline plastics, the skin may be different, both in morphology and composition. Annealing may cause more significant changes in the skin than in the interior.

### **Recycling**

The scrap from many different plastics can be recycled or reprocessed into products called secondary plastics. Industrial scrap, pre-consumer, and post-consumer plastics can all be recycled. One of the many advantages of plastics versus other materials is the flexibility of recycling options. There are mechanical machines (granulators for different materials and products based on thickness, degree of hardness, etc.), energy recovery systems (energy thermal reclamation), chemical recycling systems, and others. Deciding

which method to use involves factors such as ecology, practicability, economics, applications, and basic common sense. Ironically, when laws were enacted that certain products had to include recycled plastics, the cost of many of these products went up.

Most processing plants during the past century have been granulating, reclaiming, and recycling reprocessible thermoplastic materials such as molding flash, rejected products, and so on. Thermoset plastics (not remeltable) have been granulated and used as filler materials. The ultimate goal is to significantly reduce or eliminate any trim, scrap, etc. because these have already cost money and time to go through a fabricating process; granulating just adds extra costs. Also, it usually requires resetting the process to handle the reprocessible material alone (or blending it with virgin plastics) because of the nonuniform particle sizes and differing shapes, melt flow characteristics, and properties of the material.

In a remarkable example of post-consumer plastic recycling, Goodyear had a two-piece suit and matching tie made from recycled 2-liter PET beverage bottles in 1978 and in 1980 (Fig. 6-54) it was donated to the (then) new "Ripley's Believe It or Not" Museum in Wisconsin Dells, WI. The recycled process used shredded plastics from bottles. The small flakes were processed to make the suit and tie.

Since scrap can be a mixture ranging from fine dust to large irregular chunks of different shapes, thicknesses, etc., it is important to use a granulator that provides the most uniformity and the least damage to the scrap. Overheating during the cutting action of the granulator causes the most damage; for heat-sensitive plastics, cryogenic granulating can be used. A granulator that handles soft plastics will not work well when granulating hard plastic; one that handles thin plastic is not the proper type to handle thick plastics; size and shape (bottles, solid handles, etc.) have an influence, and so on.

Keeping the scrap before and after granulating clean is a requirement. Recycling will reduce performance properties. The amount of reduction can range from very slight to undesirable amounts. Granulated plastics that

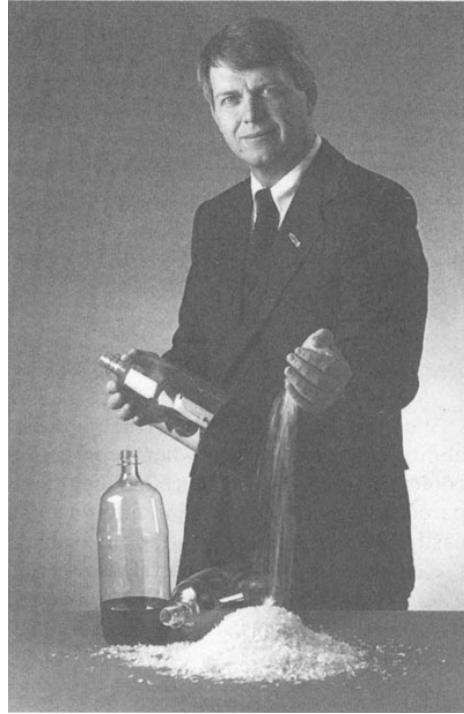


**Fig. 6-54** Recycled PET beverage bottles in 1978 made this suit and tie.

have been significantly degraded may or may not be reformulated by the addition of stabilizers, pigments, plasticizers, fillers, reinforcements, and other additives. Certain blends, particularly the general-purpose commodity plastics, can be blended with additives to improve their reduced processability and/or product performances. This type of action can improve granulated material that has suffered significant property degradation.

#### *Recycled Plastic Definitions*

Different organizations worldwide have developed definitions. The ASTM defines recycled plastics as those plastics composed of post-consumer material and recovered material only, or both, that may or may not have been subjected to additional processing steps of the types used to make products such as recycled regrind or processed or reconstituted plastics. Industry scrap, which includes what

is commonly referred to as trim or regrind in plastic production, is not considered recycled material.

#### *Recycled Plastic Identified*

Different organizations worldwide have developed identification systems. For example, the SAE has a system for Marking of Plastic Parts (SAE Document J-1344).

#### *Recycled Plastic Properties*

When plastics are granulated their processability and performance when reprocessed could be significantly reduced. When compared to virgin plastics a major difference can easily occur. Thus it is important to evaluate the characteristics of the recycled material. There are additives, etc. that can be added to improve performance. More details are provided in Reference 232.

#### *Recycling Size Reductions*

Size reduction exerts a substantial influence on quality of recycled plastics. Economical size reduction requires a machine that permits a preferably automatic solution to any problems. Depending on the material to be processed, use is made of one of the following size reducers: roll cutters/shredders, slicers, guillotine shears, and screw cutters. Recycled plastic is usually nonuniform in size so that processing with or without virgin (rather uniform in comparison) plastics is subject to operating in a larger molding process window (see Chap. 4, Materials to Products, Molding Process Windows).

#### *Recycling Mixed Plastics*

Different approaches are used to improve performances or properties of mixed plastics. These include: (1) the use of additives, fillers, and/or reinforcements (using specific types such as processing agent, talc, or short glass fibers), (2) forming active interlayers (cross-

linking, molecular wetting), and (3) dispersing and diffusing (fine grinding, enlarging molecular penetration via melt shearing).

#### *Integrated Recycling*

A number of systems are used for integrated recycling. For example, there is a dual plasticator system used that combines compounding steps for processing TPs. Recycled plastics are first melted in one preplasticizing unit. They are then fed into a self-cleaning melt-filtration system, which eliminates collecting impurities through a secondary discharge. A fine-mesh (50 micron) screen gives a high degree of purity. A pressure and time control device regulates automatic filter cleaning, while a degassing unit removes traces of solvents and liquids. A second plasticizing unit supplies virgin plastics and additives. The two melt streams are blended in a melt accumulator and can be located upstream of an extruder or injection molding machine.

#### *Recycling Methods and Economic Evaluations*

Various methods are used to recycle materials to provide plastics with a continuing life. The choice of method is influenced by factors such as quantity involved, weight involved, size and shape, costs, and continued availability of material. Methods include pyrolysis, repolymerization, etc. Recycled materials can also be used as a source of energy through incineration or chemical recycling and can be combined with production of electricity and/or hot water. The processes used include depolymerization to thermal liquefaction and gasification (back to feedstocks or intermediates), chemical pyrolysis, chemical depolymerization methods such as methanalysis and glycolysis, alcoholysis, catalytic cracking, gasification, hydrogenation, hydrolysis, and thermal steam cracking of plastics. Each technique has advantages and drawbacks. Some require careful plastic sorting of mixed materials and cleaning.