Designing With Plastic

The Fundamentals

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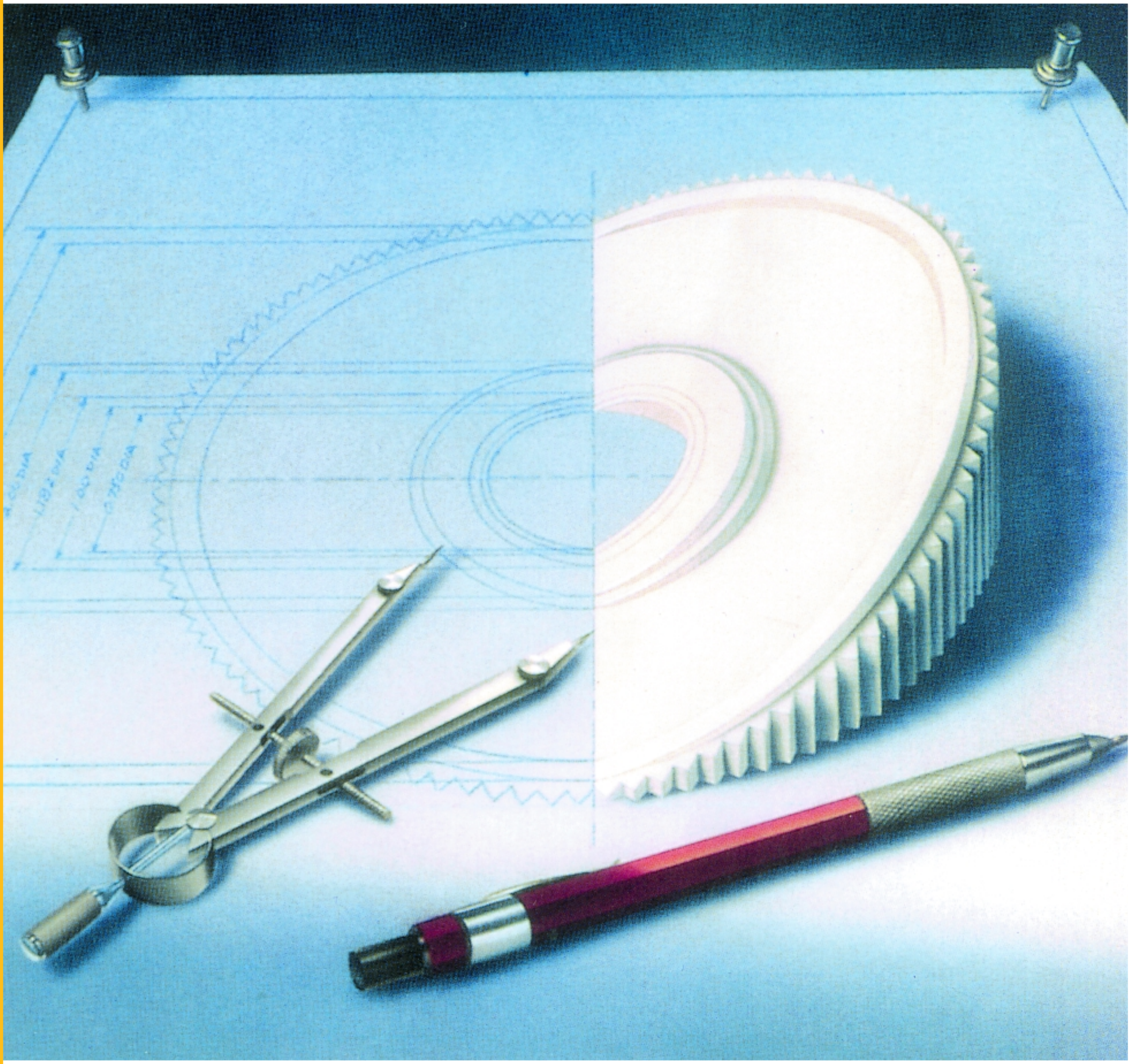
Designing With Plastic *The Fundamentals*



Ticona

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Introduction

This design manual was written to serve as a general purpose reference source for the experienced plastic product designer as well as the design engineer new to plastics. It should also be of interest to nondesigners and management personnel who need a general overview of the concepts and critical issues related to the world of plastics. Although the manual is not a guide to injection molding, many of the design considerations are based upon molding criteria, so those involved in the manufacturing and processing of plastic parts should also find it useful.

Most design manuals deal with a specific family of plastic resins, and present properties, design criteria, assembly, and other information related to these resins. The product line of Ticona includes crystalline, amorphous, liquid crystalline, and elastomeric polymers. Due to this diversity, this manual deals with issues common to all injection-moldable thermoplastic resins. Tables, figures, and other descriptive methods are used to help illustrate significant design differences.

The first part, Chapters 1 through 6, introduces the nature of plastic materials, their properties and testing methods. Key advantages, as well as limitations, of certain thermoplastics are discussed. Where appropriate, we compare the properties of various engineering thermoplastics, often including the properties of metals or other structural materials. However, our goal is to review fundamental concepts rather than list the various testing methods. Discussion of specific testing methods from the numerous governmental, industrial, and standards organizations involved with testing is beyond the scope of this manual.

The second part, Chapters 7 through 10, deals with the actual design of parts. It starts with structural analysis and injection molding considerations and concludes with assembly, finishing, and decorating techniques. This part of the manual will serve as both a general reference and a “how-to” guide for those new to plastic design.

For further information on design-related topics, the reader is urged to consult the following individual product brochures: Designing with Celcon® acetal copolymer (CE-10), Designing with Fortron® polyphenylene sulfide (FN-10) and Designing with Vectra® liquid crystal polymers (VC-10). These may be obtained by calling the Ticona Product Information Services Department at (800) 833-4882. Additional design information on Celcon® acetal copolymer, Celanese® nylon 6/6 and Celanex® thermoplastic polyester is also available.

1. Plastic Materials – An Overview

Plastics are synthetic materials called polymers, which are long-chain molecules made up of repeating units joined together. These units contain various combinations of oxygen, hydrogen, nitrogen, carbon, silicon, chlorine, fluorine, and sulfur. Although plastics are soft and moldable and approach a liquid condition during manufacture, they are solid in their finished state. As more repeating units are added, the plastic's molecular weight increases. Addition of more repeating units to the chain makes the molecule heavier. For example, Figure 1.01 shows the simple compound, methane (CH_4), a gas. As molecular weight increases, typical materials are pentane (a liquid), paraffin wax (a solid), and finally polyethylene (a widely used thermoplastic material). The mechanical and physical properties of plastics are directly related to the bonds between molecular chains, as well as to the chain length and composition. Plastic properties can also be modified both by alloying and blending with various substances and reinforcements.

1.1 Classification

The classification of plastics can be extensive and confusing, as illustrated in Figure 1.02. However, two major groups can be identified: **thermoplastics**, which are the main focus of this manual, and **thermosets**, which are discussed only in general terms here.
In addition to the broad categories of thermoplastics and thermosets, polymers can be classified in terms of their structure, i.e., **crystalline**, **amorphous**, and **liquid crystalline**. Other classes of plastics commonly referred to in the literature are **copolymers**, **alloys**, and **elastomers**. Finally, **additives**, **reinforcements**, and fillers play a major role in modifying properties. Each of these is discussed briefly.

Fig 1.01 · Example of Increasing Molecular Weight

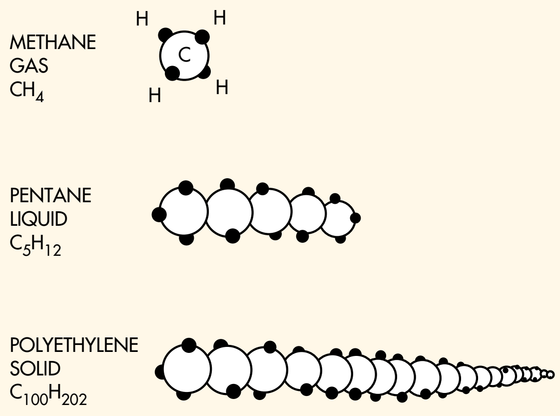
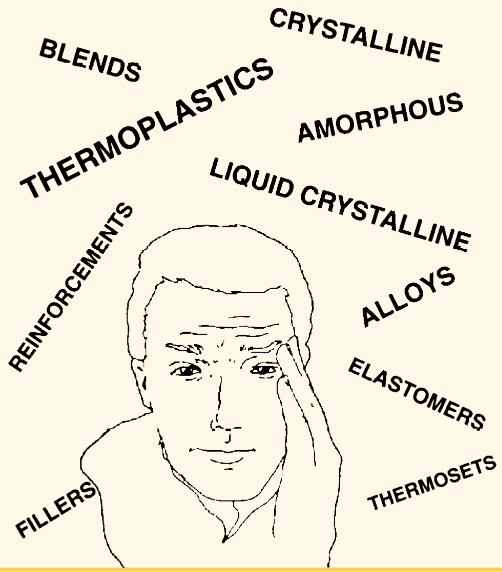


Fig 1.02 · Plastic classification



1.1.1 Thermoplastics

Thermoplastics are resins that repeatedly soften when heated and harden when cooled. Most thermoplastics are soluble in specific solvents and can burn to some degree. Softening temperatures vary with polymer type and grade. Because of thermoplastics' heat sensitivity, care must be taken to avoid degrading, decomposing, or igniting the material. Nylon, acrylic, acetal, polystyrene, polyvinyl chloride, polyethylene, and cellulose acetate are just a few examples of the many rigid thermoplastic resins currently available. Also within this group are highly elastic, flexible resins known as thermoplastic elastomers (TPEs) .

Most thermoplastic molecular chains can be thought of as independent, intertwined strings resembling spaghetti (Figure 1.03). When heated, the individual chains slip, causing plastic flow. When cooled, the chains of atoms and molecules are once again held firmly. When subsequently heated, the chains slip again. There are practical limitations to the number of heating/cooling cycles to which thermoplastics can be subjected before appearance and mechanical properties are affected.

1.1.2 Thermosets

Thermosets are plastics that undergo chemical change during processing to become permanently insoluble and infusible. Phenolic, amino, epoxy, and unsaturated polyester resins are typical thermoset plastics. Natural and synthetic rubbers such as latex, nitrile, millable polyurethane, silicone, butyl, and neoprene, which attain their properties through a process known as vulcanization, are also thermoset polymers.

The structure of thermoset plastics is also chainlike and, prior to molding, very similar to thermoplastics. However, cross-linking is the principal difference between thermoset and thermoplastic systems (Figure 1.04). When thermosets are cured or hardened, cross-links are formed between adjacent molecules, resulting in a complex, interconnected network. These cross bonds prevent the individual chains from slipping, thus preventing plastic flow when heat is added. If excessive heat is added to the thermoset resin after the cross-linking is complete, the polymer is degraded rather than melted. This behavior is somewhat similar to an egg when it is cooked; further heating does not return the egg to its liquid state, it only burns.

Fig 1.03 · Thermoplastic molecular chains

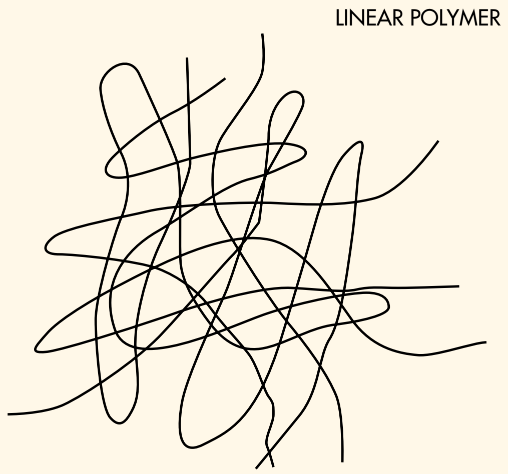
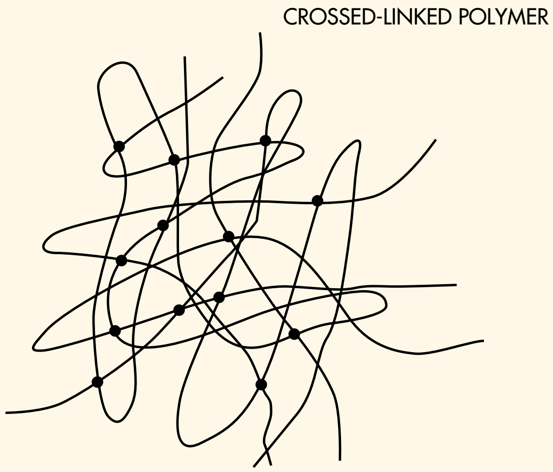


Fig 1.04 · Thermoset cross-linked molecules



1.1.3 Crystalline, Amorphous, and Liquid Crystalline Polymers

In some thermoplastics, the chemical structure allows the polymer chains to fold on themselves and pack together in an organized manner (see Figure 1.05). The resulting organized regions show the behavior characteristics of crystals. Plastics that have these regions are called crystalline. Plastics without these regions are called amorphous. All of the crystalline plastics have amorphous regions between and connecting the crystalline regions. For this reason, crystalline plastics are often called semicrystalline in the literature. Table 1.01 gives some common examples of crystalline and amorphous thermoplastics.

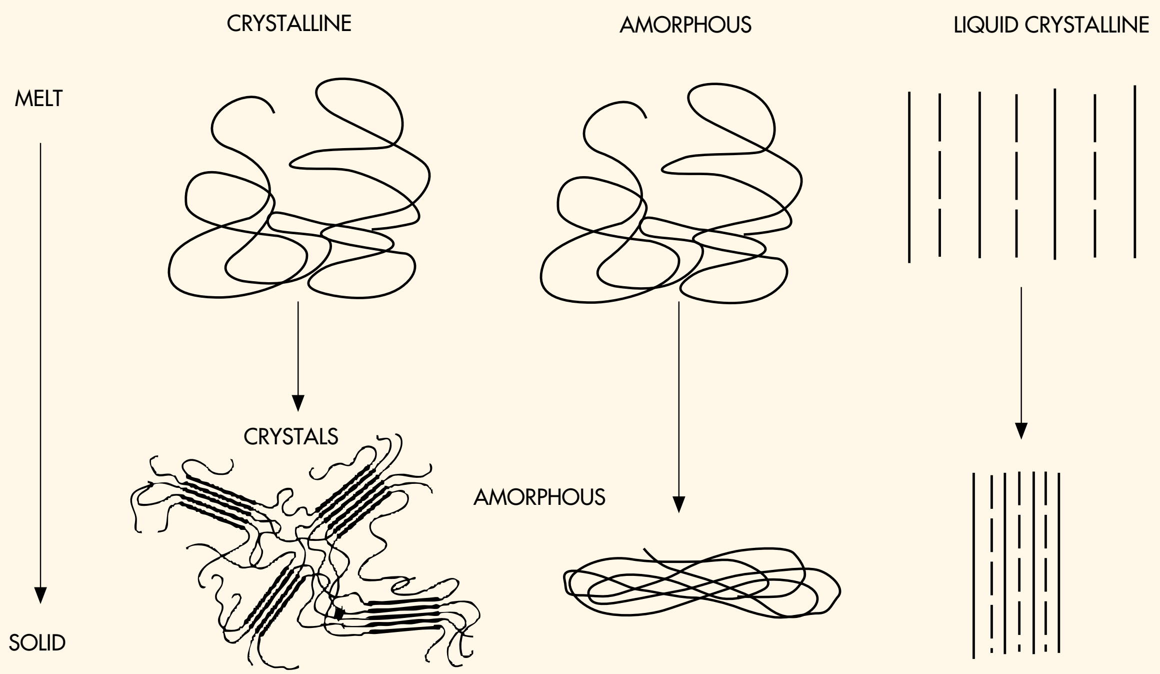
Liquid crystalline polymers are best thought of as being a separate and unique class of plastics. The molecules are stiff, rodlike structures that are organized in large parallel arrays or domains in both the melt and solid states. These large, ordered domains provide liquid crystalline polymers with unique characteristics compared to those of crystalline and amorphous polymers.

Many of the mechanical and physical property differences between plastics can be attributed to their structure. In general, the ordering of crystalline and liquid crystalline thermoplastics makes them stiffer, stronger, and less resistant to impact than their amorphous counterparts. Crystalline and liquid crystalline materials are also more resistant to creep, heat, and chemicals. However, crystalline materials require higher melt temperatures to process, and they tend to shrink and warp more than amorphous

Table 1.01 · Typical crystalline and amorphous polymers

Typical Crystalline Thermoplastic Resins	**Typical Amorphous Thermoplastic Resins**
Acetal Nylon Polyethylene Polypropylene Polyester (PET, PBT)	Polystyrene ABS SAN Polycarbonate PVC

Fig 1.05 · Two dimensional representation of crystalline, amorphous, and liquid crystalline structure



polymers. Amorphous polymers soften gradually and continuously as heat is applied, and in the molding process they do not flow as easily as molten crystalline polymers. Liquid crystalline polymers have the high melt temperature of crystalline plastics, but soften gradually and continuously like amorphous polymers. They have the lowest viscosity, warpage, and shrinkage of all thermoplastics. Table 1.02 generalizes the relative polymer properties.

1.1.4 Copolymers

A copolymer is a polymer made with two or more different kinds of repeating units. A terpolymer is a copolymer with three different kinds of repeating units. When a polymer family includes copolymers, as with acetal resins, the term homopolymer identities the polymer with a single type of repeating unit. Copolymers can have different properties from those of the homopolymers making up either repeating unit.

1.1.5 Alloys

Alloying is another way to create tailored variations in plastics. The exact definition of a plastic alloy is not clear, however it is generally accepted that alloys are combinations of polymers that are mechanically blended. They may depend on chemical bonds, but often have special compatibilizers to join different constituent polymers together to improve performance (e.g., impact strength and chemical resistance), to lower cost, or to improve processability.

Generally, the properties of plastic alloys fall between those of the starting polymers. However, some alloys are able to achieve a synergistic combination that is better than the properties of either component alone.

1.1.6 Elastomers

Thermoplastic elastomers are generally lower modulus, flexible materials that can be stretched repeatedly to at least twice their original length at room temperature and are able to return to their approximate original length when stress is released. Thermoset rubber materials have been available for a long time, but currently many families of injection-moldable thermoplastic elastomers (TPE's) are replacing traditional rubbers. In addition, TPE's are widely used to modify the properties of rigid thermoplastics, usually improving the impact strength.

1.1.7 Additives, Reinforcements, and Fillers

The physical and mechanical property profile of plastics can also be modified by adding a wide variety of fillers, fibers, and other chemical compounds. In general, mechanical properties are most significantly increased by adding reinforcing fibers. Particulate fillers usually increase modulus, and plasticizers usually decrease modulus and enhance flexibility. Flame retardants, thermal and UV stabilizers, and oxidation inhibitors are other common additives. Electrical properties may be affected by many additives, especially those that are conductive. When the mechanical properties are improved, the resin is called a reinforced resin. An example is glass-reinforced nylon. When the additive does not significantly improve the mechanical properties, but does affect the physical nature of the material, the resin is usually called a filled resin. An example is mineral-filled polyester. Table 1.03 lists a variety of common plastic fillers, reinforcements, and other additives.

Table 1.02 · General relative polymer properties

Property	Crystalline	Amorphous	Liquid 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
Max. Usage Temp.	Higher	Lower	High
Shrinkage and Warpage	Higher	Lower	Lowest
Flow	Higher	Lower	Highest
Chemical Resistance	Higher	Lower	Highest

Table 1.03 · Common plastic fillers, reinforcing fibers, and other additives

Fillers
Glass Spheres
Carbon Black
Metal Powders
Silica Sand
Wood Flour
Ceramic Powders
Mica Flakes
Molybdenum Disulfide

Reinforcing Fibers
Glass Fibers
Carbon Fibers
Aramid Fibers
Jute
Nylon Fibers
Polyester Fibers

Other Additives
UV Stabilizers
Plasticizers
Lubricants
Colorants
Flame Retardants
Antioxicants
Antistatics
Preservatives
Processing Aids
Fungicides
Smoke Supressants
Foaming Agents
Viscosity Modifiers
Impact Modifiers

2. Physical Properties and Terminology

The following is a discussion of some physical properties and fundamental concepts that apply to plastics. Most are familiar to readers who have worked with other engineering materials. A few, however, are specific to plastics.

2.1 Density

The density of any material is a measure of the mass per unit volume, usually expressed as pounds per cubic inch (lbs/in^3) or grams per cubic centimeter (g/cm^3) (see Figure 2.01). The density of a particular plastic resin is necessary to calculate the relationship between the weight and volume of material in a particular part.

2.2 Specific Gravity

The specific gravity is the ratio of the mass of a given volume of material compared to the mass of the same volume of water, both measured at 23°C. In other words, specific gravity is the density of a material divided by the density of water. Since it is a dimensionless quality, it is convenient for comparing different materials. Like density, specific gravity is used extensively in determining part cost, weight, and quality control.

2.3 Water Absorption

Water absorption is the percentage increase in weight of a material due to absorption of water. Standard test specimens are first dried for 24 hours and then weighed before and after immersion in 23°C water for various lengths of time. Water absorption is important since it affects mechanical and electrical properties, as well as part dimensions. Plastics with very low water absorption rates tend to have better dimensional stability.

2.4 Mold Shrinkage

Mold shrinkage is the ratio of the expected reduction of the plastic part dimension as the part solidifies in the mold and cools to room temperature to the original mold dimensions (Figure 2.02). The mold maker must know this value to properly size the mold to allow for shrinkage. For a given material, mold shrinkage can vary with a number of design and molding variables, such as wall thickness, flow direction, and molding conditions. This measure is important to the design engineer, not only for new designs, but also when considering substitute materials for a specific application. In general, amorphous and liquid crystalline thermoplastics have lower mold shrinkage than do crystalline thermoplastics. In addition, glass-reinforced or filled materials have lower shrinkage than unfilled or "neat" resins.

Fig 2.01 · a. Density and b. specific gravity

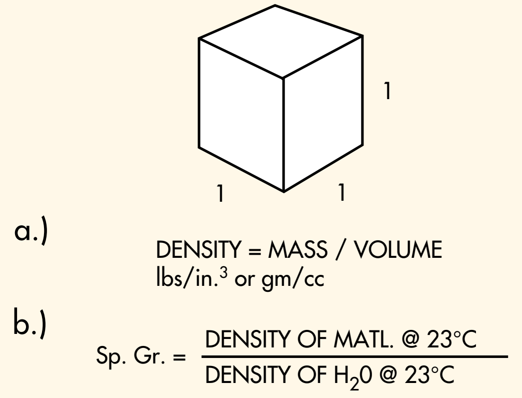
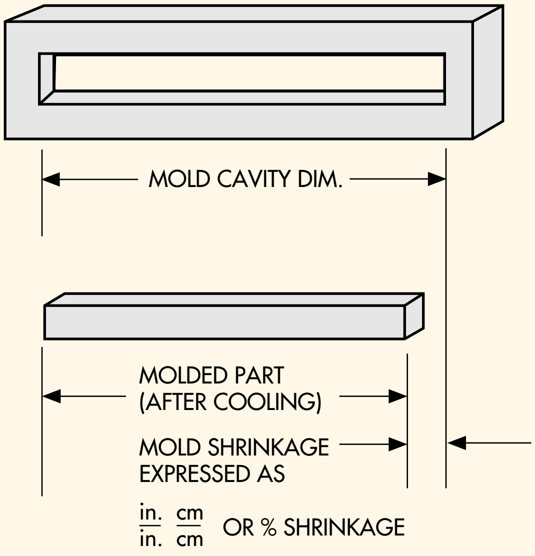


Fig 2.02 · Mold shrinkage



2.5 Opacity/Transparency

Opacity or transparency are important when light transmission is a consideration. These properties are usually measured as haze and luminous transmittance. Haze is measured as the percentage of transmitted light through a test specimen that is scattered more than 2.5° from the incident beam. Luminous transmittance is measured as the ratio of transmitted light to incident light.

2.6 Elasticity

Elasticity is the ability of a material to return to its original size and shape after being deformed (Figure 2.03). Most plastic materials have limited elasticity. Rubber and thermoplastic elastomers (TPEs) have excellent elasticity. Throughout this manual, it is generally assumed that plastics respond elastically unless otherwise indicated.

2.7 Plasticity

Plasticity is the inverse of elasticity. A material that tends to stay in the shape or size to which it is deformed has high plasticity. Plastic materials exhibit plasticity when they are stressed beyond the yield point. This accounts for the ability of some plastics to be cold-formed. Of course, when thermoplastics are heated to their softening point, they have almost perfect plasticity.

2.8 Ductility

Ductility is the ability of a material to be stretched, pulled, or rolled into shape without destroying the integrity of the material.

2.9 Toughness

Toughness refers to a material's ability to absorb mechanical energy without fracturing. A tough material can absorb mechanical energy with either elastic or plastic deformation. In general, high-impact unfilled resins have excellent toughness. However, low- or moderate-impact resins can also display considerable toughness if the material has sufficiently high ultimate strength. This will become apparent when the stress-strain curve is discussed in Chapter 3. Toughness is often measured by the area under the stress-strain curve of the resin, as shown in Figure 2.04.

Fig 2.03 · a) Material exhibiting elasticity
b) Material exhibiting plasticity

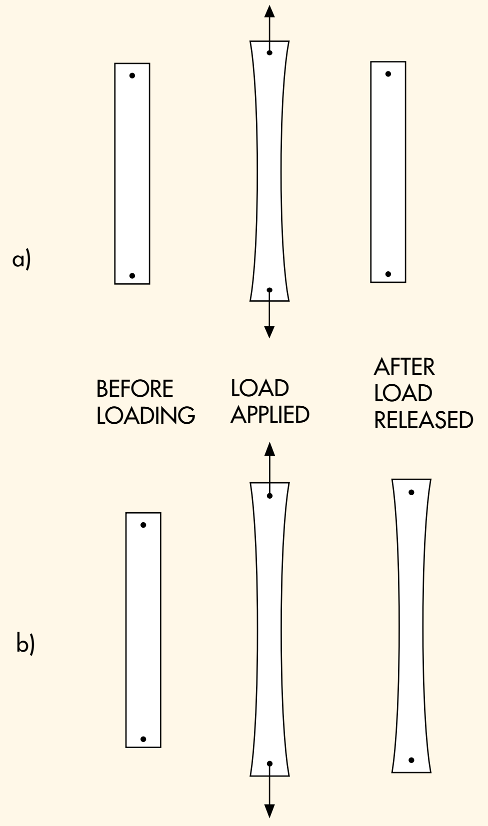
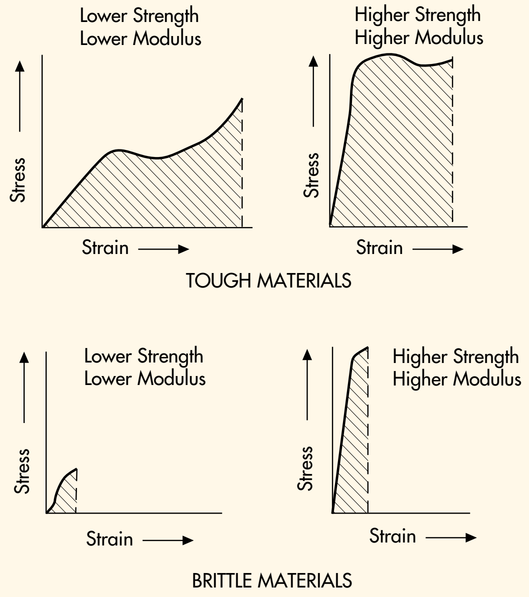


Fig 2.04 · Toughness can be measured by the area under the stress-strain curve



2.10 Brittleness

Brittleness is the lack of toughness. Plastic materials that are brittle frequently have lower impact and higher stiffness properties. Many glass-reinforced and mineral-filled materials display brittleness.

2.11 Notch Sensitivity

Not to be confused with brittleness, notch sensitivity is a measure of the ease with which a crack propagates through a material from a pre-existing notch, crack, or sharp corner.

2.12 Lubricity

Lubricity refers to the load-bearing characteristics of a material under relative motion. Plastics with good lubricity tend to have low coefficients of friction with other materials (or with themselves) and do not have a tendency to gall (wear away by friction).

2.13 Homogeneity

The term homogeneous means uniform. As one moves from point to point in a homogeneous material, the material's composition remains constant. Furthermore, the smallest sample of material cut from anywhere in a homogeneous body has the same physical properties as those of the whole body. An unfilled thermoplastic is a good example of a reasonably homogeneous material.

2.14 Heterogeneity

Heterogeneous means varying. The material's composition varies from point to point in a heterogeneous body. A glass-reinforced plastic is heterogeneous. However, for design purposes, many heterogeneous materials are treated as homogeneous. This is because a "reasonably" small sample of material cut from anywhere in the body has the same physical properties as those of the body.

2.15 Isotropy

The physical properties of an isotropic material at a point are the same, independent of the direction in which they are measured.

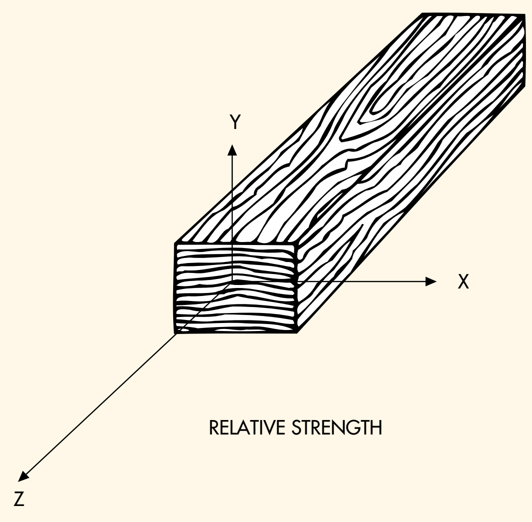
2.16 Anisotropy

The physical properties of an anisotropic material depend on the direction in which they are measured. The varying degrees of anisotropy depend on the amount of symmetry that exists in the material. A few examples should clarify.

Cast metals and plastics tend to be reasonably isotropic. Samples cut in any direction within the cast body tend to have the same physical properties. However, rolled metals tend to develop crystal orientation in the rolling direction. Thus, rolled and sheet metal products have different mechanical properties in the rolling and transverse directions. Likewise, extruded plastic film can have very different properties in the material and transverse directions. Thus, these materials are oriented biaxially and are anisotropic. Composite materials, in which fiber reinforcements are carefully oriented in the directions of applied load and surrounded by a plastic matrix, have a high degree of property orientation with direction at various points in the structure and are anisotropic.

Wood is an anisotropic material with distinct properties in three directions (Figure 2.05). It is very stiff and strong in the growth direction, and has fair properties in one direction perpendicular to the growth direction. However, the mechanical properties are much lower in the third direction (perpendicular to the other two directions), as observed by anyone who has seen a baseball bat shatter.

Fig 2.05 · Anistropy of wood



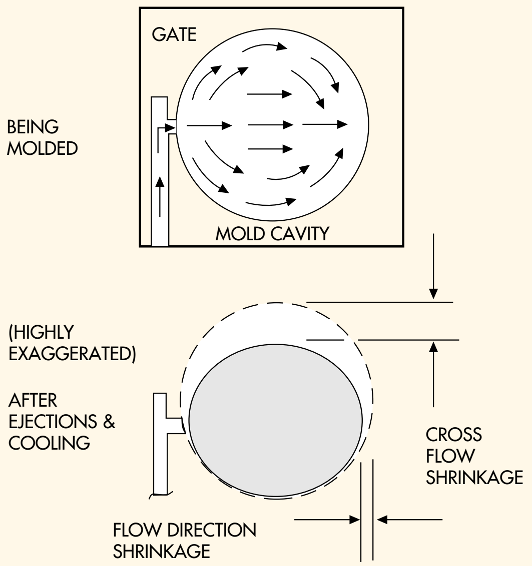
While the above examples demonstrate primarily mechanical properties, anisotropy is also involved when a material shrinks in the mold (Figure 2.06). Anisotropic mold shrinkage is an important consideration when crystalline and glass-fiber-reinforced materials are being molded. These materials are usually listed with mold shrinkage values in the "flow direction" and "cross-flow direction." Although these values are mainly of concern to the toolmaker and molder, the existence and severity of anisotropic shrinkage must be considered by the design engineer in choosing a resin for a new part with tight tolerances on the drawing.

2.17 Significance of Elasticity, Homogeneity, and Isotropy

In typical structural analyses performed while designing parts, an engineer generally uses two independent constants to describe the mechanical response of materials, Young's modulus and Poisson's ratio (defined in Chapter 3). However, only elastic, isotropic materials that respond linearly to load (i.e., load is proportional to deformation) can be analyzed by using these two constants. Furthermore, designers use the same values of these constants everywhere in the structure. This is only correct if the material is homogeneous. Thus, in typical structural analyses, engineers generally assume that the material is linearly elastic, homogeneous, and isotropic, which is reasonable for many analyses and is always a good starting point. However, it can lead to significant errors when one is designing in plastics, particularly glass-reinforced plastics and liquid crystalline polymers, which tend to be highly anisotropic.

In this manual, it is generally assumed that plastics may be treated as linearly elastic, homogeneous, and isotropic. This affords a simpler presentation of mechanical properties (Chapter 3), which is consistent with the data typically provided in the plastics marketplace. This assumption is also required by the standard equations of structural analysis, i.e., bending, torsion, pressure in a pipe, etc. (Chapter 7).

Fig 2.06 · Mold shrinkage of anisotropic plastics



The designer and engineer must be aware that as the degree of anisotropy increases, the number of constants or moduli required to describe the material increases (to a maximum of 21). Uncertainty of material properties, as well as questionable applicability of the simple analysis techniques that are generally used, provides justification for extensive end-use testing of plastic parts before certification in a particular application. However, please note that as finite element analysis (FEA) methods become more prevalent in plastic part design, the ability of FEA methods to handle anisotropic materials demands a better understanding of the anisotropic nature of plastic materials.

3. Mechanical Properties

Mechanical properties are crucial since virtually all end-use applications involve some degree of mechanical loading. Material selection for a variety of applications is often based on mechanical properties such as tensile strength, modulus, elongation, and impact strength. These values are normally available in the product data sheets provided by material suppliers. More often than not, too much emphasis is placed on comparing the published values of different types and grades of materials and not enough on determining the true meaning of mechanical properties and their relation to end-use requirements.

In practical applications, materials are seldom, if ever, subjected to a single, steady deformation without the presence of other adverse factors such as environment and temperature. Since published values of mechanical properties are generated from tests conducted in laboratories under standard conditions, the danger of selecting and specifying a material using only this information is obvious. A thorough understanding of mechanical properties and tests employed to determine such properties, as well as the effect of adverse (or beneficial) conditions on mechanical properties over long periods of time, is extremely important.

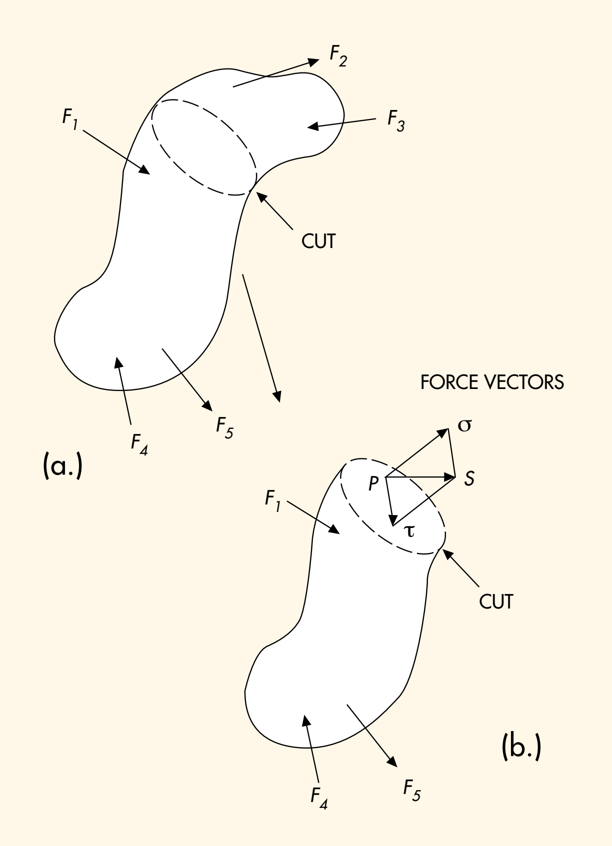
3.1 Basic Definitions

The following review of the fundamental concepts associated with the mechanical properties of materials should be familiar to anyone who normally deals with other material systems. Here we will discuss linear elasticity in more detail, completing our review of the simplified property assumptions used in this manual - that plastics, for design purposes, may be treated as linearly elastic, homogeneous, isotropic materials. In the next section, properties of plastics that represent a concession to their anisotropic and nonlinear nature is introduced. Finally, the last section deals with the time-dependent properties of plastics.

3.1.1 Stress

Consider a three-dimensional body with a balanced system of forces acting on it, F_1-F_5 in Figure 3.01a, such that the body is at rest. A body is subjected to external forces develops internal forces to transfer and distribute the external load. Imagine that the body in Fig. 3.01a is cut at an arbitrary cross-section and one part is removed. To keep the body at rest, a system of forces must be acting on the cut surface to balance the external forces. The same system of forces exists within the uncut body and is called stress. Stress must be described with both a magnitude and a direction. Consider an arbitrary point P on the cut surface in Figure 3.01b, where the stress, S, is as indicated. For analysis, it is more convenient to resolve the stress, S, into two stress components. One acts perpendicular to the surface and is called a normal or direct stress, σ. The second stress acts parallel to the surface and is called a shear stress, τ.

Fig 3.01 · Internal forces, stresses in a body



3.1.2 Normal Stress

A basic understanding of load, deflection, and stress starts with a simple tension test, shown in Figure 3.02. Direct Stress is the ratio of applied load to the original cross-sectional area, expressed in pounds per square inch (lb/in.^{2}), or psi. In the International System of units (SI), stress is expressed as Newtons per square meter, or Pascals (Pa).

Stress = load/area

$$\text{or} \quad \sigma = \frac{F}{A}$$

If the load is applied as shown, the member is said to be in tension. If the load is reversed, the member is in compression.

3.1.3 Normal Strain

If a bar is subjected to a direct load, and thus a stress, the bar changes in length. If the bar has an original length L and changes in length by an amount ΔL, the strain produced is defined as:

$$\text{strain} = \frac{\text{change in length}}{\text{original length}}$$

or

$$\varepsilon = \frac{\Delta L}{L}$$

Strain is a measure of the deformation of the material and is dimensionless; i.e., it has no units. It is simply a ratio of two quantities with the same units.

In general, the extensions of materials under load are very small. With most metals, it is convenient to measure and express strain in the form of microinches per inch, or 10^{-6} inches per inch (10^{-6} cm/cm). The symbol $\mu\varepsilon$, called microstrain, expresses this. With plastics, which generally undergo greater deformation than metals under the same loading, strain is normally expressed as 10^{-5} inches per inch. Another common way to express strain is as percent strain. The equivalence of the three is as follows:

$1000\mu\varepsilon = 1000 \text{ X } 10^{-6} = 0.001 = 0.1\%$ strain
$10000\mu\varepsilon = 10000 \text{ x } 10^{-6} = 0.01 = 1.0\%$ strain

Figure 3.03 illustrates a typical tensile testing arrangement with a common test specimen. The results obtained from this testing may be plotted in the form shown in Figure 3.04. This is a stress-strain curve, which characterizes the mechanical behavior of a material in tension.

Fig 3.02 · Simple tension load

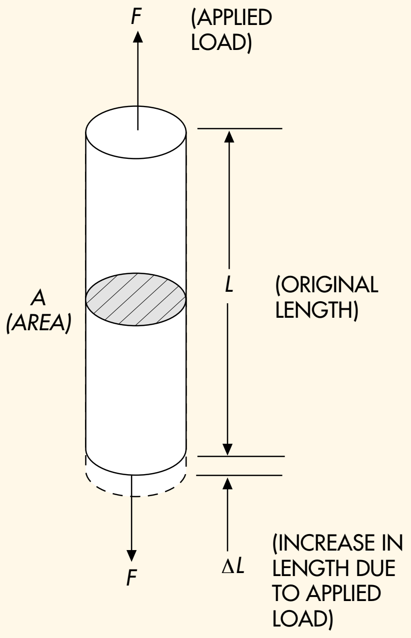


Fig 3.03 · Typical test setup and specimen

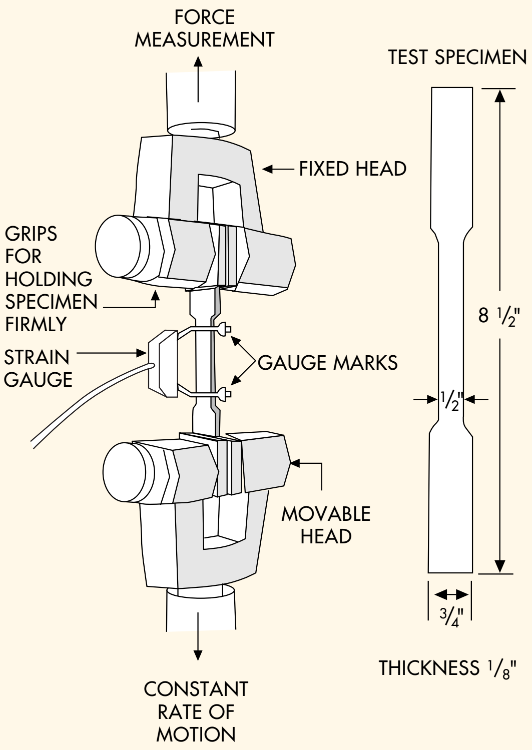
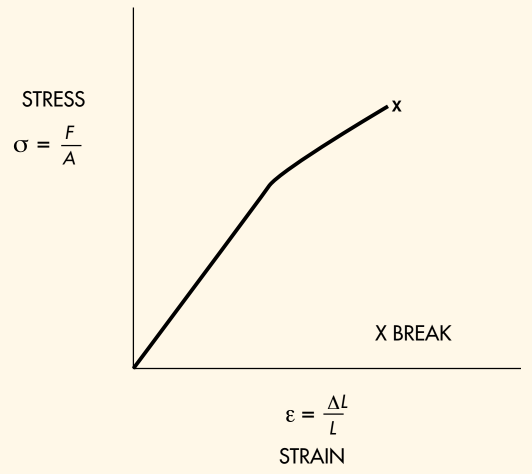


Fig 3.04 · Plot of results of tensile test (stress-strain curve)



3.1.4 Modulus of Elasticity

Most materials, including metals and plastics, have a deformation that is proportional to the imposed loads over at least a range of loads. Since stress is proportional to load and strain is proportional to deformation, this also implies that stress is proportional to strain. Hooke's law is the statement of that proportionality.

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

The constant E is called the modulus of elasticity, Young's modulus, or in the plastics industry, tensile modulus. In terms of the bar in Figure 3.02, the tensile modulus is given by

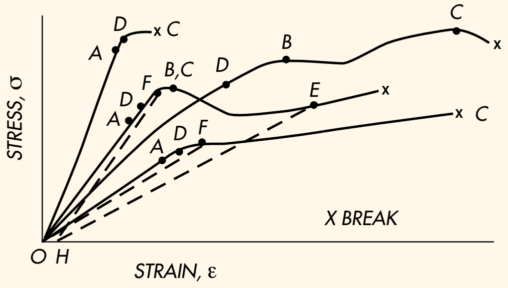
$$E = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L}$$

The modulus is, therefore, the slope of the initial portion of the stress-strain curve. It must be noted that an elastic material does not necessarily obey Hooke's law. A material may return to its original shape without the stress being proportional to the strain. However, if a material obeys Hooke's law, it is elastic. In many plastic materials, the straight region of the stress-strain curve is so difficult to locate that a straight line tangent to the initial portion of the curve must be constructed to obtain a "modulus." A modulus obtained in this manner is called the initial modulus. For some plastic materials, the initial modulus can be misleading due to the material's nonlinear elasticity. For this reason, some suppliers provide the 1% secant modulus (see below) as a better representation of the material's behavior. The designer is cautioned that the product data sheets do not always clarify whether the supplier is providing Young's modulus, an initial modulus, or a secant modulus. Thus, the designer is reminded of the warning at the beginning of this chapter on placing too much emphasis on the published data.

For metals, Young's modulus is normally expressed in terms of 10^6 psi, or Mpsi (MPa or GPa). For plastics, the tensile modulus is often expressed as 10^3 psi or kpsi (MPa).

A number of stress-strain curves are shown in Figure 3.05. The explanation of points *A* through *F* on the curves is provided below.

Fig 3.05 · Typical stress-strain curves



3.1.4.1 Proportional Limit, A

With most materials, some point exists on the stress-strain curve where the slope begins to change and the linearity ends. The proportional limit is the greatest stress at which a material is capable of sustaining the applied load without deviating from the proportionality of stress to strain. This limit is expressed in psi (Pa) and is shown as Point *A* in Figure 3.05. Note that some materials maintain this proportionality for large measures of stress and strain while others show little or no proportionality, as previously discussed.

3.1.4.2 Yield Point, B

Yield point is the first point on the engineering stress-strain curve where an increase in strain occurs without an increase in stress. This is shown as Point *B* in Figure 3.05. The slope of the curve is zero at this point. Note that some materials may not have a yield point.

3.1.4.3 Ultimate Strength, C

The ultimate strength is the maximum stress a material withstands when subjected to an applied load. This is expressed in psi (Pa) and is denoted by Point *C* in Figure 3.05.

3.1.4.4 Elastic Limit, D

Many materials may be loaded beyond their proportional limit and still return to zero strain when the load is removed. Other materials, particularly some plastics, have no proportional limit in that no region exists where the stress is proportional to strain (the material obeys Hooke's law). However, these materials may also sustain significant loads and still return to zero strain when the load is removed. In either case, the point on the stress-strain curve, D in Figure 3.05, represents the point beyond which the material is permanently deformed if the load is removed. This point is called the elastic limit.

3.1.4.5 Secant Modulus, E

The secant modulus is the ratio of stress to corresponding strain at any point on the stress-strain curve. For instance, in Figure 3.05, the secant modulus at Point *E* is the slope of the line *OE*.

3.1.4.6 Yield Strength, F

Some materials do not exhibit a yield point. For such materials, it is desirable to establish a yield strength by picking a stress level beyond the elastic limit. Although developed for materials that do not exhibit a yield point, this value is often used for plastics that have a very high strain at the yield point to provide a more realistic yield strength. This is shown as Point *F* on the curves on Figure 3.05. The yield strength is generally established by constructing a line parallel to *OA* at a specified offset strain, Point *H*. The stress where the line intersects the stress-strain curve at point *F* is the yield strength at *H* offset. For instance, if Point *H* were at 2% strain, then Point *F* would be termed the "yield strength at a 2% strain offset."

3.1.5 Poisson's Ratio

Under the action of a tensile load, the bar shown in Figure 3.06 increases in length by an amount ΔL, giving a longitudinal strain in the bar of

$$\varepsilon = \frac{\Delta L}{L}$$

The bar also exhibits a reduction in dimensions laterally; i.e., its breadth and depth both decrease. The associated lateral strains are opposite in sign (contracting vs. stretching) to the longitudinal strain, and are given by

$$\varepsilon_{\text{lateral}} = \frac{-\Delta b}{b} = \frac{-\Delta d}{d}$$

Provided the material deformation is within the elastic range, the ratio of the lateral to longitudinal strains is always constant. This ratio is called Poisson's ratio, and is designated by the greek letter ν.

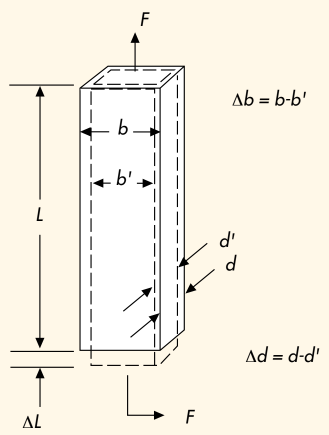
$$\nu = \frac{\text{lateral strain}}{\text{longitudinal strain}} = \frac{\Delta d/d}{\Delta L/L}$$

For most engineering materials, the values of ν lie between 0.20 and 0.40; however, a default value of 0.35 is usually sufficient. Typically, ν is between zero (no lateral contraction) and 0.5 (constant volume deformation). Table 3.01 shows typical values of ν for various structural materials. Poisson's ratio is a necessary constant for the stress and deflection analysis of plastic structures such as plates, shells, and rotating discs.

Table 3.01 · Typical values of Poisson's ratio

Material	Range of Poisson's Ratio
Aluminum	0.33
Carbon Steel	0.29
Rubber	0.50
Rigid Thermoplastics	
Neat	0.20 – 0.40
Filled or Reinforced	0.10 – 0.40
Structural Foam	0.30 – 0.40
Rigid Thermosets	
Neat	0.20 – 0.40
Filled or Reinforced	0.20 – 0.40

Fig 3.06 · Loaded tensile bar showing dimensional change in length and width



3.1.6 Shear Stress

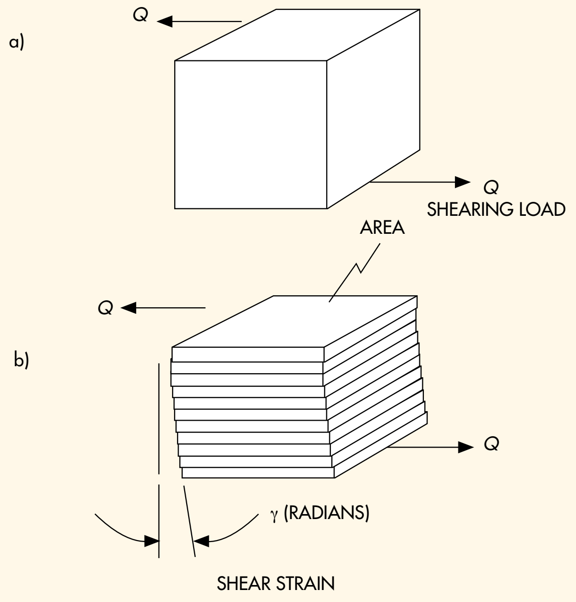
A block of material shown in Figure 3.07a is subjected to a set of equal and opposite shearing forces, *Q*. If the material is imagined as an infinite number of infinitesimally thin layers, as shown in Figure 3.07b, a tendency exists for one layer of the material to slide over another to produce a shear form of deformation, or failure if the force is great enough.

The shear stress, τ, is defined as

$$\tau = \frac{\text{shear load}}{\text{area resisting shear}} = \frac{Q}{A}$$

The shear stress is always tangential to the area on which it acts. The shearing strain is the angle of deformation, γ, and is measured in radians.

Fig 3.07 · Shear stress



3.1.7 Shear Modulus

For materials that behave according to Hooke's law, the shear strain is proportional to the shear stress producing it. Thus,

$$\frac{\text{shear stress}}{\text{shear strain}} = \frac{\tau}{\gamma} = \text{constant} = G$$

The constant *G* is called the shear modulus or modulus of rigidity, and is directly comparable to the modulus of elasticity used in direct stress applications.

3.2 Relating Material Constants

It was previously noted that only two material constants are required to characterize a material if one assumes the material is linearly elastic, homogeneous, and isotropic. However, three material constants have been introduced: tensile modulus, *E*, Poisson's ratio, ν; and shear modulus, *G*, Therefore, an equation relating these three constants is needed. On the basis of elasticity principles that are beyond the scope of this manual, the following equation may be developed:

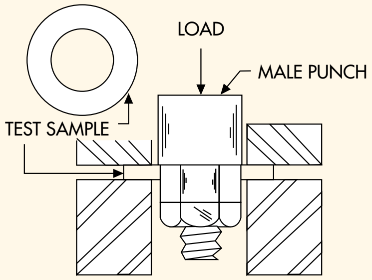
$$\frac{E}{G} = 2\,(1 + \nu)$$

This holds true for most metals and is generally applied to injection-moldable thermoplastics. However, the designer is reminded of the inherently nonlinear, anisotropic nature of most plastics, particularly fiber-reinforced and liquid crystalline materials.

3.2.1 Direct Shear

Figure 3.08 shows a typical shear strength setup used for plastics. Data obtained by this method is often reported in marketing data sheets as the shear strength of the material. In strength of materials literature, this type of test is called direct shear. The reader is cautioned to use the "shear strength" reported by this method only in similar direct shear situations. This is not a pure shear test. The test cannot be used to develop shear stress-strain curves or to determine the shear modulus because a considerable portion of the load is transferred by bending and/or compressing rather than by pure shear. In addition, the results can depend on the susceptibility of the material to the sharpness of the load faces. When plastics are analyzed in a pure shear situation or when the maximum shear stress is calculated in a complex stress environment, the use of a shear strength equal to half the tensile strength, or the above reported shear strength, is recommended, whichever is less.

Fig 3.08 · Direct shear stress test used in plastics industry



3.2.2 True Stress

Though infrequently used, the terms "true stress and strain" are worth noting. In Figure 3.09, the normal stress is calculated on the basis of an increasing load *F*, acting over a constant area, *A*. This form of the direct stress, discussed previously, is often called "engineering stress." With most materials, however, a "necking down" occurs in a critical area where failure will eventually result. If the smaller cross-section, A^1, were used in place of *A*, then the calculated stress would be referred to as "true stress." In addition, the direct strain discussed previously, i.e., total change in length over original length, is often called "engineering strain." The true strain would be the instantaneous deformation over the instantaneous length. Therefore, the shape of a true stress-strain curve would not be the same as a simple stress-strain curve. Almost universally, however, modulus values and stress-strain curves are based on engineering stress and strain.

3.3 Other Measures of Strength and Modulus

For many engineering materials that are treated as linearly elastic, homogeneous, and isotropic, the tensile and compression properties are considered identical. This eliminates the need to measure properties in compression. Further, if tension and compression properties are identical, there is no need to measure the properties in bending (under standard beam bending theory). However, in concession to the nonlinear, anisotropic nature of most plastics, these properties, particularly flexural properties, are often reported on product data sheets.

Fig 3.10 · Tensile and compressive moduli

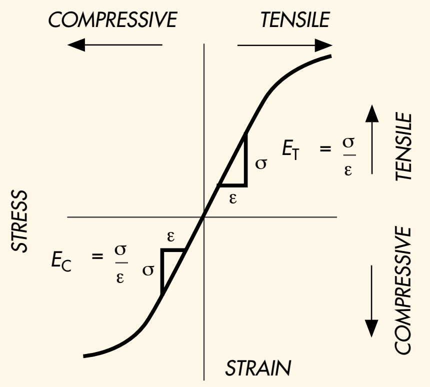
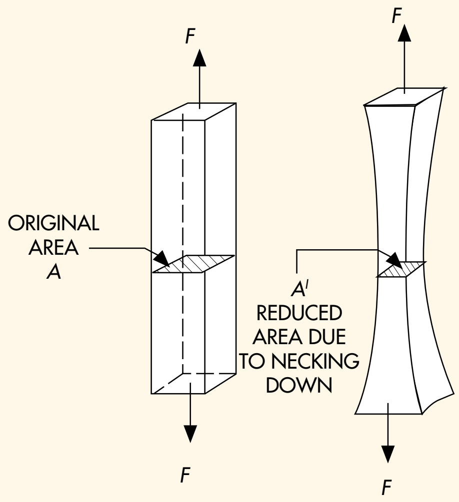


Fig 3.09 · True stress



3.3.1 Compression Strength and Modulus

Because of the relative simplicity of testing in tension, the elastic modulus of a material is usually measured and reported as a tension value. A material can also be loaded in compression. However for design, the stress-strain curve for compression loading is often required.

With most elastic materials at low stress levels, the tensile and compressive stress-strain curves are nearly equivalent, as depicted by the curve in Figure 3.10. However, at higher stress levels, the compressive strain is less than the tensile strain. Unlike tensile loading, which usually results in a clear failure, stressing in compression produces a slow, indefinite yielding, which seldom leads to a failure. Therefore, the compressive strength is customarily expressed as the stress in psi (Pa) required to deform a standard plastic specimen to a certain strain.

Compression modulus is not always reported, since defining a stress at a strain is equivalent to reporting a secant modulus. However, if a compression modulus is reported, it is generally an initial modulus.

3.3.2 Bending Strength and Modulus

If a piece of plastic or metal, most conveniently a rectangular cross-section, is bent between one's fingers, it is readily apparent that one surface of the material stretches in tension while the opposite surface compresses (Figure 3.11). It follows that there is a line or region of zero stress between the two surfaces, called the neutral axis. In simple beam bending theory, the following assumptions are made:

1. The beam is initially straight, unstressed, and symmetric.
2. The material of the beam is linearly elastic, homogeneous, and isotropic.
3. The proportional limit is not exceeded.
4. Young's modulus for the material is the same in tension and compression.
5. All deflections are small, so that planar cross-sections remain planar before and after bending.

Bending properties can be measured as shown in Figure 3.12. Using classical beam formulas and section properties (see Chapter 7), the following relationships can be derived:

Bending Stress $\sigma = \dfrac{3FL}{2bh^2}$

Bending or Flexural Modulus $E = \dfrac{FL^3}{4bh^3Y}$

where Y is the deflection at the load point.

With these relationships, the flexural strength and flexural modulus (of elasticity) can be determined in a testing laboratory. Again, the reported flexural modulus is usually the initial modulus from the load deflection curve. Since most plastic parts must be analyzed in bending, flexural values should lead to more accurate results than if the corresponding tensile values are used.

Fig 3.11 · Beam in bending

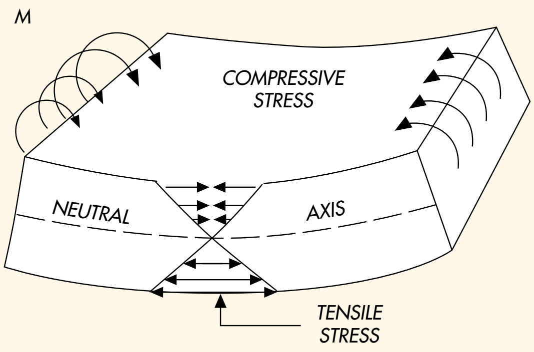
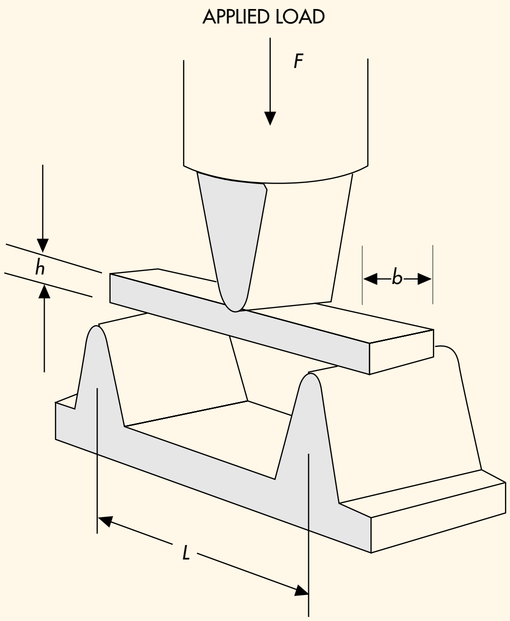


Fig 3.12 · A simple bending fixture



3.4 Rate Dependence of Mechanical Properties

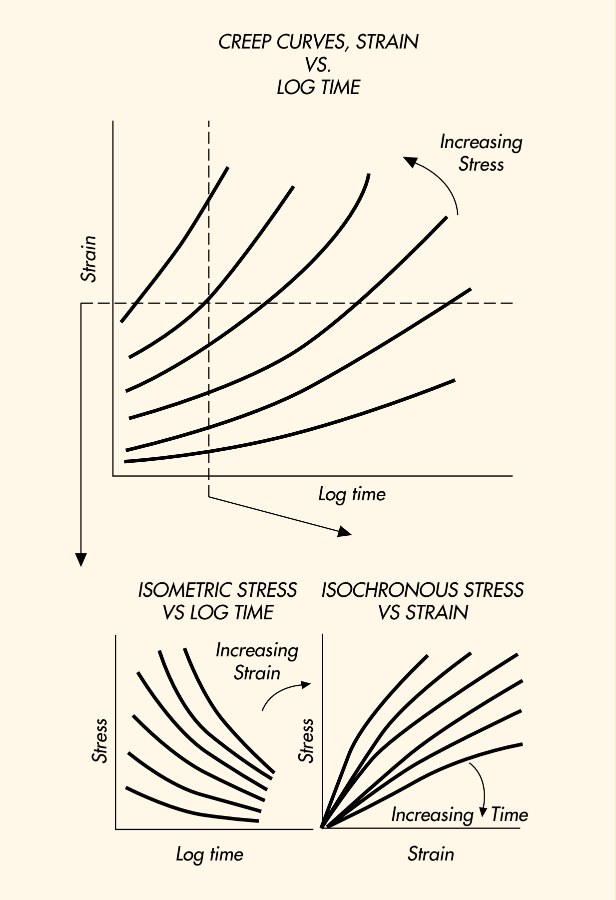
The tensile and flexural data reported in product data sheets are measured at a particular displacement rate. Unfortunately, this rate is rarely consistent with the end-use loading environment. The same plastic material, under differing rate and/or environmental conditions, can produce different stress-strain curves. The designer must be aware of the loading rate in a particular application and request the appropriate data. Often the data are not available. Therefore, the importance of end-use testing must be kept in mind.

3.5 Time-Related Mechanical Properties

In the previous discussion, the given mechanical properties involved a gradually applied, short-term load. In this section the effects of time-related loading, both long term and very short term, are considered. With high-performance thermoplastic materials, creep, impact, fatigue, and related issues are important considerations. Unfortunately, laboratory test data are not always directly applicable in estimating the structural response of actual parts. The laboratory method of applying the time-dependent load is rarely consistent with the end-use environment. Furthermore, in the actual end use, other factors are usually involved which are not covered by the laboratory test conditions.

This section reviews time-related loading phenomena with regard to meaning, testing methods, and the use of data in the design and analysis of plastic parts.

Fig 3.13 · Typical presentation of creep data



3.5.1 Creep

When a part or structure is subjected to a given load, there is a corresponding predictable deformation. If the deformation continues to increase without any increase in load or stress, the material is said to be experiencing cold flow or creep. Thus, creep can be defined as increasing strain over time in the presence of a constant stress. The rate of creep for any given material depends on applied stress, temperature, and time.

In parts that are to be subjected to loads for extended periods of time and where the maximum deflection is critical, the creep behavior of a material is very important. Test samples may be loaded in tension, compression, or flexure in a constant-temperature environment. With the load constant, the deflection or strain is noted at regular intervals of hours, days, weeks, and/or months. Generally, results are obtained at four or more stress levels. Stress-strain-time data are usually presented as creep curves of strain vs. log time. Sets of such creep curves, illustrated in Figure 3.13, can be produced by smoothing and interpolating on a computer. These same data may be presented in other ways to facilitate the selection of information for particular requirements. Sections may be taken through the creep curves at constant times, yielding isochronous stress-strain curves; or at constant strain, giving isometric stress vs. log time curves. These derivations are shown schematically in Figure 3.13.

In general, crystalline materials have lower creep rates than amorphous resins. Glass reinforcement generally improves the creep resistance of a plastic material.

3.5.2 Apparent or Creep Modulus

If the deflection of a part subject to continuous loading is calculated by using the modulus of elasticity, *E*, the result is likely to be inaccurate since the effects of creep have not been considered. However, if the stress level and temperature are known and the creep curves are available at the temperature, an apparent or creep modulus, E_{app}, can be calculated by using the creep curves as follows:

$$E_{app} = \frac{\sigma}{\varepsilon_c}$$

where

σ is the calculated stress level
ε_c is the strain from the creep curve at the expected time and temperature.

This value, E_{app}, can then be used instead of *E* to predict the maximum deflection, using the methods discussed in Chapter 7.

Curves of creep modulus or log creep modulus vs. log time at either constant stress or strain are often derived from the creep data and plotted as in Figure 3.14. Data may also be provided as tables at constant stress and temperature at various times. Many material suppliers provide creep data in the form of creep modulus rather than by the various curves of Figure 3.13.

3.5.3 Creep Rupture

Failure may occur in creep when a part exceeds allowable deformation or ruptures. In creep rupture failures, the fracture may be brittle or ductile with some degree of necking. Creep rupture data are obtained in the same manner as the creep data except that higher stresses are used and time is measured to failure. The strains are sometimes recorded, but are not necessary for creep rupture. The results are generally plotted as log stress vs. log time to failure (Figure 3.15).

Fig 3.14 · Creep modulus

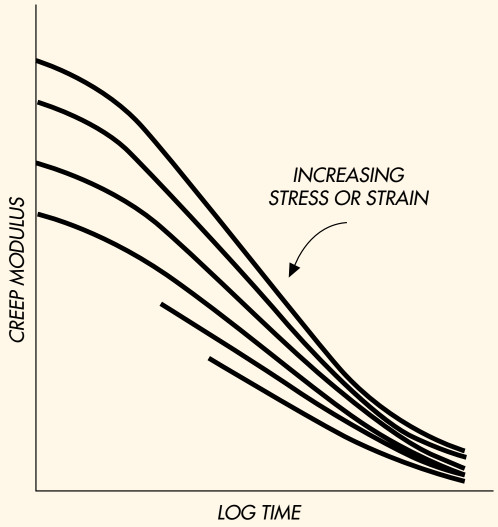
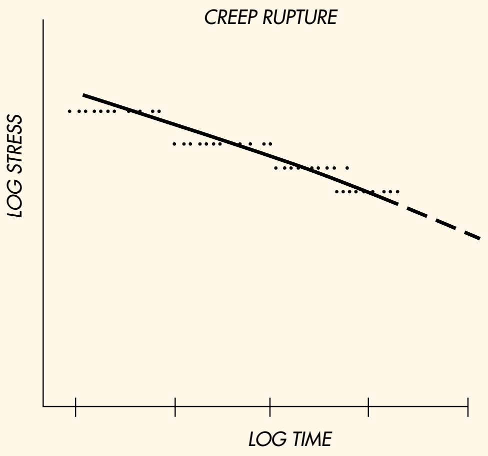


Fig 3.15 · Creep rupture data – a curve showing one cycle log time projection



3.5.4 Stress Relaxation

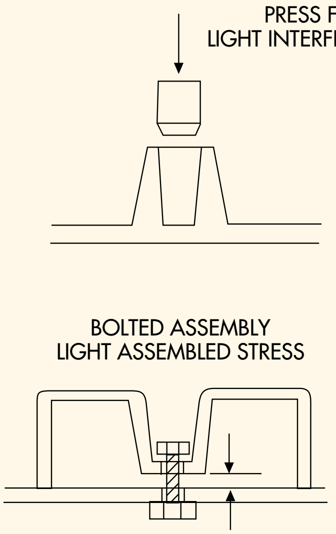
In many cases when plastic parts are assembled, they are placed into a permanently deflected condition. Examples are press-fits, bolted assemblies, and some plastic springs (see Figure 3.16). In time, with the strain constant, the stress level decreases due to the same internal molecular movement that produces the creep phenomenon. This gradual decay in stress at constant strain is known as stress relaxation. This becomes important in applications such as bolt preload and springs, where there is a concern for the retention of load. The relaxation can be measured by applying a fixed strain to a sample and measuring the load with time. The resulting data can then be presented as a series of curves very similar to the isometric stress curves in Figure 3.13. In addition; a relaxation modulus similar to the creep modulus, can be derived from the relaxation data. Generally, relaxation data are not as available as creep data. However, the decrease in load due to stress relaxation can be approximated by using the creep modulus, E_{app}, calculated from the creep curves, as in Figure 3.14.

Plastic parts often fail due to excessive fixed strains imposed on them for extended periods of time. An example would be the splitting of a plastic tube press fit over a steel shaft. Unfortunately, there is no “relaxation rupture” corollary to creep rupture. For purposes of initial design concept development, a strain limit of 20% of the strain at the yield point or yield strength is suggested for high-elongation plastics. Likewise, 20% of the elongation at break is suggested for low-elongation, brittle materials that do not have a yield point. However, this is only a guideline for initial design. Prototype parts should be thoroughly tested at end-use conditions to confirm the design. In addition, data that suggest a higher or lower limit may be available on the specific material of interest.

3.5.5 Extrapolating Creep and Relaxation Data

It is sometimes necessary to predict material behavior for times greater than those for which creep and relaxation data are available. This must be undertaken with caution. However, there is generally a less pronounced curvature when creep and relaxation data are plotted log property vs. log time. This facilitates extrapolation and is commonly practiced, particularly with creep modulus and creep rupture data. Even so, extrapolation should not exceed one logarithmic unit of time, as illustrated in Figure 3.15. In addition, the strain limit of 20% of the yield or ultimate strength mentioned in the above paragraph is suggested .

Fig 3.16 · Examples of constant strain loads



3.5.6 Impact Loading

Whenever a part is loaded rapidly, the part is subjected to impact loading. Any moving body has kinetic energy. When the motion is stopped due to a collision, energy must be dissipated. The ability of a plastic part to absorb energy is determined by its shape, size, thickness, and the type of material. Unfortunately, the impact testing methods presently available do not provide the designer with information that can be used analytically. However, the tests are useful for comparing the relative notch sensitivity of materials or the relative impact resistance. This can be very useful in choosing a series of materials to be evaluated in an application or in rank ordering materials within a series.

3.5.7 Izod Impact

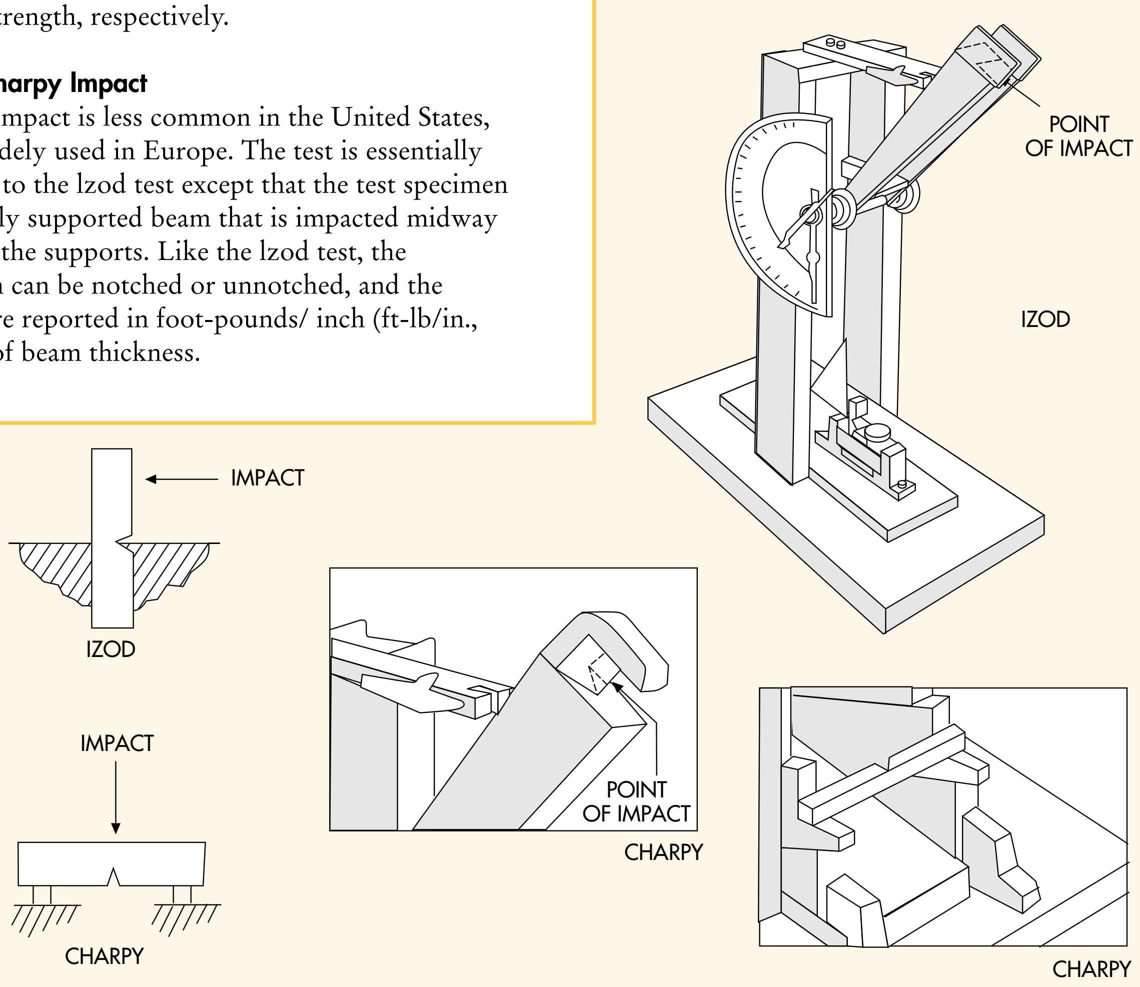
Probably one of the most widely used tests for impact strength is the notched Izod impact test. In this test a pendulum arm swung from certain height is made to impact a notched, cantilevered beam (see Figure 3.17). After fracturing the test specimen, the pendulum continues to travel in the same direction, but with less energy due to the impact with the specimen. This loss of energy, measured in foot-pounds per inch (ft-lb/in., or J/m) of beam thickness, is known as the Izod impact strength.

This test can also be run with an unnotched specimen or with the notch reversed, in which case it is reported as unnotched or a reversed notch Izod impact strength, respectively.

3.5.8 Charpy Impact

Charpy impact is less common in the United States, but is widely used in Europe. The test is essentially identical to the Izod test except that the test specimen is a simply supported beam that is impacted midway between the supports. Like the Izod test, the specimen can be notched or unnotched, and the results are reported in foot-pounds/ inch (ft-lb/in., or J/m) of beam thickness.

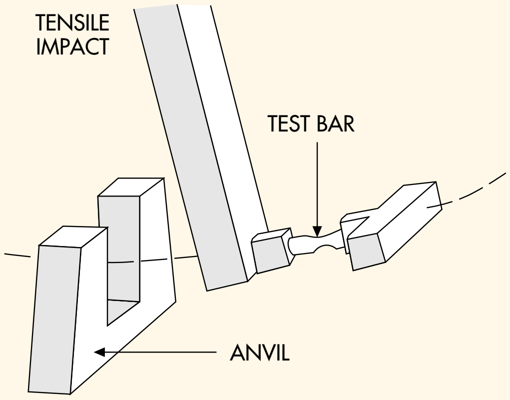
Fig 3.17 · Izod and Charpy impact tests



3.5.9 Tensile Impact

This test uses a swinging pendulum similar to that used in the Izod impact test, except the sample specimen is a tensile bar that is mounted (as shown in Figure 3.18) to measure energy required to fracture it due to tensile impact loading.

Fig 3.18 · Tensile impact



3.5.10 Falling Dart Impact Test

In this test, a weight is dropped onto a flat disk of the material being tested. The leading edge of the dart where it impacts the specimen has a specific diameter. Figure 3.19 is one example of a falling dart apparatus. This test is valuable for ranking materials since it tends to better represent the impact on actual parts in certain applications.

3.5.11 Fatigue Endurance

Generally, a material is subjected to fatigue when it is stressed repeatedly or in some defined cyclic manner. Examples are a snap-action plastic latch that is constantly opened and closed, a reciprocating mechanical part on a machine, a gear tooth, a bearing, any structural component subjected to vibration, and any part that is to be subjected to repeated impacts. Such cyclic loading can cause mechanical deterioration and progressive fracture of the material, leading to ultimate failure.

Typical fatigue tests are conducted on a machine which subjects a cantilever beam to reverse flexural loading cycles at different maximum stress levels. The number of cycles to failure is recorded for each stress level. The data are generally presented in a plot of log stress vs. log cycles, called an *S-N* curve. The cycle rate loading profile and environmental temperature should be reported with the curve. Figure 3.20 illustrates a typical *S-N* curve.

With thermoplastic materials there is the added complication of a heat buildup that can sometimes contribute to the actual failure. Figure 3.20 also illustrates the possible thermal failure that can occur in a fatigue test. Thermal failure is attributed to heat buildup resulting from the frequency of the cyclic stress. Significant differences in the *S-N* curve can also be produced by testing at different frequencies, different mean stresses, different waveforms, and different test methods, i.e., tension rather than bending.

Although fatigue test data give some indication of the relative ability of plastic materials to survive fatigue, the designer must be aware of the above variables. The tests are run on specially prepared samples in a test environment, which never resembles the actual loading and environment of the actual parts. Therefore, it is essential that tests be run on actual injection-molded parts under end-use operating conditions to determine the true fatigue endurance of any part on which significant cyclic loading occurs.

Fig 3.19 • A typical dart impact apparatus

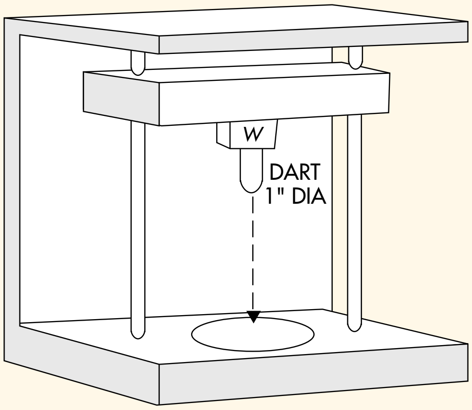
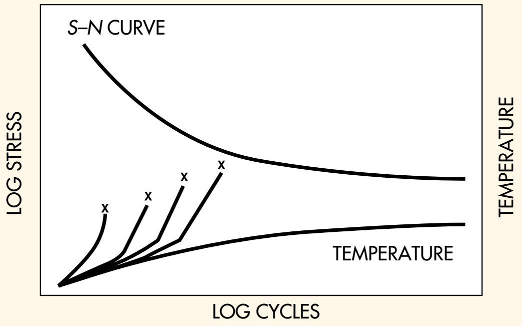


Fig 3.20 • Typical *S-N* curve is shown along with thermal effects which sometimes occur when plastics are fatigue tested



4. Thermal Properties

To select materials that will maintain acceptable mechanical properties and dimensional stability in end-use applications, the design engineer must be aware of the normal and extreme operating environment to which the final product is to be subjected. Following are some of the basic thermal properties that characterize thermoplastic materials.

4.1 Melting Point

Thermoplastic materials become more fluid when temperatures increase. While crystalline materials have sharp, clearly defined melting points, amorphous and liquid crystalline thermoplastics soften and become more fluid over a wider range of temperatures. There are many methods for determining melting points of plastics. However, this property is of greater significance to molding and assembly operations than to product design.

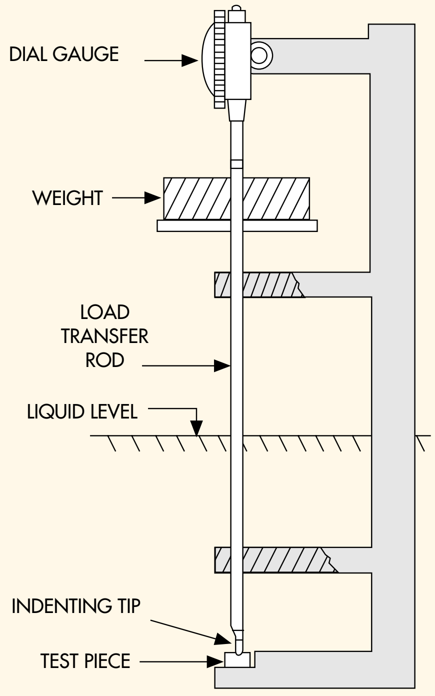
4.2 Glass Transition Temperature

At the glass transition temperature, T_g, a material undergoes a significant change in properties. Generally, below the glass transition temperature, the material has a stiff, glassy, brittle response to loads, while above the T_g, it has a more ductile, rubbery response.

4.3 Vicat Softening Point

This is the temperature at which a small, circular, heated, lightly loaded probe penetrates a specific distance into a thermoplastic test specimen. Figure 4.01 shows a typical test apparatus. This test is useful for crystalline materials, but is of somewhat limited value for amorphous thermoplastics, which tend to creep during the test. This test indicates the ability of a thermoplastic to withstand a short-term contact with a heated surface.

Fig 4.01 · Vicat softening point apparatus



4.4 Deflection Temperature under Load

The deflection temperature under load is the temperature at which a 1/2 in. deep test bar, loaded to a specified bending stress, deflects by 0.010 in. Figure 4.02 shows a schematic of a typical apparatus. This test is generally run at 66 psi and/or 264 psi. Sometimes called the “heat distortion temperature” (HDT), this value is useful to the design engineer as a relative measure of the ability of various materials to perform at elevated temperatures while supporting loads. Since a stress and deflection for a certain depth test bar is specified, this test may be viewed as establishing the temperature at which the flexural modulus decreases to particular values, i.e., 35,200 psi at 66 psi stress and 140,800 psi at 264 psi.

Table 4.01 · Typical values for coefficient of linear thermal expansion for thermoplastics and other common materials

Material	in./in./F10^{-5}	cm/cm/°C10^{-5}
Liquid Crystal (GR)	0.3	0.6
Glass	0.4	0.7
Steel	0.6	1.1
Concrete	0.8	1.4
Copper	0.9	1.6
Bronze	1.0	1.8
Brass	1.0	1.8
Aluminum	1.2	2.2
Polycarbonate (GR)	1.2	2.2
Nylon (GR)	1.3	2.3
TP Polyester (GR)	1.4	2.5
Magnesium	1.4	2.5
Zinc	1.7	3.1
ABS (GR)	1.7	3.1
Polypropylene (GR)	1.8	3.2
Epoxy (GR)	2.0	3.6
Polyphenylene Sulfide	2.0	3.6
Acetal (GR)	2.2	4.0
Epoxy	3.0	5.4
Polycarbonate	3.6	6.5
Acrylic	3.8	6.8
ABS	4.0	7.2
Nylon	4.5	8.1
Acetal	4.8	8.5
Polypropylene	4.8	8.6
TP Polyester	6.9	12.4
Polyethylene	7.2	13.0

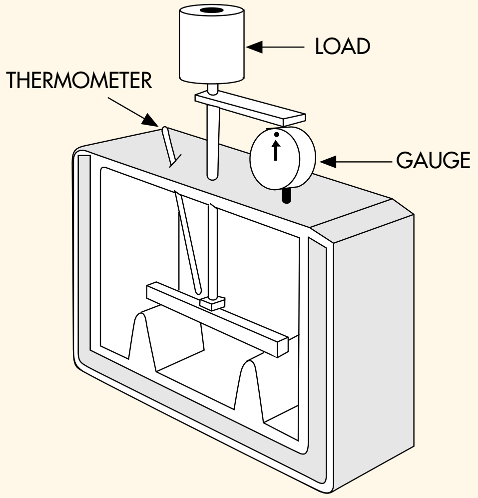
NOTES: Plastic materials are unfilled unless specified otherwise.

(GR) indicates typical glass-fiber-reinforced grade;
TP indicates thermoplastic.

These are only typical, average values and do not account for various grade differences, molding conditions, wall thickness, flow direction, etc.

Request information for the specific resin of interest.

Fig 4.02 · Test apparatus for deflection temperature under load



4.5 Coefficient of Linear Thermal Expansion

Like metals, thermoplastic materials expand when heated and contract when cooled. Generally, for a given change in temperature, plastic materials change dimensionally much more than metals. The coefficient of linear thermal expansion, CLTE, is the ratio of the change of a linear dimension to the original dimension of the material for a unit change of temperature. It is generally given in units of in./in./°F or cm/cm/°C. Table 4.01 presents typical values for many common materials. This is a very important consideration if dissimilar materials are to be assembled. It should be noted that many thermoplastics, especially those with glass reinforcement or liquid crystalline resins, may have different coefficients for the mold flow, cross-flow, and thickness directions. Since the CLTE of plastics can vary with temperature over a broad temperature range, the extent of the variability must be known. This is especially important if the temperature range includes a transition, such as T_g.

4.6 Thermal Conductivity

Thermal conductivity is the rate at which a material conducts heat energy along its length or through its thickness. This is an important factor, since plastics are often used as an effective heat insulator in heat-generating applications and in structures in which heat dissipation is important.

4.7 Aging at Elevated Temperatures

Typically, aging at elevated temperatures involves storing a large number of samples at a particular temperature for an extended time. Samples are then removed from storage at various time intervals and tested at standard conditions for whatever physical, mechanical, thermal, or electrical property is of interest. The data are generally presented as a plot of property vs. aging time for the various aging temperatures. Thus, the results from aging at elevated temperatures may be used as a measure of the thermal stability of the resins, and must be considered in design situations.

4.8 Relative Thermal Index (UL)

Underwriters Laboratories tests and recognizes plastic materials used in electrical applications for certain continuous operating temperatures. These ratings are listed separately for electrical properties, mechanical properties including impact, and mechanical properties without impact. The Relative Thermal Index is important if the final product must receive UL recognition.

4.9 Flammability

For many plastic applications, the consequences of exposure to an actual flame must be considered. This is important not only in electrical applications, but also in any application where the plastic constitutes a significant percentage of the exposed area of a defined enclosed space. An example of this is the plastic panels used in the interior of an aircraft cabin. Typical tests measure combustibility, smoke generation, and ignition temperatures. Some of the following tests are common:

1. UL 94 Flammability Class (V-0, V-1, V-2,5V, HB)

In this test, specimens are subjected to a specified flame exposure, and the relative ability to maintain combustion after the flame is removed becomes the basis for classification. In general, the more favorable ratings are given to materials that extinguish themselves rapidly and do not drip flaming particles. Each rating is based on a specific material thickness.

2. Oxygen index

This test measures the percentage of oxygen necessary to sustain combustion of the plastic material. Obviously, the higher the value (more oxygen needed), the lower the combustibility. Since air contains about 21 % oxygen, any material with a rating below 21 will probably support combustion in a normal, open air environment.

4.10 Effect of Temperature on Mechanical Properties

An important behavior characteristic of materials, which the designer must understand when working in plastics, is the inverse relationship between strain rate and temperature. Very high strain rates and very low temperatures produce similar material responses. Conversely, very low strain rate effects, i.e., creep effects, can be seen much more quickly by testing at elevated temperatures. The designer might make use of the concept by testing at temperatures around and above the highest values expected in end use. The data can be used to estimate long-term performance of a part at times much longer than can be reasonably used for testing. A number of theoretical and empirical models are used to describe this behavior of materials. They have been used successfully, provided they are not applied near or across the transition temperatures or near the melting point. However, these models are well beyond the scope of this manual.

4.10.1 Strength, Modulus, and Elongation

The strength, modulus, and elongation behavior are similar for tensile, compressive, flexural, and shear properties. In general, strength and modulus decrease and elongation increase with increasing temperature. Figure 4.03 illustrates a series of stress-strain curves that might be produced by testing a plastic material at one strain rate and several temperatures. The same set of curves might also be generated by testing at constant temperature and various strain rates, as indicated.

Fig 4.03 · Effect of temperature or strain rate on stress-strain curves

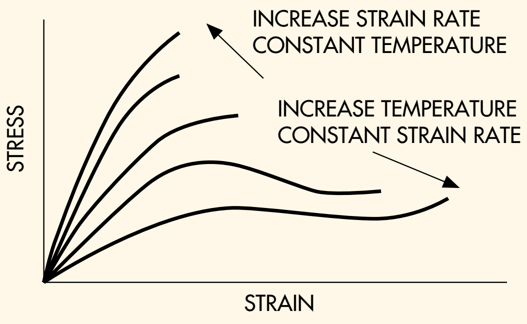


Figure 4.04 illustrates modulus behavior as temperature increases. In general, a gradual drop in modulus occurs as the temperature increases to the glass transition temperature. Above the glass transition temperature, amorphous materials experience a rapid loss of modulus. However, crystalline materials maintain a significant, usable modulus at temperatures approaching the crystalline melting point. Glass fiber reinforcement can significantly improve the modulus of crystalline materials above the glass transition temperature. Amorphous materials, even when reinforced with glass, still display a rapid drop in modulus above the glass transition temperature. Strength vs. temperature curves are similar to modulus curves. In general, the elongation of materials increases with increasing temperature, as indicated in Figure 4.05.

Fig 4.04 · Modulus behavior of crystalline and amorphous resin showing T_g and melt temperatures and the effect of reinforcement on HDT

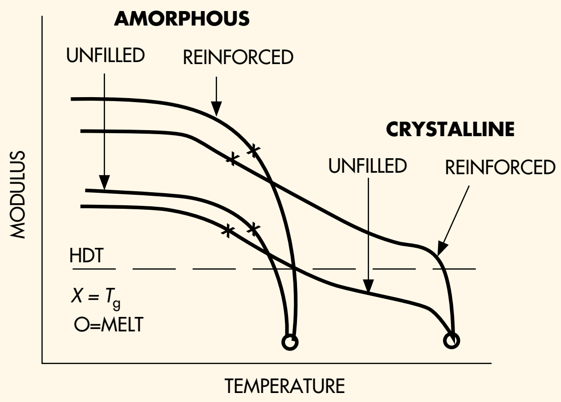


Fig 4.05 · Effect of temperature on tensile elongation

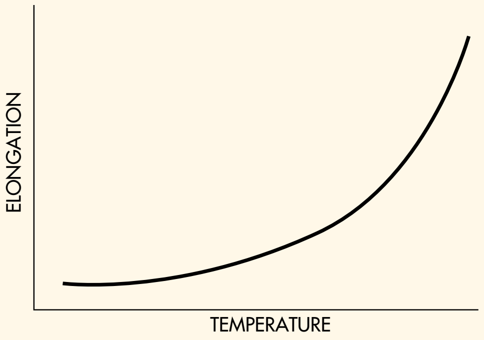


Fig 4.06 · Apparent modulus curves at different temperatures showing time-temperature shifting to estimate expended time values at lower temperatures

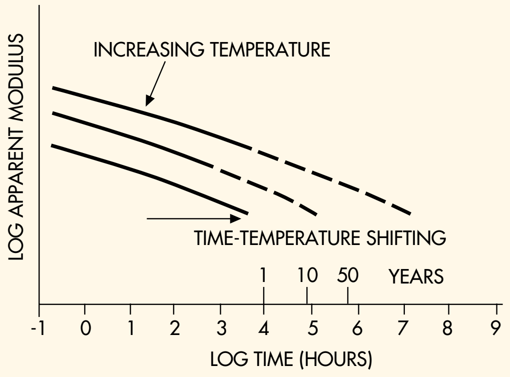
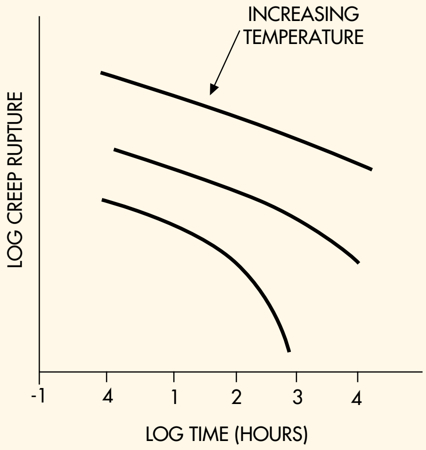


Fig 4.07 · Creep rupture curves indicating danger of linear projection to longer times at lower temperatures



4.10.2 Creep

Creep, isochronous stress, and isometric stress curves are produced from measurements at a fixed temperature. Complete sets of the curves are sometimes available at temperatures other than ambient. It is common to find creep rupture or apparent modulus curves plotted vs. log time with temperature as a parameter. Figure 4.06 illustrates time-temperature shifting of the apparent modulus curves projecting to times beyond a normal testing range. These curves suggest that it would be reasonable to estimate moduli at somewhat longer times than the available data at the lower temperatures. However, a set of creep rupture curves at various temperatures (such as those in Figure 4.07) would suggest that projecting the lowest temperature curves to longer times as a straight line could produce a dangerously high prediction of rupture strength.

4.10.3 Impact

Testing impact properties at various temperatures produces a plot of impact property vs. temperature, which looks very much like the elongation vs. temperature curve in Figure 4.05. As temperatures drop significantly below ambient temperature, most plastic materials lose much of their room-temperature impact strength. A few materials are on the lower, almost horizontal portion of the curve at room temperature and show only a gradual decrease in impact property with decreases in temperature. An interesting exception is provided by the long-fiber-reinforced plastics, which have relatively high Izod impact values at room temperature and essentially the same values at -40°F (40°C).

4.10.4 Fatigue

Occasionally, one finds *S-N* curves for plastic materials at various temperatures showing a decrease in the strength values with increasing temperature. However, as discussed in Chapter 3, laboratory fatigue data rarely model the end-use fatigue environment adequately and should be used only as guides for the selection of materials for end-use testing.

5. Electrical Properties

Plastic materials have found widespread use in a multitude of electrical and electronic applications throughout virtually all industries. The combination of mechanical and electrical properties provides an ideal choice for everything from tiny electronic components to very large electrical equipment enclosures. The most notable electrical property of plastic materials is that they are good insulators, but as seen in this chapter, plastics have many other important electrical properties that must be considered in the design of plastic parts.

5.1 Conductivity in Solids

Solid materials vary in electrical conductivity, depending on the availability and mobility of movable charge carriers within the material. Metals are excellent conductors largely due to the structure of a metal atom, which has a loosely held, outermost electron. Metal atoms are in close proximity in a regular lattice. This allows the outer electron to easily break free and move within the lattice (Figure 5.01). The presence of these “free” electrons accounts for the ability of a metal to conduct large currents even with low voltages.

In materials such as glass, porcelain, and plastics, the outer electrons are tightly bound to the atoms or molecules and no free electrons are present. These materials cannot readily conduct electrical current; thus, they are insulators. Other materials, such as silicon and germanium, have conductivities between those of conductors and insulators, and are classified as semiconductors. These materials, in the pure state and at low temperatures, are actually insulators. However, they can be made to conduct current by adding impurities or by raising the temperature.

5.2 Volume Resistivity

A standard measure of conductivity is the electrical resistance of a material when a direct current potential is applied to it. Figure 5.02 shows one of many test configurations used to measure the resistance across a volume of material. This test, known as volume resistivity, is the resistance measured in ohms times the area of the smaller electrode divided by the thickness of the specimen. Thus, the volume resistivity is generally given in ohm-cm. Testing conditions such as temperature, relative humidity, test voltage, and conditioning of the sample can affect the results. Materials with values above 10^8 ohm-cm are considered to be insulators, while those between 10^8 and 10^1 ohm-cm are considered to be partial conductors. Table 5.01 shows the volume resistivity values for various plastics.

Fig 5.01 · Free electrons in a metal lattice

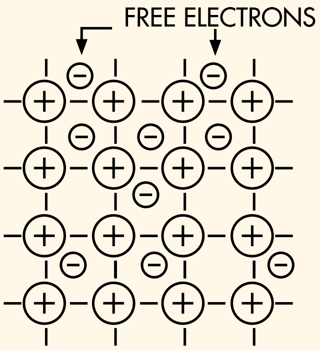


Table 5.01 · Typical values of volume resistivity for thermoplastics

Material	Volume Resistivity, ohm-cm
Acetal	$10^{14} – 10^{16}$
Acrylic	$10^{14} – 10^{18}$
ABS	10^{16}
Nylon	$10^{12} – 10^{16}$
Polycarbonate	$10^{15} – 10^{17}$
TP Polyester	$10^{14} – 10^{17}$
Polypropylene	$10^{14} – 10^{17}$
Polysulfone	$10^{15} – 10^{17}$
Modified PPO/PPE	$10^{15} – 10^{17}$
Polyphenylene Sulfide	10^{16}
Polyarylate	$10^{16} – 10^{17}$
Liquid Crystal Polymer	10^{15}

5.3 Surface Resistivity

This test measures the ability of current to flow over the surface of a material. Unlike the volume resistivity test, the test electrodes are both placed on the same side of the test specimen, as illustrated in Figure 5.02. While volume resistivity is a property of the material, surface resistivity is essentially a measure of the susceptibility of the material to surface contamination, particularly moisture. Data from this test are best used when materials are being evaluated and selected for testing in applications in which surface leakage may be a problem. The data are subject to large errors and should be used with large safety factors in design analysis.

5.4 Dielectric Strength

When an insulator is subjected to increasingly high voltage, it eventually breaks down and allows a current to pass. The voltage reached just before it breaks down divided by the sample thickness is known as the dielectric strength of the material, measured in volts/mil. It is generally measured by putting electrodes on either side of a test specimen and increasing the voltage at a controlled rate (see Figure 5.03). Factors that affect the test results are temperature, sample thickness, conditioning of sample, rate of increase in voltage, and duration of test. Any contamination of, or internal voids in, the sample may cause premature failure in this test.

5.5 Dielectric Constant (Permittivity)

When an electrical field is imposed across an insulator, the molecules become polarized. If the potential is reversed, the polarization of the molecules also reverses. The ease with which a material can be polarized is measured by a material constant called permittivity. The ratio of a material's permittivity to the (negligible) permittivity in a vacuum is called relative dielectric constant or more commonly, dielectric constant. This is a dimensionless constant that becomes an important factor when plastics are used as dielectric materials in high frequency applications. The value of this constant can vary with changes in temperature, moisture level, frequency, and part thickness. Table 5.02 gives the dielectric constants for various insulating materials.

Fig 5.02 · One type of text apparatus for volume and surface resistivity

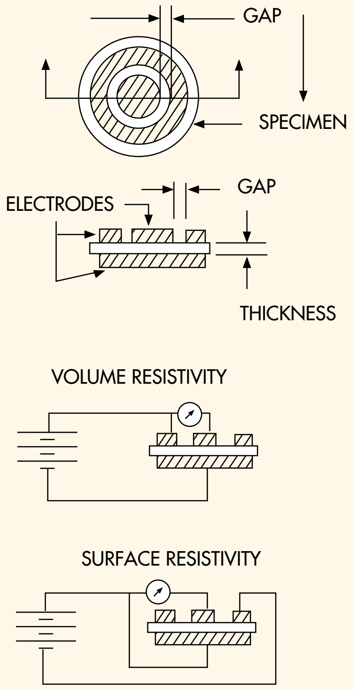
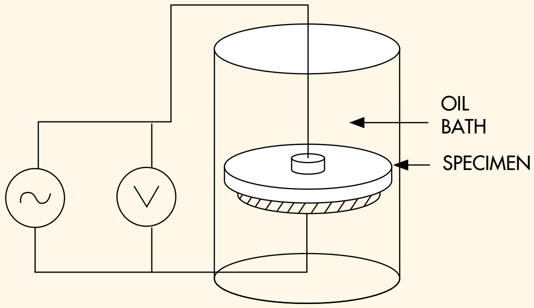


Fig 5.03 · A typical test configuration for dielectric strength



5.6 Dissipation Factor

The dissipation factor can be measured along with the dielectric constant in the same apparatus. If the polarizing reversals mentioned above occur rapidly, as with an alternating current, energy is dissipated as heat due to the rapid change in polarization. The dissipation factor is a measure of that heat dissipation. It can also be viewed as the ratio of the energy dissipated (lost) as heat compared to that transmitted, and is usually measured at 1 MHz (10^6 cycles/sec); see Table 5.02. A low dissipation factor becomes important when plastics are used as insulators in high-frequency applications such as radar and microwave equipment.

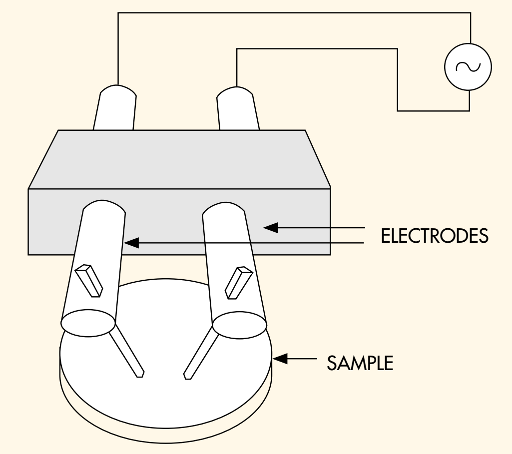
Table 5.02 · Typical values for dielectric constant and dissipation factor for various thermoplastics at room temperature

Material Description	Dielectric Constant	Dissipation Factor
Acetal	3.7 - 3.9	0.001 - 0.007
Acrylic	2.1 - 3.9	0.001 - 0.060
ABS	2.9 - 3.4	0.006 - 0.021
Nylon 6/6	3.1 - 8.3	0.006 - 0.190
Polycarbonate	2.9 - 3.8	0.0006 - 0.026
TP Polyester	3.0 - 4.5	0.0012 - 0.022
Polypropylene	2.3 - 2.9	0.003 - 0.014
Polysulfone	2.7 - 3.8	0.0008 - 0.009
Modified PPE (PPO)	2.4 - 3.1	0.0002 - 0.005
Polyphenylene Sulfide	2.9 - 4.5	0.001 - 0.002
Polyarylate	2.6 - 3.1	0.001 - 0.022
Liquid Crystal Polymer	3.7 - 10	0.010 - 0.060

5.7 Arc Resistance

If an electrical arc is imposed on the surface of an insulating material, the material can develop a conductive path (Figure 5.04). The arc resistance test measures the time in seconds for this to occur. This test was developed for thermosets, since a conductive path can be formed from the decomposition products produced by this kind of localized heating. While arc resistance times are often available for thermoplastics, the mechanisms can be very different and should be understood. The specimen for this test is dry and free of contaminants. A material with a high value in this test would be advantageous in electrical applications where the possibility of arcing exists. Examples are switches, circuit breakers, automotive ignition components, and high-voltage apparatus.

Fig 5.04 · A typical test configuration for arc resistance



5.8 Comparative Tracking Index (CTI)

This is an Underwriters Laboratories test run similar to the arc resistance test except that an electrolyte (solution of ammonium chloride) is put on the surface. The CTI for a material is the numerical value of the voltage required to cause a conductive path to form between the electrodes. This test is useful since it measures the arc resistance on a contaminated surface, which is often the case with actual electrical and electronic equipment.

6. Environmental Considerations

When specifying a particular material for use in an application, the design engineer must carefully consider the end-use environment. While rust and corrosion can plague metals, cracking, crazing, discoloration, loss of properties, melting, or dissolution can affect thermoplastics in the presence of chemical substances, energy sources, or radiation. An important aspect of the environmental assessment that is sometimes overlooked is the processing, assembly, finishing, and cleaning operations to which the product may be subjected even before it reaches its ultimate use.

6.1 Factors Affecting Environmental Resistance

6.1.1 Stress Level

Stress level is a very significant factor affecting the performance of a part. In general, as the stress level increases, resistance to a particular environment decreases. In addition to the obvious applied loads, stresses can result from injection molding, forming, and assembly operations.

6.1.2 Temperature

In general, as temperature increases, the detrimental effect (if any) of a substance on a particular resin is greater. Temperature often determines whether a particular plastic will survive a specific environment.

6.1.3 Exposure

The compatibility of a plastic material with a particular environment is frequently determined by the actual amount of exposure that exists. Among the factors to be considered are the following:

1. Actual time of exposure to adverse environment
2. Concentration of adverse substance
3. State of substance (solid, liquid, or gas)
4. Radiation level and intensity
5. Protective barriers (coatings or paints), integral “black” color

Data on the response of thermoplastics to stress and temperature are usually available for established, commercially available materials. Generally available environmental data include resistance to various chemical substances and weathering information, particularly ultraviolet (UV) stability. For purposes of this discussion water is treated as simply another chemical. However, for many polymers, resistance to water receives separate, special treatment independent from general chemical compatibility.

6.2 Chemical Compatibility

Part of the wide acceptance of thermoplastics is due to their relative compatibility with the ambient environment, particularly moisture, as compared to metals. This is in spite of the fact that many plastics are hygroscopic, thereby absorbing water. This results in dimensional and property changes. However, the mechanism of chemical attack in plastics is complicated, making compatibility assessments difficult. The same chemical may react differently with plastics in the same family or even with different compounds of the same base resin. Conversely, a given resin compound may behave very differently in chemicals that are considered similar. In addition, a variety of mechanisms exists by which a chemical might attack a plastic.

6.2.1 Reaction

The chemical can attack the polymer chain directly producing a progressive lowering of the molecular weight of the polymer. Changes in the short-term mechanical properties are evidence of reaction.

6.2.2 Solvation

Most thermoplastics are soluble in some chemical. However, high molecular weight plastics usually dissolve very slowly. Therefore, the solvation process usually appears similar to a chemical reaction. Generally, weight and dimensional changes and swelling are present along with a loss of properties.

6.2.3 Plasticization

If a chemical is miscible with a polymer, absorption and plasticization may result. Evidence of plasticization of the plastic includes reduction of strength, stiffness, and creep resistance and increased impact resistance. The plastic tends to swell, and warpage may occur due to relaxation of molded-in stresses.

6.2.4 Environmental Stress Cracking

An unstressed plastic may appear to be unaffected by exposure to a chemical. However, the same chemical may cause catastrophic failure when the plastic is stressed. This mechanism is called environmental stress cracking.

Chemical compatibility data are generally obtained in a manner similar to “aging at elevated temperatures,” discussed in Chapter 4. That is, standard test bars are placed in the chemical and stored at the desired temperature for some time interval. The test bars are then removed from the exposure environment, cleaned, and tested for whatever properties are of interest, typically tensile strength, flexural modulus, dimensional change, weight, and discoloration. Table 6.01 shows the chemical resistance of commonly used thermoplastic materials. These are only general guidelines. The design engineer must consult marketing data sheets, test results, and the material supplier for accurate information concerning a particular grade of resin. Even when the information indicates the material is highly compatible, end-use testing must be performed.

While this method is easy, it can be misleading since the response of stressed samples to the chemical environment can be very different; i.e., it cannot generally detect agents causing environmental stress cracking. Some test procedures expose a test sample to a chemical in the presence of either a fixed stress or fixed strain distribution along the length of the sample. The samples may then be examined for the stress or strain location at which damage begins. However, these tests are more difficult and expensive to run. Therefore, such data for a resin in a particular chemical are often unavailable.

Finally, the above tests may provide information about the chemical compatibility of a plastic, but are of little value for establishing the performance properties of a plastic for design purposes. The only test that provides this information is the creep rupture test conducted at appropriate temperatures in the chemical environment. This testing is difficult and expensive to conduct and is infrequently done.

The design engineer should be prepared to pursue creep rupture testing in the actual end-use environment on test bars or, preferably, prototype parts to determine the suitability of a plastic in that environment. Thus, it is advantageous for the designer to select several different plastics or components of the same plastic for evaluation in the end-use environment.

6.3 Weathering Resistance

Many applications for plastics require that the material withstand exposure to “sunlight,” i.e., UV, when used in naturally lighted areas or outdoors. All plastic materials are affected by ultraviolet light exposure and suffer some degree of degradation. The degradation is usually noticed by fading, chalking, and embrittlement of the plastic material. Often, UV-resistant variants of popular grades of plastic materials are available from suppliers.

UV test data are usually obtained through actual outdoor exposure or in special test cabinets. Outdoor exposure tests may be as simple as attaching test samples to a surface at a suitable angle for the latitude where the test is being conducted or as complicated as having mirrors and sun tracking equipment to accelerate the effective exposure. Test cabinets are available to accelerate testing. Generally, they employ high-intensity xenon or carbon-arc lamps to generate high levels of UV exposure in a relatively short time.

Table 6.01 · Chemical resistance of various materials by chemical classes

	Acetal Copolymer	Acetal Homopolymer	Nylon 6/6	Thermoplastic Polyester (PBT)	Thermoplastic Polyester (PET)	Polyester Elastomer	Liquid Crystal Polymer*	Polyphenylene Sulfide	Polyarylate	Polycarbonate	Polysulfone*	Modified Polyphenylene Ether	Polypropylene	ABS	316 Stainless Steel	Carbon Steel	Aluminum	Examples
Acids and Bases																		
Acids, Weak	A	B	C	A	A	A	A	A	A	A	B	A	A	A	A	A	C	Dilute Mineral Acids
Acids, Strong	C	C	C	B	–	C	B	A	–	C	C	–	A	A	B	C	C	Concentrated Mineral Acids
Bases, Weak	A	C	A	B	B	A	B	A	–	C	A	A	A	A	A	B	C	Dilute Sodium Hydroxide
Bases, Strong	A	C	B	–	–	B	C	A	–	C	A	–	A	A	B	B	C	Concentrated Sodium Hydroxide
Acids, Organic, Weak	A	B	C	A	A	A	A	A	A	A	B	A	A	A	A	C	C	Acetic Acid, Vinegar
Acids, Organic, Strong	C	C	C	B	–	C	B	A	–	C	C	A	A	A	B	C	C	Trichloroacetic Acid
Automotive																		
Automotive Fuel	A	A	A	A	A	A	A	A	C	C	A	C	C	A	A	A	A	
Automotive, Lubricants	A	A	A	A	A	A	A	A	C	C	A	A	A	A	A	B	A	
Automotive, Hydraulic	A	A	A	A	A	–	A	A	C	C	C	A	A	A	–	–	–	
Solvents																		
Aliphatic Hydrocarbons	A	A	A	A	A	A	A	A	A	A	A	B	C	A	A	A	A	Heptane, Hexane
Aliphatic Hydrocarbons, Halogenated	A	B	B	B	B	A	A	A	C	C	C	–	–	–	B	B	B	Ethylene Chloride, Chloroform
Alcohols	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	B	Ethanol, Cyclohexanol
Aldehydes	A	A	A	A	B	B	A	A	–	C	B	–	A	–	A	B	A	Acetaldehyde, Formaldehyde
Amines	A	C	–	–	–	–	C	B	–	C	C	–	A	–	A	B	B	Aniline, Triethanolamine
Aromatic Hydrocarbons	A	B	A	A	B	B	A	A	C	C	C	C	C	C	A	A	A	Tolulene, Xylene, Naphtha
Aromatic Hydrocarbons, Halogenated	B	B	–	–	–	C	–	A	C	C	C	–	–	–	A	A	A	Chlorobenzene
Aromatic, Hydroxy	A	C	C	C	–	C	A	A	–	C	C	–	A	–	B	C	A	Phenol
Esters	A	B	A	B	B	B	A	A	C	C	C	–	C	–	B	B	B	Ethyl Acetate, Dioctyl Phthalate
Ethers	A	–	A	A	–	–	–	A	–	A	B	–	C	–	A	A	A	Butyl Ether, Diethyl Ether
Ketones	A	B	A	B	B	B	A	A	C	C	C	–	B	C	A	A	A	Methyl Ethyl Ketone, Acetone
Miscellaneous																		
Detergents	A	–	A	–	B	–	–	A	A	A	–	B	A	–	A	A	B	Laundry and Dishwashing Detergents, Soaps
Inorganic Salts	B	B	B	–	A	–	–	A	–	A	–	–	A	A	B	B	B	Zinc Chloride, Cupric Sulfate
Oxidizing Agents, Strong	A	C	C	–	C	–	B	B	–	C	–	–	A	–	C	C	C	30% Hydrogen Peroxide, Bromine (Wet)
Oxidizing Agents, Weak	C	C	C	A	–	A	A	A	–	A	–	A	A	A	B	C	A	Sodium Hypochlorite Solution
Water, Ambient	A	A	B	A	A	A	A	A	A	A	A	A	A	–	A	C	B	
Water, Hot	B	C	B	C	C	B	A	A	–	C	–	A	C	–	A	C	B	
Water, Steam	A	C	C	C	C	C	B	A	–	C	–	–	C	–	A	C	–	

This information is presented for instructional purposes and is not intended for design. The data were extracted from numerous sources, making consistent rating assignments difficult. Further, the response of any given material to specific chemicals in any one class can vary significantly. Indeed, during the preparation of the table, the effect of various chemicals in the same category on one plastic ranged from essentially no effect to total dissolution. Therefore, an "A" rating for a particular plastic exposed to a particular class of chemicals should not be interpreted as applying to all chemicals in that class. The rating simply means that for the chemicals in that class found in the literature reviewed, the rating was generally an "A". There may be other chemicals in the same class for which the rating would be a "C." Finally, the typical chemicals listed do not necessarily correspond to the ones on which the individual ratings are based.

A – Minimal Effect B – Some Effect C – Generally Not Recommended
Room temperature except hot water, steam, and "*"
Generally, extended exposure (more than a week) data was used *200°F

7. Structural Analysis

7.1 Introduction

In the design or analysis of any mechanical component, a systematic approach is desirable. Frequently the product is one in which no significant loads or deflection limitations occur. In such cases, the "gut feel" of the design engineer is usually all that is required. This is especially true with small, load-free plastic parts in which processing requirements dictate a minimum wall thickness that is more than adequate for the part function. Still, even in these cases, engineers new to plastic design often neglect the effects of stresses caused by assembly, handling, shipping, processing, temperature changes, and other environmental changes.

In this section, simple analysis techniques are presented that assist the design engineer in developing new parts to handle anticipated loading while keeping stress and deflections within acceptable limits. These techniques are also useful in product improvement, cost reduction, and failure analysis of existing parts. Thus, this chapter is devoted to applying simplified classical stress and deflection equations to plastic parts. As the complexity of the part increases or when very accurate results are required, more exact classical methods or computerized finite element analysis may be required. However, such methods are beyond the scope of this manual.

7.2 Defining the Structure

7.2.1 Loads

The first step in analyzing any part is to determine the loads to which the part is to be subjected. These loads generally fall into the following categories:

7.2.1.1 Directly Applied Loads

These loads, usually easy to understand, are defined loads applied to specific part areas, either concentrated at a point, line, or boundary or distributed over an area. The magnitude and direction of such loads are known or are easily determined from service conditions. In larger plastic parts, the weight of the part itself is a significant load. Figure 7.01 presents examples of directly applied loads.

Fig 7.01 · Directly applied loads

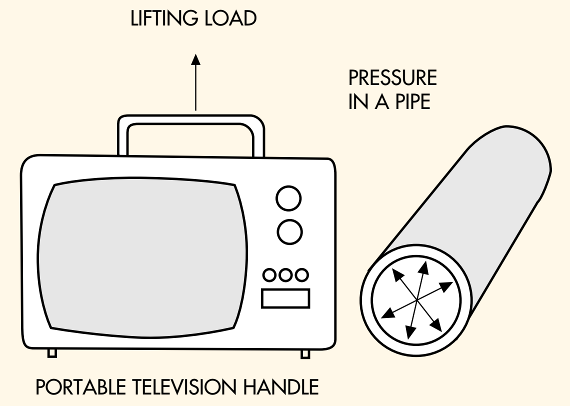
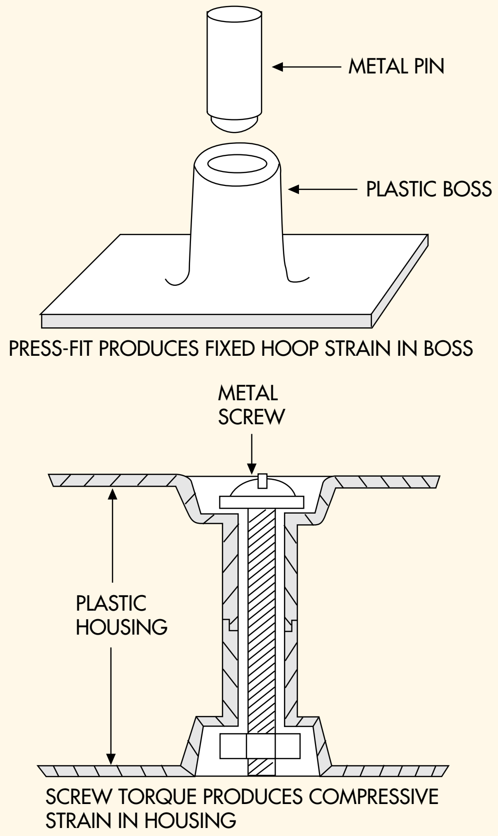


Fig 7.02 · Strain-induced loads



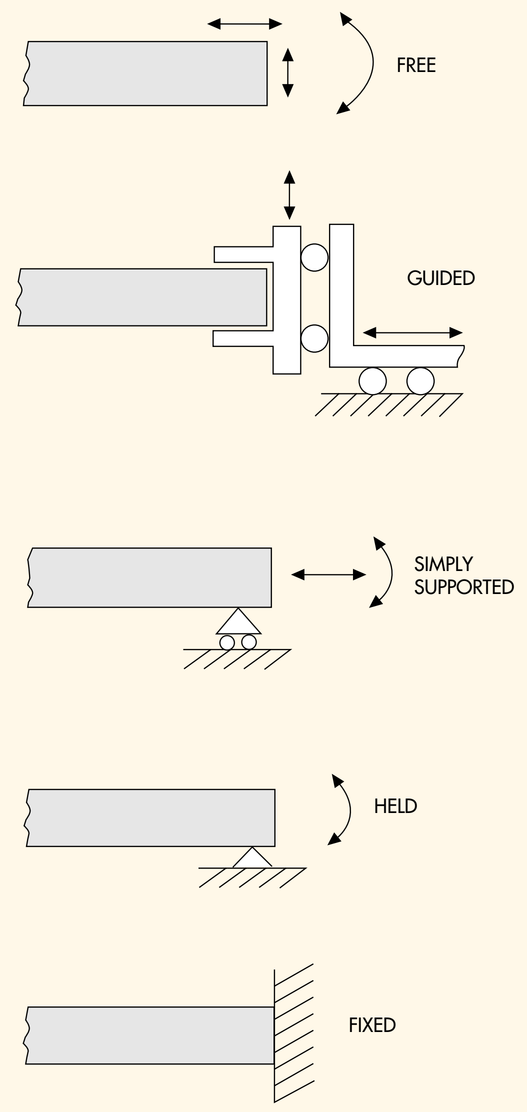
7.2.1.2 Strain-Induced Loads

Frequently, a part becomes loaded when it is subjected to a defined deflection. The actual load results from the structural reaction of the part to the applied strain. Unlike directly applied loads, strain-induced loads depend on the modulus of elasticity of the material and, in the case of thermoplastic materials, generally decrease in magnitude over time. Many assembly stresses and thermal stresses are a result of strain-induced loads. Figure 7.02 shows two common examples.

7.2.2 Support Conditions

When a load is applied to a part, for the part to remain in equilibrium there must be equal forces acting in the opposite direction. These balancing forces are the reactions at the supports. For purposes of structural analysis, several support conditions must be defined (Figure 7.03):

Fig 7.03 · Support conditions



7.2.2.1 Free (Unsupported)

This is the support condition in which the edge of a body is totally free to translate or rotate in any direction.

7.2.2.2 Guided

This condition is similar to a free end except that the edge is prevented from rotating.

7.2.2.3 Simply Supported

In this support condition, transverse displacement in one direction is restricted, as illustrated in Figure 7.03.

7.2.2.4 Held (Pinned)

This is similar to a simply supported condition except that only rotations are allowed.

7.2.2.5 Fixed (also Clamped or Built-in)

This is a support condition at the end of a beam or plate which prevents transverse displacements and rotations. The condition can be viewed as an end support firmly embedded into a fixed solid wall. In practice, especially with plastic parts, this condition rarely exists in its pure form since the mounting points of the parts usually have some give.

Free, simply supported, and fixed are the most frequently encountered support conditions.

7.2.3 Simplifications and Assumptions

For the purposes of the discussion and examples in this chapter, the following simplifications and assumptions are made:

1. The part under load can be broken down into one or more simple structures, beams, plates, pressure vessels, etc. for analysis.
2. The material being analyzed may be considered to be linearly elastic, homogeneous, and isotropic. While not necessarily true for plastic materials, this assumption is fundamental to the equations that follow.
3. The equations assume that the load is a single concentrated or distributed static load, gradually applied for a short period and then removed. However, creep, relaxation, or fatigue loads may be analyzed by using the same equations, provided the appropriate modulus and/or rupture (strength) conditions are applied.
4. The part being analyzed has no residual or molded-in stresses.
5. The equations apply to regions that are remote both from the point of application of the load and from any shoulder, hole, or other sudden change in dimension of the structure.
6. The equations may be used at shoulders, holes, or other sudden dimensional changes as long as appropriate stress concentration factors are used (see Chapter 8 of this manual or almost any machine design text or mechanical engineering handbook for stress concentration factors).

7.3 Safety Factors

No firm rules are available for setting safety factors for plastic parts. However, the most important consideration is, of course, the consequence of failure. For example, a little extra deflection in an outside wall or a crack in one of six internal screw bosses may be of little concern, but the failure of a pressure vessel or water valve may have serious safety or product liability implications. Before any product is put into the market, actual parts should be tested at the most extreme operating conditions. For example, a maximum working load should be applied at the maximum temperature and in the presence of any chemicals that might be expected in the end use. Further, the loads, temperatures, and chemicals to which a product is exposed prior to reaching its end use must not be overlooked, e.g., paint oven temperatures.

Impact loading should be applied at the lowest expected temperature, including shipping and assembly temperatures. The effects of variations in resin lots and molding conditions must also be considered.

Many failures in testing on preproduction parts can often be corrected with selective use of increased wall thickness, ribs, gussets, or elimination of stress concentrations. A material change to another grade of the same resin or to a different plastic with a suitable mechanical property profile may also solve the problem.

Engineers unfamiliar with plastic product design often ask for a design strength for use during the initial design phase. A review of product data and discussions with experienced engineers suggest that the ranges in Table 7.01 are generally appropriate. These ranges, applied to the strength on standard product data sheets, are suitable for use with the equations presented here only in the preliminary design phase, where general product dimensions are being evaluated. Any product designed by using these guidelines must be thoroughly tested to ensure satisfactory performance.

Table 7.01 · Design strength* for preliminary part design

	Failure Noncritical	Failure Critical
Intermittent (nonfatigue) Loading	25 – 50%	10 – 25%
Continuous Loading	10 – 25%	5 – 10%

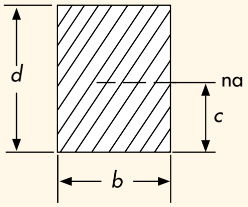
* Suggested percentage of strength values published in product data sheets, based on type of stress and maximum temperature. These are intended for preliminary design analysis only, and are not to be used in place of thorough product testing.

7.3.1 Failure Criteria

Experienced designers not familiar with plastics often ask, "What failure criterion should be used?" This question implies the rationalization of complex stress states, which are beyond the scope and intent of this manual. For the simple stress states considered here, the design strength given in Table 7.01 is adequate for preliminary design analysis. However, for designers who choose to perform the more complex analyses, the maximum shear (a.k.a. Coulomb, a.k.a. Tresca) theory of failure is suggested. It is further suggested that the shear strength be taken as the published shear strength or, one-half the tensile strength, whichever is lower. Even better, one-half the strength at the elastic limit, if available, is preferred.

Fig 7.04 · Section properties for some common cross-sections (na = neutral axis)

RECTANGULAR



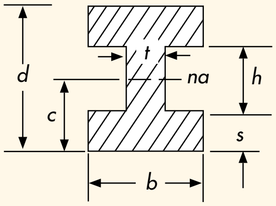
$A = bd$

$c = \dfrac{d}{2}$

$I = \dfrac{bd^3}{12}$

$Z = \dfrac{bd^2}{6}$

I-BEAM



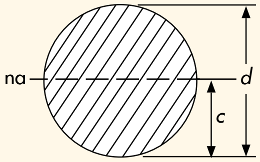
$A = bd - h(b - t)$

$c = \dfrac{d}{2}$

$I = \dfrac{bd^3 - h^3(b - t)}{12}$

$Z = \dfrac{bd^3 - h^3(b - t)}{6d}$

CIRCULAR



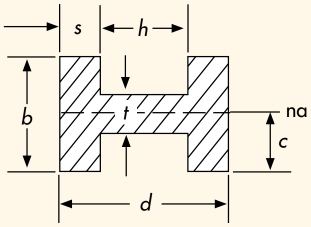
$A = \dfrac{\pi d^2}{4}$

$c = \dfrac{d}{2}$

$I = \dfrac{\pi d^4}{64}$

$Z = \dfrac{\pi d^3}{32}$

H-BEAM



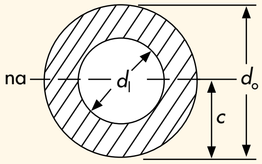
$A = bd - h(b - t)$

$c = \dfrac{b}{2}$

$I = \dfrac{2sb^3 + ht^3}{12}$

$Z = \dfrac{2sb^3 + ht^3}{6b}$

TUBE



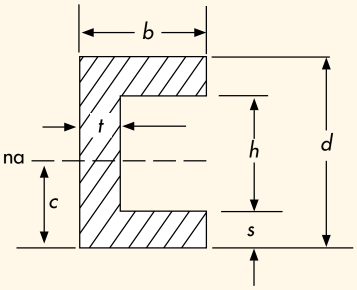
$A = \dfrac{\pi(d_o^2 - d_i^2)}{4}$

$c = \dfrac{d_o}{2}$

$I = \dfrac{\pi(d_o^4 - d_i^4)}{64}$

$Z = \dfrac{\pi(d_o^4 - d_i^4)}{32d_o}$

C-BEAM



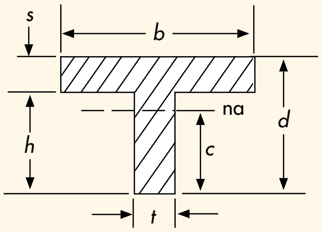
$A = bd - h(b - t)$

$c = \dfrac{d}{2}$

$I = \dfrac{bd^3 - h^3(b - t)}{12}$

$Z = \dfrac{bd^3 - h^3(b - t)}{6d}$

T-BEAM OR RIB



$A = bs + ht$

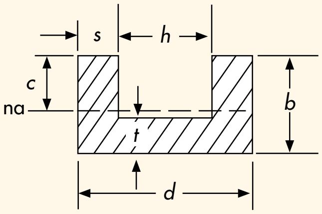
$c = d - \dfrac{d^2t + s^2(b - t)}{2\,(bs + ht)}$

$Z = \dfrac{I}{c}$

$Z^{\prime} = \dfrac{I}{(d - c)}$

$I = \dfrac{tc^3 + b(d - c)^3 - (b - t)(d - c - s)^3}{3}$

U-BEAM



$A = bd - h(b - t)$

$c = b - \dfrac{2b^2s + ht^2}{2A}$

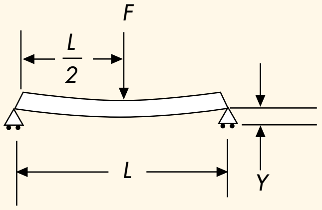
$I = \dfrac{2b^3s + ht^3}{3} - A(b - c)^2$

$Z = \dfrac{I}{c}$

$Z^{\prime} = \dfrac{I}{(b - c)}$

Fig 7.05 · Maximum stress and deflection equations for selected beams

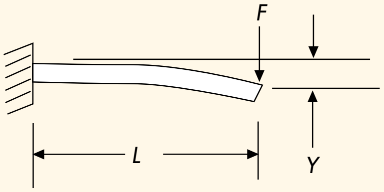
SIMPLY SUPPORTED BEAM
CONCENTRATED LOAD AT CENTER



(at load) $\sigma = \frac{FL}{4Z}$

(at load) $Y = \frac{FL^3}{48EI}$

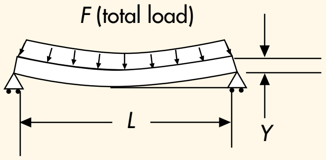
CANTILEVERED BEAM (ONE END FIXED)
CONCENTRATED LOAD AT FREE END



(at support) $\sigma = \frac{FL}{Z}$

(at load) $Y = \frac{FL^3}{3EI}$

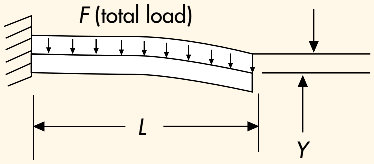
SIMPLY SUPPORTED BEAM
UNIFORMLY DISTRIBUTED LOAD



(at center) $\sigma = \frac{FL}{8Z}$

(at center) $Y = \frac{5FL^3}{384EI}$

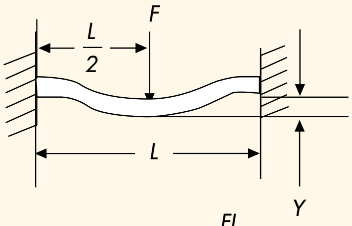
CANTILEVERED BEAM (ONE END FIXED)
UNIFORMLY DISTRIBUTED LOAD



(at support) $\sigma = \frac{FL}{2Z}$

(at free end) $Y = \frac{FL^3}{8EI}$

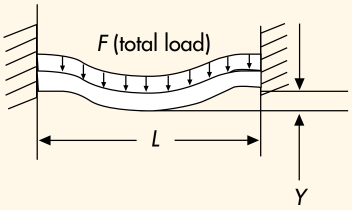
BOTH ENDS FIXED
CONCENTRATED LOAD AT CENTER



(at supports) $\sigma = \frac{FL}{8Z}$

(at load) $Y = \frac{FL^3}{192EI}$

BOTH ENDS FIXED
UNIFORMLY DISTRIBUTED LOAD



(at supports) $\sigma = \frac{FL}{12Z}$

(at center) $Y = \frac{FL^3}{384EI}$

7.3.2 Beam Bending Stresses

As indicated in Chapter 3, in simple beam bending theory, the following additional assumptions are made:

1 . The beam is initially straight, unstressed, and symmetric.
2. The proportional limit is not exceeded.
3. Young's modulus for the material is the same in tension and compression.
4. All deflections are small, so that plane cross-sections remain planar before and after bending.

The maximum stress occurs at the surface of the beam farthest from the neutral surface and is given by

$$\sigma = \frac{Mc}{I} = \frac{M}{Z}$$

where

M = bending moment, inch pounds
c = distance from neutral axis to outer surface where maximum stress occurs, inches (see Figure 7.04)
I = moment of inertia, inches^4 (see Figure 7.04)
Z = l/c, section modulus, inches^3 (see Figure 7.04); this is a geometric property not to be confused with the modulus of the material, a material property.

I, c, Z, and the cross-sectional area, *A*, for some common cross-sections are given in Figure 7.04. The maximum stress and deflection equations for some common beam loading and support geometries are given in Figure 7.05. Note that for the T- and U-sections in Figure 7.04, the distance from the neutral surface to the outermost surface is not the same for the top and the bottom of the beam. Occasionally, it may be desirable to determine the maximum stress on the "other" surface, particularly if it is in tension. For this reason, Z^{I} is provided for these two sections.

7.3.3 Shear Stress, Torsion

A shaft subjected to a torque (see Figure 7.06) is generally considered to have failed when the strength of the material in shear is exceeded. For a torsional load, the recommended shear is the published value or one-half the tensile strength, whichever is less. The maximum shear stress on a shaft in torsion is given by

$$\tau = \frac{Tc}{J}$$

where

T= applied torque, inch-pounds
c = distance from the center of the shaft to the location on the outer surface of the shaft where maximum stress occurs, inches (see Figure 7.07)
J = polar moment of inertia, inches^4 (see Figure 7.07)

The angular rotation of the shaft due to the torque is given by

$$\theta = \frac{TL}{GJ}$$

where

L= length of the shaft, inches
G= shear modulus, psi

$$= \frac{E}{2\,(1 + \nu)}$$

E= Young's modulus (tensile modulus), psi
ν= Poisson's ratio (if unknown, use 0.35)

Fig 7.06 · Shaft of diameter, *d*, and length, *L*, subjected to torque, *T*, with angular deformation, θ

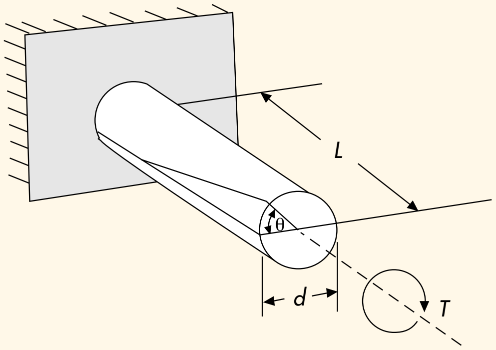
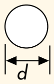
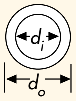
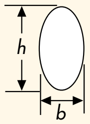
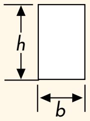
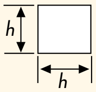


Fig 7.07 · Polar moments of inertia for common cross-sections

CROSS-SECTION	POLAR MOMENT OF INERTIA, J	LOCATION OF MAX SHEAR STRESS, C
	$\frac{\pi d^4}{32}$	$\frac{d}{2}$
	$\frac{\pi(d_o^4 - d_i^4)}{32}$	$\frac{d_o}{2}$
	$\frac{\pi b^3 h}{32}$	$\frac{b}{2}$
	$\frac{bh(b^2 + h^2)}{12}$	$\frac{b}{2}$
	$\frac{h^4}{6}$	$\frac{h}{2}$

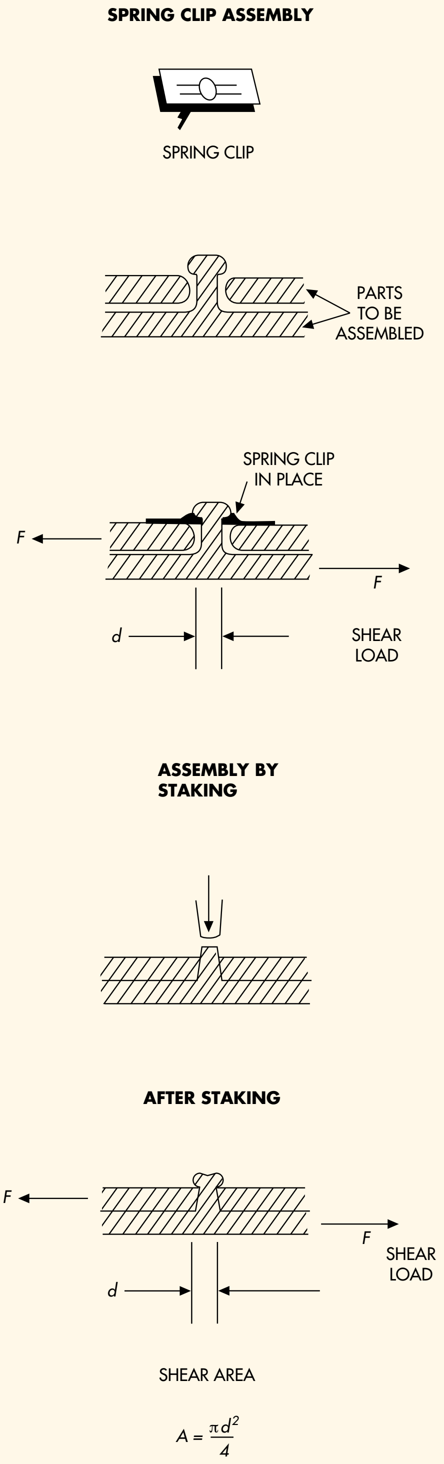
7.3.4 Shear Stress, Direct Shear

Many situations occur in which direct shear is applied to a plastic part. Figure 7.08 illustrates assembly by staking and by a spring clip in which a load may be applied in direct shear. Other examples include spot welds (Figure 9.11) and pinned structures such as hinges and conveyor links. For direct shear (as in Figure 7.08), the shear stress is simply the applied load divided by the shear area:

$$\tau = \frac{F}{A}$$

Direct shear situations, such as those illustrated, are the only appropriate times to use the shear strength data reported on marketing data sheets. However, since the load is not only transferred by shear, but also contains a considerable bending and/or compressing component, all of which depend greatly on geometry, the actual strength can vary greatly. Therefore, it is suggested that safety factors be increased significantly in direct shear situations.

Fig 7.08 · Direct shear examples

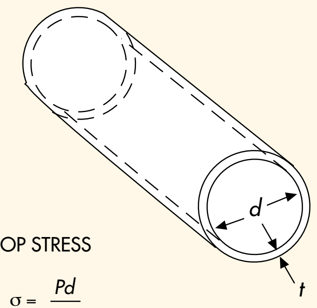


7.4 Pressure Vessels

The most common plastics pressure vessel application is a tube with internal pressure. In the selection of the wall thickness for the tube, the thin-wall tube hoop stress equation is convenient (see Figure 7.09). It is very useful in determining an approximate wall thickness, even when the condition $t < d/10$ is not met. After the thin-wall equations have been applied, the thick-wall equation in Figure 7.10 can be used to verify the design.

Fig 7.09 · Cylindrical pressure vessel, thin wall tube

UNIFORM INTERNAL PRESSURE, *P*



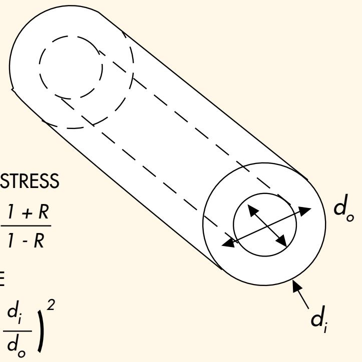
HOOP STRESS

$$\sigma = \frac{Pd}{2t}$$

This equation is reasonably accurate for $t < d/10$. As the wall thickness increases, the error becomes quite large.

Fig 7.10 · Cylindrical pressure vessel, thick wall tube

UNIFORM INTERNAL PRESSURE, *P*



HOOP STRESS

$$\sigma = P\,\frac{1+R}{1-R}$$

WHERE

$$R = \left(\frac{d_i}{d_o}\right)^2$$

This equation is for the maximum hoop stress which occurs at the surface of the inside wall of the tube.

7.5 Press-Fits

Although the use of press-fit assemblies can be dangerous with thermoplastic parts, their low cost, assembly, speed, and convenience often result in their use. A common use is with a plastic hub or boss accepting either a plastic or metal shaft or pin. The press-fit operation tends to expand the hub, creating a tensile or hoop stress. If the interference is too great, a very high strain and stress develops. The plastic part either:

1 . fails immediately by developing a crack parallel to the axis of the hub relieving the stress, a typical hoop stress failure, or

2. survives assembly but fails prematurely when the part is in use for a variety of reasons related to the high induced stress levels, or

3. undergoes stress relaxation sufficient to reduce the stress to a lower level that can be maintained.

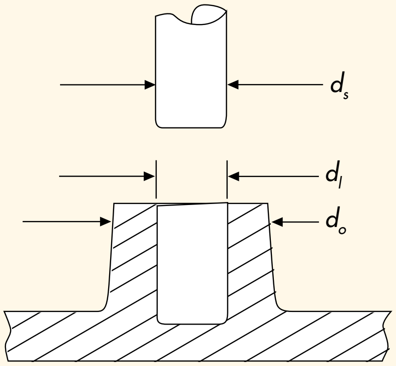
Hoop stress equations for two typical press-fit situations are shown in Figure 7.11. The allowable design stress depends on the particular plastic resin, temperature, and other environmental considerations.

A simpler, although less accurate, method of evaluating these press-fits is to assume that the shaft will not deform when pressed into the hub. This is reasonably accurate when a metal shaft is used in a plastic hub. The hoop strain developed in the hub is then given by

$$\varepsilon = \frac{i}{d_i}$$

The hoop stress can then be obtained by multiplying by the appropriate modulus. For high strains, the secant modulus gives the initial stress. However, for longer term stresses, the apparent or creep modulus should be used. The main point is that the maximum strain or stress must be below the value that produces creep rupture in the material. It must be noted that a weld line is usually present in the hub, which can significantly affect the creep rupture strength of most plastic materials. An additional frequent complication with press-fits is that a round hub or boss is often difficult to mold. There is a tendency for the hub to be slightly elliptical in cross-section, increasing the stresses on the part. In view of the preceding, all press-fits must be given end-use testing under actual operating conditions to assure product reliability. Design alternatives to a standard press-fit are given in Chapter 9.

Fig 7.11 · Press-fit equations for two typical situations



GEOMETRY FACTOR

$$\Gamma = \frac{1 + \left(\frac{d_s}{d_o}\right)^2}{1 - \left(\frac{d_s}{d_o}\right)^2}$$

E_p = MODULUS OF ELASTICITY OF PLASTIC HUB OR BOSS
ν_p = POISSON'S RATIO OF PLASTIC
σ_a = ALLOWABLE DESIGN STRESS FOR PLASTIC
$i = d_s - d_i$ = DIAMETRAL INTERFERENCE
i_a = ALLOWABLE INTERFERENCE

CASE A

SHAFT AND HUB ARE BOTH THE SAME OR ESSENTIALLY SIMILAR MATERIALS. HOOP STRESS GIVEN i IS

$$\sigma = \frac{i}{d_s} E_p \frac{\Gamma}{\Gamma + 1}$$

OR, THE ALLOWABLE INTERFERENCE IS

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\Gamma + 1}{\Gamma}$$

CASE B

SHAFT IS METAL, HUB IS PLASTIC
HOOP STRESS GIVEN i IS

$$\sigma = \frac{i}{d_s} E_p \frac{\Gamma}{\Gamma + \nu_p}$$

OR, THE ALLOWABLE INTERFERENCE IS

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\Gamma + \nu_p}{\Gamma}$$

7.6 Thread Strength

When threads are either molded or tapped into a plastic part, the assembly torque must be controlled to prevent excessive shear stress, which results in stripped threads, and to limit hoop stress, which can result in tensile failures. Although the mechanics of stress analysis for screw threads are readily available, the equations are complicated and few wish to take them on. For this reason, the following simple, approximate equations are provided (see Figure 7.12).

The relationship between the torque on a screw and the generated axial force is approximately

$$T = \frac{4}{3} \mu d F$$

where

μ = dynamic coefficient of friction between the sliding surfaces.

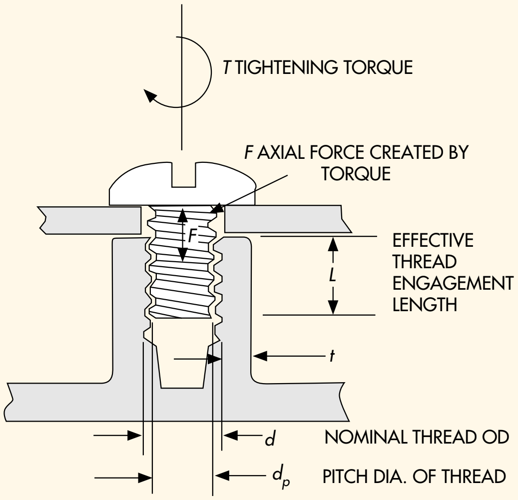
The shear area of the threads, A, is approximately one-half the thread engagement cylinder or

$$A = \frac{1}{2} \pi d L$$

Therefore, the thread-stripping shear stress is

$$\tau = \frac{F}{A} = \frac{2F}{\pi d L}$$

Fig 7.12 · Illustration for torque-force relationships for screw threads



For standard 60° unified threads, the radial component of force is approximately 60% of F. This force is spread over the thread engagement cylinder, producing an internal pressure in the boss. Therefore, the internal pressure in the boss is approximately

$$P = \frac{0.6F}{\pi dL}$$

This pressure can then be used in the simple thin-wall, hoop stress equation:

$$\sigma = \frac{P(d + 2t)}{2t}$$

to obtain the hoop stress produced in the boss.

A major problem with the thread torque-force equations is that the coefficient of friction varies significantly with material and surface finish. In addition, most published data for coefficient of friction are generated from high speeds and low load conditions rather than the low speed and high loads involved in thread engagement. Thus, these approximate equations are probably adequate. Furthermore, for initial design purposes, it is probably worthwhile to pick a median value for the coefficient of friction. A value of 0.15 is suggested. When this value is used, the previous equations can be further simplified as follows:

The torque-force relationship is

$$T = 0.2dF \quad or \quad F = \frac{5T}{d}$$

The thread-stripping shear stress equation is

$$\tau = \frac{2F}{\pi dL} = \frac{10T}{\pi d^2 L} \quad \text{or} \quad \frac{\left(\frac{10T}{d}\right)}{\pi dL}$$

The pressure generated on the inside of the boss is

$$P = \frac{0.2F}{dL} = \frac{T}{d^2 L}$$

The hoop stress generated in the boss is

$$\sigma = \frac{0.2F}{Lt} = \frac{T}{dLt}$$

if it is assumed that $d + 2t \approx 2d$.

Finally, the following observations should be clearly understood concerning screw threads:

1. The torque values are based on the coefficient of friction of the mating parts and can vary significantly. The use of any compatible lubricant that reduces friction also increases the shear and hoop stresses if the torque remains the same. Therefore, the allowable torque must be reduced when lubricants are present.

2. High assembly torque for the purpose of preventing vibrational loosening is frequently ineffective since creep of the plastic material reduces the effective assembly torque even if the fastener does not rotate. Vibration-proof screws, lock washers, lock nuts, and thread-locking adhesives, all specifically designed for thermoplastics, are usually a better alternative when loosening is considered a problem.

3. Self-tapping screws require additional torque to cut or form the thread. This torque must usually be added to the allowable safe assembly torque only for the first assembly. The appropriate hole design for self-tapping screws depends greatly on the material and screw design. Consult the screw manufacturer and Ticona for design recommendations.

7.7 Pipe Threads

Pipe threads are commonly used in plastic plumbing and pneumatic devices. Properly designed plastic pipe threads usually require only hand-tight assembly to effect a good seal, especially if a compatible sealant tape or compound is used. Assembling a tapered male pipe thread into a mating female thread in a plastic part is analogous to driving a cone into a round hole. Many split bosses are a result of improper field installation. Figure 7.13 shows some alternatives. Sometimes the use of straight threads and an O-ring seal can avoid the need for pipe threads. When pipe threads must be used, torque control is critical. The following general recommendations should be followed whenever possible:

1 . When metal is mated with plastic using pipe threads, make the plastic-threaded member the male thread so that the plastic is in compression.

2. When torque can be controlled during assembly of female plastic pipe threads, specify fluoroplastic tape and hand-tighten only.

3. When torque cannot be controlled, such as during field assembly, consider the use of an external or molded-in hoop ring.

4. Never design flats into plastic parts with threads for assembly purposes. This only encourages overtightening. If necessary, add “wings” or a textured surface for improved grip.

An approximate formula for the hoop stress produced in a plastic boss with internal pipe threads as illustrated in 7.13 is

$$\sigma = \frac{3T}{tdL}$$

As with the screw thread equations in the previous section, this equation assumes certain geometric relationships and a coefficient of friction of 0.15. Obviously, the torque must be reduced if compatible thread lubricants are used during assembly. As with all threaded assemblies, long-term testing under the extremes of operating pressure, temperature, and installation procedure is essential to ensure reliability.

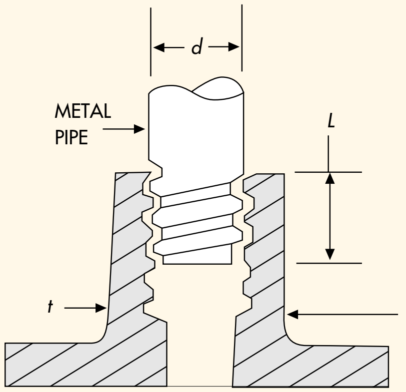
7.8 Impact Loads

One of the assumptions made at the beginning of this chapter is that the load is gradually applied. In reality, loads are often applied abruptly. This has the effect of significantly increasing the stress and strain. However, due to the elasticity of most thermoplastic materials, recovery is usually complete and the assumption is valid. Therefore, the steady-state stress and deflection of the plastic part is, for all practical purposes, identical to that of the part loaded gradually.

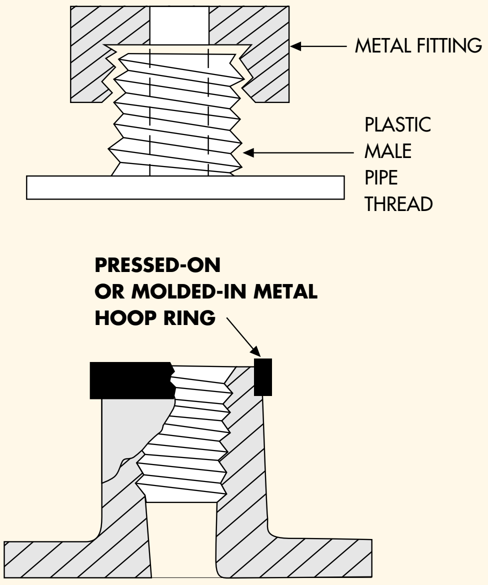
However, when impact loading becomes severe, impact failure can result. Figure 7.14 presents a method for estimating an “impact stress” and “impact deflection” for the case of a falling weight. (It is interesting to note that when the drop height is zero, the stress and deflection double.)

Fig 7.13 · Designing with pipe threads

POOR DESIGN

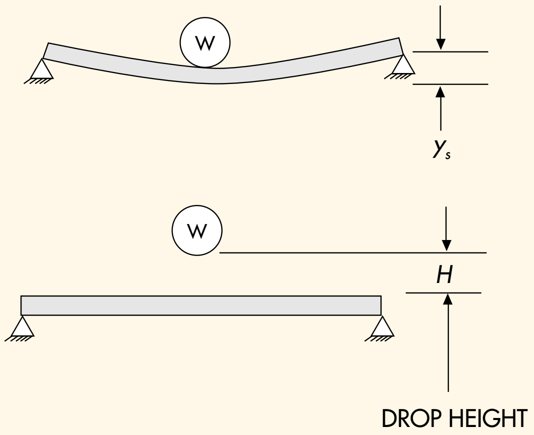


BETTER DESIGNS



Many high-impact materials can survive very large deflections or strains during impact without the permanent deformations or failure one would expect from the stress-strain curve of the material measured at standard loading rates. Therefore, the calculated impact stress of successful parts often appears unreasonably high. For many of these materials, the stress-strain characteristics are very different under rapid loading conditions as compared to the slow, steady loading conditions used in normal testing of plastic resin specimens. This partially accounts for the ability of many plastic parts to successfully dissipate large amounts of mechanical energy when subjected to impact.

Fig 7.14 • Estimating impact stress and deflection due to dropping a weight on the part



Calculate static stress and deflection from placing weight on part.

Static Stress

$$\sigma_a$$

Static Deflection

$$y_s$$

Impact Stress

$$\sigma_s = \sigma_s \left(1 + \sqrt{1 + \frac{2H}{y_s}}\right)$$

$$y_i = y_s \left(1 + \sqrt{1 + \frac{2H}{y_s}}\right)$$

NOTES:

- — This is only an estimate; actual testing is essential.
- — Calculated impact stress will often exceed ultimate stress listed in data sheets for high-imact materials.

7.9 Thermal Stresses

When materials with different coefficients of thermal expansion are bolted, riveted, bonded, crimped, pressed, welded, or fastened by any method that prevents relative movement between the parts, there is a potential for thermal stress. The typical case where problems develop (see Figure 7.15) involves the joining of nonreinforced thermoplastic parts with materials such as metals, glass, or ceramics, which generally have much lower coefficients of thermal expansion.

Figure 7.16 illustrates the equations for thermal expansion that apply in various situations. The basic relationship for the thermal expansion of a part is

$$\Delta L = \alpha L \Delta T$$

where

ΔL = change in length
α = coefficient of linear thermal expansion (see Table 4.01)
L = linear dimension under consideration (including hole diameters)
ΔT = temperature change

If the part is confined so that it cannot expand or contract, the strain induced by the temperature change is

$$\varepsilon_T = \frac{\Delta L}{L} = \alpha \Delta T$$

The stress can then be calculated by multiplying the strain by the tensile modulus of the material at the given temperature. However, a typical situation occurs where a plastic part is mounted to a metal part. While both expand due to a change in temperature, the plastic usually applies insignificant load to the metal, while a considerable stress is generated in the plastic. In this case, the approximate thermal stress, σ_T, in the plastic is

$$\sigma_T = (\alpha_m - \alpha_p)\, E_p \Delta T$$

where

α_m = coefficient of thermal expansion of the metal
α_p = coefficient of thermal expansion of the plastic
E_p = tensile modulus of the plastic at the temperature in question

Note that as the temperature increases, most plastics expand more than metals while their modulus drops. This produces a compressive load in the plastic part, which often results in buckling. Conversely, as the temperature drops, the plastic part shrinks more than the metal part and develops an increased tensile modulus. This can result in tensile rupture of the plastic part.

In many assemblies, clearances around fasteners, failure or yield of adhesives, warpage, or creep tend to relieve the thermal stress. Good design practice allows for these temperature changes, especially with large parts, which can experience wide temperature swings. Automotive interior and body panels are typical examples of such parts. This is often done by allowing for relative motion, as illustrated in Figure 7.16. The relative motion, ΔL_{rel}, between two attachment points of joined plastic and metal parts in which motion is allowed is as follows:

$$\Delta L_{rel} = (\alpha_p - \alpha_m)\, L \Delta T$$

Fig 7.15 · Typical assemblies in which thermal stress can be a problem

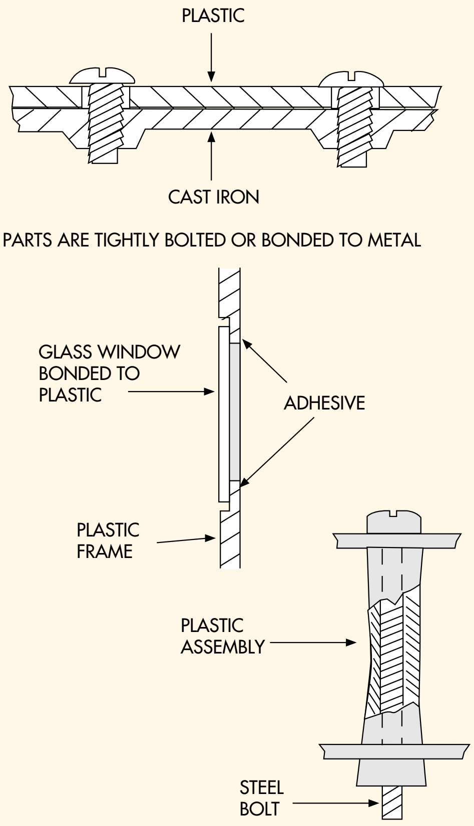
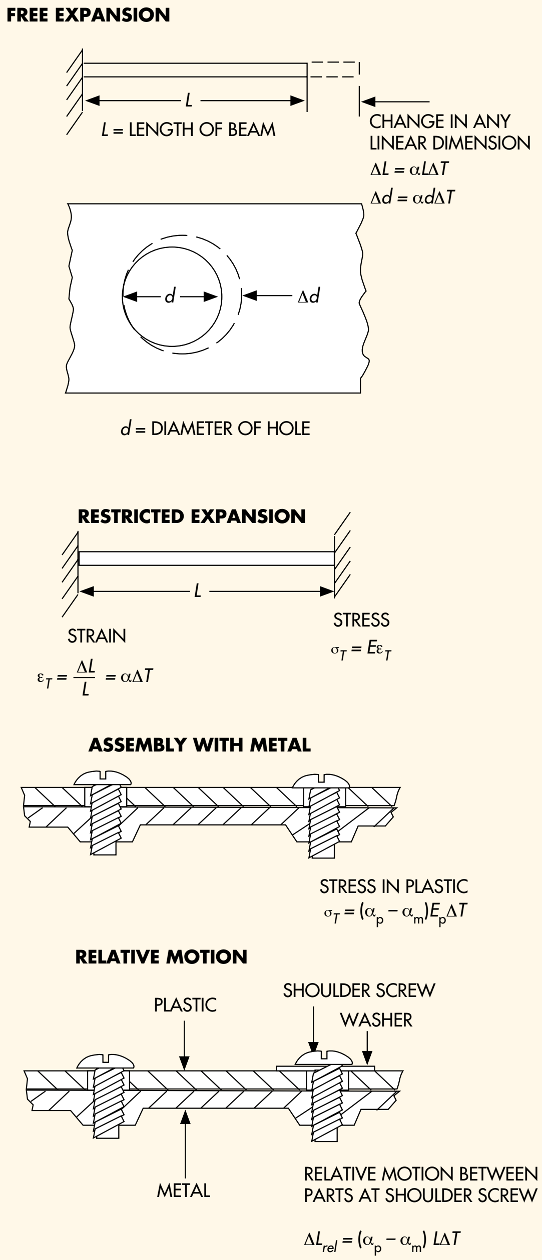


Fig 7.16 · Equations of thermal expansions for various conditions



8. Design Considerations for Injection Molded Parts

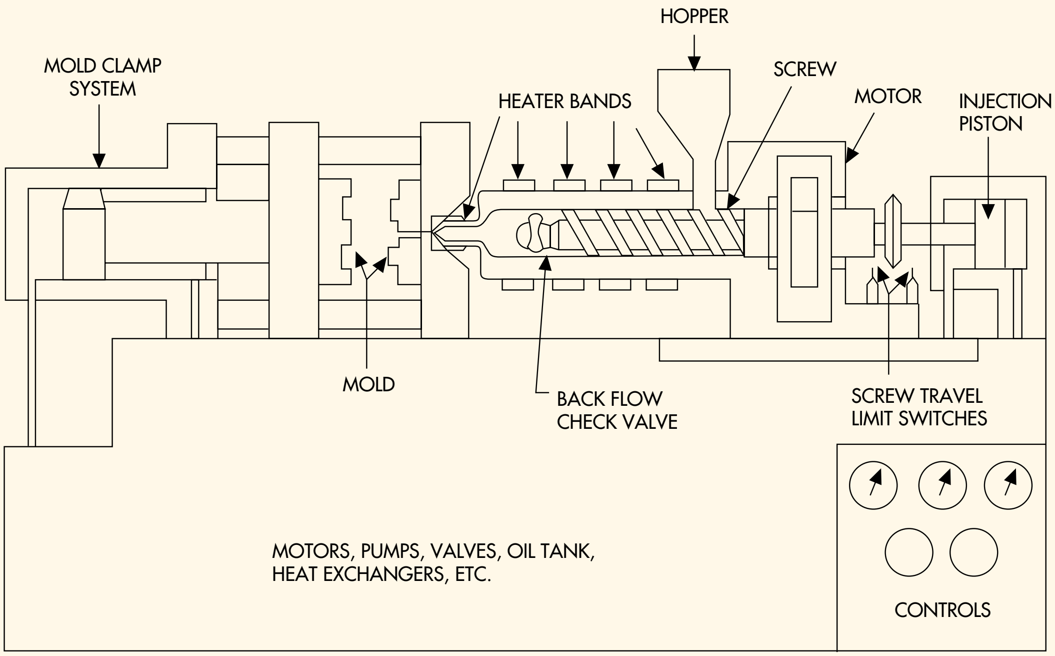
The most prevalent method for producing thermoplastic parts in large quantities is injection molding. This is a highly economical, efficient, and precise manufacturing method, which can be highly automated and produces almost no waste. It does, however, require expensive machinery and tooling. In addition, certain established geometric and other design considerations must be followed to consistently produce quality molded parts. These design considerations, or rules for injection-molded parts, are the subject of this chapter.

8.1 Injection Molding Process

A brief explanation of the injection molding process is useful at this point to help understand the importance of proper design (see Figure 8.01). The molder receives plastic resin in the form of small chopped pellets (usually 1/8 in. long). These are fed into the hopper of an injection molding machine, where they fall into an augur-type screw channel, which feeds the pellets forward inside the heated barrel. As the mass of plastic moves toward the front of the barrel, it is plasticized or melted. The screw is allowed to travel back until a sufficient quantity of molten plastic accumulates in front of the screw to fill the cavity in the mold. The screw is then pushed forward under high pressure to force the molten plastic through the machine nozzle into the closed mold. Once in the mold, the plastic flows through a distribution system called runners and then through gates into the part cavities. As soon as the plastic cools and solidifies in the mold cavity, the mold is opened and the part is removed.

The mold is usually heated or cooled to provide the proper temperature for plastic solidification. The mold also has some type of mechanical assist, called ejection, to help extract the part from the mold. While the part is cooling in the mold, the next shot is being plasticized within the barrel. The mold then closes and the process is repeated. Although this is a very elementary explanation of the injection molding process, it should be observed that the cooling time in the mold is usually the controlling factor in the total molding cycle time and, thus, a key factor in determining the production rate of the machine. An overly thick wall section, even in just a small portion of the part, can significantly lengthen the cooling time and hurt the overall economics of the part.

Fig 8.01 · Schematic of reciprocating screw injection molding machine



8.2 Design Strategy

In the design of any injection-molded part, the designer should strive for the following goals:

1. Maximize Functionality

Since injection molds are costly, the engineer should design as much function as possible into each part. This means that a single part may take the place of many individual separate parts, eliminating assembly operations, reducing weight, and frequently improving the overall structural integrity. Figure 8.02 illustrates this point by comparing a sheet metal electronics enclosure with a well-designed injection molded plastic replacement.

2. Optimize Material Selection

On the basis of the desired functionality of the part, the operating environment, cost constraints, and any special requirements, several candidate materials should be selected for the proposed part.

3. Minimize Material Use

The minimum volume of plastic that satisfies the structural, functional, appearance, and molding requirements of the application is usually the best choice. This contrasts sharply with machining operations, where one starts with a solid block of material and machines away until only the material necessary to make the part function remains. Figure 8.03 illustrates this contrast between a machined valve body and a properly designed injection molded, equally functional part.

The remainder of this chapter presents guidelines for implementing these goals.

8.3 Efficient and Functional Design

Injection molding should be considered when a new part is being redesigned or an existing part is redesigned. The key advantage is injection molding's ability to accurately and repeatedly produce multifunctional or complex molded plastic parts in a single, highly automated operation. Keeping this in mind during the initial planning stage, one should consider the following questions:

Fig 8.02 · Injection-molded one piece housing replaces fabricated sheet metal and many miscellaneous parts and eliminates most assembly operations

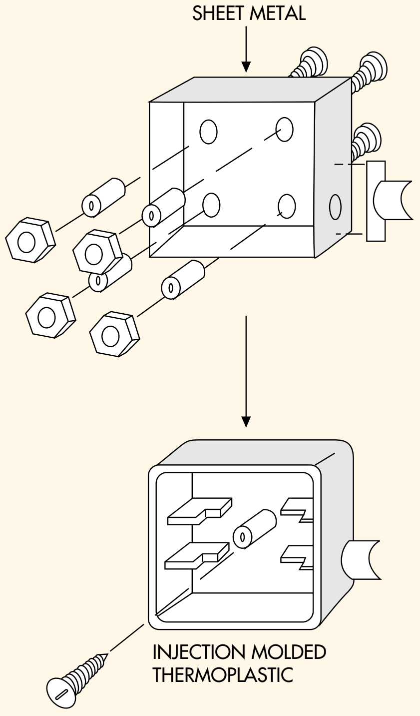
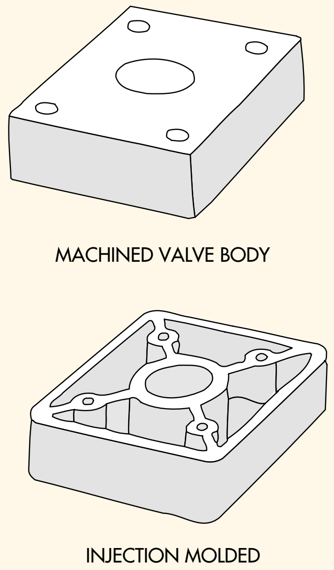


Fig 8.03 · Minimize material usage for plastic redesign



1 . If the product consists of more than one part, can they be combined into a single molded part, eliminating extra materials, molds, molding operations, and assembly procedures?

2. Can hardware items or other components be eliminated from the proposed part by integrating them with the molded part?

If the answer to either of the above questions is yes, more work is probably needed in planning the most efficient and cost-effective product. Of course, in some cases, trying to design multiple features into a single part or putting too much complexity into a part causes the tooling to be prohibitively expensive or the part too difficult to mold. This is especially true when the mold must open in many directions to eject the molded part. The product engineer must weigh the increased cost for a more complex tool against the cost savings per unit over the expected production volume.

8.4 Material Selection

The wide variety of injection moldable thermoplastic materials often makes selection of a plastic resin very difficult. The chosen material is often one used before or one that a molder, toolmaker, or material supplier recommends. Unfortunately, the person making the selection may not fully understand the requirements of the application or the properties of the plastic. Therefore, the material selected is not always optimal. The designer should carefully consider the following items, not necessarily in order of importance.

1. Temperature

Determine the capability of the plastic material to withstand the normal, as well as extreme, operating temperature of the product. Be sure to check shipping temperatures, sources of internal heat, and any assembly or finishing operations. Keep in mind that mechanical and electrical properties usually depend on temperature. (Consult Chapter 4 of this manual.)

2. Environment

Every substance, solid, liquid, or gas, that can come in contact with the plastic part over its expected life span must be considered for chemical compatibility. If the compatibility information is not obvious from the product literature, the engineer should consult the material supplier and request or conduct specific testing if necessary. (Consult Chapter 6 of this manual.)

3. Agency Approvals

Refer to the material product data sheets to ensure that the resin being considered meets the requirements of the end product. These approvals could include Underwriters Laboratories (UL), Canadian Standards Association (CSA), US Food and Drug Administration (FDA), National Sanitation Foundation (NSF), United States Department of Agriculture (USDA), a variety of Military Specifications, industry-specific requirements, and many others. Many of these approvals for any specific resin grade can depend on such factors as minimum wall thickness, color additives, fillers, and the operating temperature.

4. Assembly

Check to ensure that the proposed material lends itself to the expected assembly operations. For example, certain classes of materials are difficult to solvent bond, while others may not work well with ultrasonic methods. (Consult Chapter 9 of this manual.)

5. Finish

Determine whether plastic resin can be easily molded into the proposed product with the desired final appearance. If not, can the part be easily and economically finished? (Consult Chapter 10 of this manual.)

6. Cost

To determine the economics of using a particular resin, consider the cost per pound in the applicable color and purchase volume. In addition, look at the specific gravity and typical molding cycle times of the particular resin grade, since these affect the final molded part cost. The cost per unit volume of a particular plastic resin (or any material) is as follows:

$$\text{Cost/in.}^3 = 0.0361 \times \text{Specific Gravity} \times \text{Resin Cost/Pound}$$

The material cost of a part is obtained by multiplying the cost/cubic inch by the part volume. Finally, a very rough part cost estimate is obtained by doubling the material cost of the part.

7. Availability

Check to see that the chosen resin will be readily available in sufficient quantities when needed for production.

8.5 Nominal Wall Thickness

Of all the issues in plastic design, selecting the proper nominal wall thickness is probably the most important and all-encompassing topic. Just about every subject addressed in this manual somehow relates to, affects, or is influenced by the wall thickness. Choosing proper wall sections sometimes determines the ultimate success or demise of a product. While an inadequate wall section can lead to poor performance or structural failure, a section that is too heavy, even in just certain regions, can make the product unattractive, overweight, or too expensive. Although some problems can be corrected after the mold is built, such solutions are often expensive.

The following discussion on determining wall section thickness should help the design or production engineer eliminate potential problems on paper (or computer screen) rather than in tool steel. In many parts, only some of the guidelines can be followed due to geometric, structural, or functional requirements, but at least the potential existence of a particular problem is known in advance and remedial action can be planned. For example, if a surface defect is discovered to be likely to appear in a visible area during molding, a texture, logo, or label can be planned for that region.

8.5.1 Normal Ranges of Wall Thickness

Just as metals have normal working ranges of wall thicknesses based on their processing methods (ie., casting, bending, forging, and extruding), so do injection-molded plastics. The vast majority of injection-molded plastic parts probably range from 1/32 in. (0.80 mm) to 3/16 in. (4.8 mm), with the thickness within that range generally related to the total size of the part. That does not mean that parts cannot be molded to be thinner or thicker, or that a big part cannot be thin or a tiny part thick. However, these norms can act as a starting point for the design. Table 8.01 shows some general guidelines for various classes of thermoplastics.

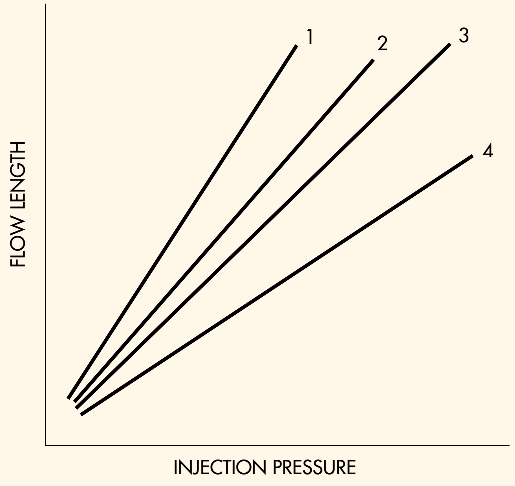
The design engineer should also refer to data related to the ability of a plastic resin to flow into the mold cavity. This information, usually shown in the form of spiral flow curves, gives a relative measure of how far one can expect the plastic resin to flow from the gate. Figure 8.04 shows some typical spiral flow curves.

Table 8.01 · Typical Nominal Thickness for Various Classes of Thermoplastics

Thermoplastic Resin Family	Typical Thickness Ranges (inches)
ABS, Acrylonitrile-Butadiene-Styrene	0.045 - 0.140
Acetal	0.030 - 0.120
Acrylic	0.025 - 0.150
Liquid Crystal Polymer	0.008 - 0.120
Long-Fiber Reinforced Plastics	0.075 - 1.000
Modified Polyphenylene Ether	0.045 - 0.140
Nylon	0.010 - 0.115
Polyarylate	0.045 - 0.150
Polycarbonate	0.040 - 0.150
Polyester	0.025 - 0.125
Polyester Elastomer	0.025 - 0.125
Polyethylene	0.030 - 0.200
Polyphenylene Sulfide	0.020 - 0.180
Polypropylene	0.025 - 0.150
Polystyrene	0.035 - 0.150
Polysulfone	0.050 - 0.150
Polyurethane	0.080 - 0.750
PVC, Polyvinyl Chloride	0.040 - 0.150
SAN, Styrene-Acrylonitrile	0.035 - 0.150

Fig 8.04 · Some typical spiral flow curves

1. Nylon 6/6
2. Thermoplastic polyester, PBT
   Liquid crystal — glass reinforced
   Polyphenylene sulfide — glass reinforced
3. Acetal copolymer
4. PBT — glass reinforced



8.5.2 Structural Requirements of the Nominal Wall

If a part is subjected to any significant loading, the load-bearing areas should be analyzed for stress and deflection. If the stress or deflection is too high, the following alternatives should be considered:

1 . Use ribs or contours to increase the section modulus. This is often the most economical solution and is discussed in detail in the structural reinforcement section.

2. Use a higher strength, higher modulus material.

3. Increase the wall section if it is not already too thick.

8.5.3 Insulation Characteristics of the Nominal Wall

Plastic materials are good insulators for electrical and heat energy. They can also serve as barriers and filters for sound and light. In general, insulating ability is directly related to the thickness of the plastic. In the case of sound transmission, change in thickness may be needed to change the resonant frequency of a plastic housing (Consult Chapter 5 of this manual for electrical properties.)

8.5.4 Impact Response of the Nominal Wall

The impact resistance of a particular part is directly related to its ability to absorb mechanical energy without fracture or plastic deformation. This, in turn, depends on the properties of the plastic resin and the geometry of the part. Increasing wall thickness generally improves the impact resistance of molded parts. However, increased wall thickness could hurt impact resistance by making the part overly stiff, unable to deflect and distribute the impact. Both of these methods of absorbing impact energy should be examined when the nominal wall thickness is being selected.

8.5.5 Agency Approvals and the Nominal Wall

When materials are recognized for flammability, heat resistance, electrical properties, or other characteristics by agencies, these ratings are usually based on a certain wall thickness. When agency approvals are important, the design engineer may be locked into a thicker wall section than would be necessary for mechanical purposes.

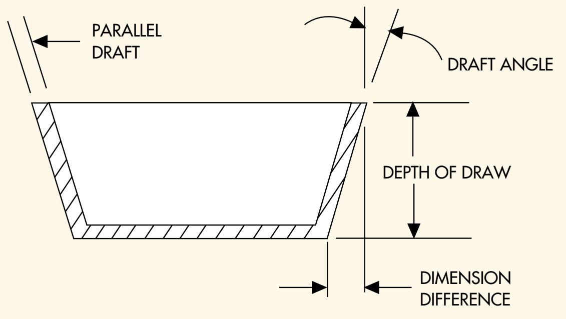
8.6 Draft

On most molded parts, some part features must be cut into the surface of the mold perpendicular to the parting line. To properly release an injection-molded part from the tool, plastic parts are almost always designed with a taper in the direction of mold movement. This is commonly referred to as draft in the line of draw. This allows the molded part to break free by creating a clearance as soon as the mold starts to open. Since plastic materials shrink as they cool, they grip cores (male parts) of the mold very tightly. Without sufficient draft, normal ejection from the mold can be difficult. Although exceptions occur, a draft of 1/2° per side is considered a minimum, with 1.5-3° per side being frequently recommended.

Table 8.02 · Dimensional Difference versus Draft Angle Dimensional Change in Inches* for Various Draft Angles and Draw Depths

	Draft Angle (degrees)							
Draw Depth (inches)	1/8	1/4	1/2	1	2	3	4	5
1	0.002	0.004	0.009	0.017	0.035	0.052	0.070	0.087
2	0.004	0.009	0.017	0.035	0.070	0.105	0.140	0.175
3	0.007	0.013	0.026	0.053	0.105	0.157	0.210	0.263
4	0.009	0.018	0.035	0.070	0.140	0.210	0.280	0.350
5	0.011	0.022	0.044	0.087	0.175	0.262	0.350	0.437
6	0.013	0.026	0.052	0.105	0.209	0.314	0.420	0.525
7	0.015	0.031	0.061	0.123	0.244	0.367	0.490	0.612
8	0.018	0.035	0.070	0.140	0.279	0.419	0.559	0.700
9	0.020	0.040	0.078	0.158	0.314	0.472	0.629	0.787
10	0.022	0.044	0.087	0.175	0.379	0.524	0.669	0.875

Fig 8.05 · Illustration of draft and associated dimension change with draft angle



The required amount of draft depends on the surface finish on the mold. A highly polished mold requires less draft than an unpolished mold, and any surface texture increases the draft required by at least 1° per side for every 0.001 in. depth of texture. When deep draws are required with only minimal draft, the product engineer should consult with a toolmaker and molder to see if the part can be properly ejected. Sometimes special mold surface treatments or regular application of mold release spray is necessary during production.

Figure 8.05 and Table 8.02 provide a quick reference for determining the amount of dimensional change required due to the draft angle. A general rule of thumb used by designers and toolmakers is:

1° of draft yields 0.017 inches of taper per inch length.

One of the difficulties encountered when draft is applied to a part is the creation of very heavy walls. Sometimes these conditions can be remedied by the use of parallel draft as shown in Figure 8.05. With parallel draft, the wall sections can be kept uniform.

8.7 Structural Reinforcement

To increase the load-carrying ability or stiffness of a plastic structure, an increase is required either in the properties of the plastic material or in the section properties of the structure. Improving the material, by changing grade or by going to a glass-reinforced version of the same material, is sometimes adequate, but is often not practical or economical. Increasing the section properties, i.e., the moment of inertia and the section modulus, is usually necessary. As previously discussed, thickening wall sections is often a practical means of increasing section properties, but economic limitations can exist in terms of material use and molding cycles. The relative effect on load-carrying capacity (maximum allowable stress) and stiffness (maximum allowable deflection) for material changes and wall section changes are shown in Figure 8.06.

8.7.1 Ribs

If sufficient space is available, the use of ribs is a practical and economical means of increasing the structural integrity of injection-molded plastic parts without creating thick walls. The efficiency of a ribbed structure can be seen in the following example. Consider the loaded beam shown in Figure 8.07 to be a simplification of a section of an actual plastic housing subjected to a concentrated load of 5 lbs.

Fig 8.06 · Interaction of wall thickness, load, stress, and deflection for a rectangular cross-section in bending

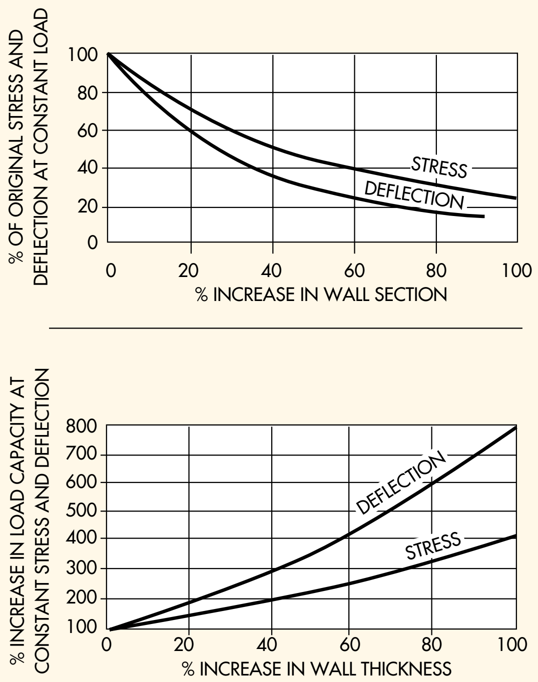
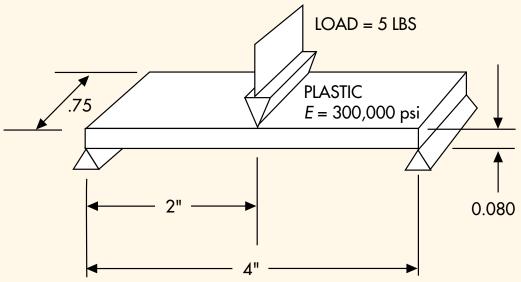


Fig 8.07 · Example of the effect of ribs on rectangular cross-section



Based on a constant wall section of 0.080 in., the maximum stress is calculated to be 6250 psi, and the maximum deflection, if the flexural modulus is 300,000 psi, is calculated at 0.694 in. It is determined that both the stress and deflection are far too high and, thus, unacceptable for the plastic resin chosen. To reinforce the structure, a 0.040 in. wide by 0.400 in. high rib with 1/2° draft per side is added to the underside of the part. By use of the new section properties, the calculated stress drops to 2273 psi and the deflection drops to 0.026 in., which is now deemed acceptable for both the resin and the application. To achieve the same reduction in deflection by thickening walls alone, the wall thickness would be an uneconomical 0.239 in. thick. Besides being impractical to injection mold, the added thickness would triple the weight of the part. By contrast, the rib only adds 25% to the total section weight. Table 8.03 shows a summary of the results of this example.

Although the use of ribs gives the design engineer great latitude in efficiently tailoring the structural response of a plastic part, the use of ribs can result in warping and appearance problems. In general, experienced design engineers do not use ribs if there is doubt as to whether they are structurally necessary. Adding ribs after the tool is built is usually simple and relatively inexpensive since it involves removing steel.

Certain basic guidelines should be followed. The most general is to make the rib thickness at its base equal to one-half the adjacent wall thickness. With ribs opposite appearance areas, the width should be kept as thin as possible. In areas where structure is more important than appearance, or when dealing with very low shrinkage materials, ribs are often 75%, or even 100%, of the outside wall thickness. As seen in Figure 8.08, a goal in rib design is to prevent formation of a heavy mass of material that can result in a sink, void, distortion, long cycle time, or any combination of these problems.

All ribs should have a minimum of 1/2° of draft per side and should have a minimum radius of 0.005 in, at the base. Generally, the draft and thickness requirements limit the height of the rib. Therefore, multiple, evenly spaced ribs are preferred to single, large ribs. Wherever possible, ribs should be smoothly connected to other structural features such as bosses, side walls, and component mounting pads. Ribs need not be constant in height or width and are often matched to the stress distribution in the part.

Table 8.03 · Summary of the Effect of Rib and Cross-Section change in example, Figure 8.07

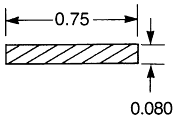
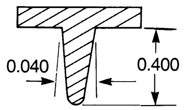
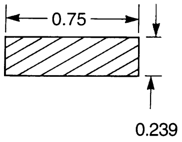
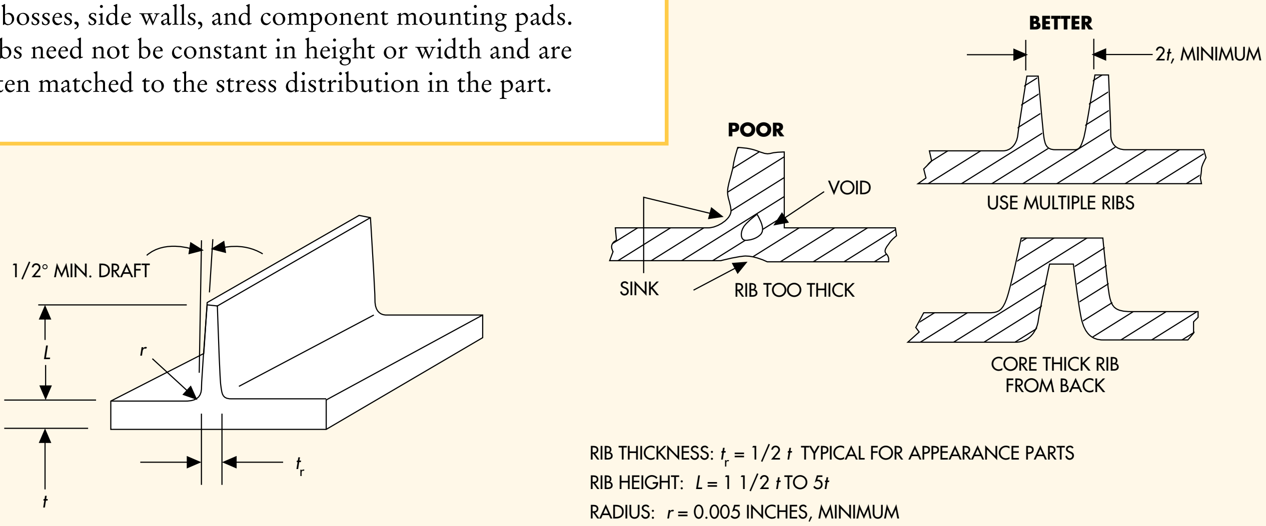
Geometry	Cross-Section Area (square inches)	Max. Stress (psi)	Max. Deflection (inches)
 ORIGINAL SECTION	0.0600	6250	0.694
 ORIGINAL SECTION WITH RIB	0.0746	2273	0.026
 THICK SECTION	0.1793	699	0.026

Fig 8.08 · Rib design for reinforcing thermoplastic parts



RIB THICKNESS: t_r = 1/2 t TYPICAL FOR APPEARANCE PARTS
RIB HEIGHT: L = 1 1/2 t TO 5t
RADIUS: r = 0.005 INCHES, MINIMUM

8.7.2 Other Geometric Reinforcement

Besides ribs, there are other acceptable methods of improving section properties. Many of these can often be worked into functional or appearance features of the part. Some typical examples are shown in Figure 8.09.

8.8 Bosses

Bosses and other projections from the nominal wall are commonly found in injection-molded plastic parts. These often serve as mounting or fastening points. Figure 8.10 shows some typical boss designs along with common problems. As with rib design, avoiding overly thick wall sections is important for minimizing the chance of appearance or molding problems. When bosses are designed to accommodate self-tapping screws, the inside diameter and wall thickness must be controlled to avoid excessive buildup of hoop stresses in the boss. Ribs are frequently used in conjunction with bosses when lateral forces are expected. Special care must be used with tapered pipe threads, since they can create a wedging action on the boss. If there is a choice, the male rather than the female pipe thread should be the one molded into the plastic.

8.9 Coring

The term coring in injection molding refers to the addition of steel to the mold for the purpose of eliminating plastic material in that area. Usually, coring is necessary to create a pocket or opening in the part, or simply to reduce an overly heavy wall section (see Figure 8.11). For simplicity and economy in injection molds, cores should be parallel to the line of draw of the mold. Cores placed in any other direction usually create the need for some type of side action (either a cam or hydraulic cylinder) or manually loaded and unloaded loose cores.

Blind holes in molded plastic parts are created by a core supported by only one side of the mold. The length of the core and depth of the hole are limited by the ability of the core to withstand the bending forces produced by the flowing plastic without excessive deflection. For this reason, the depth of a blind hole should not exceed three times its diameter or minimum cross-sectional dimension. For small blind holes with a minimum dimension below 1/2 in., the L/d ratio should be kept to 2. With through holes, the cores can be longer since they are supported by the opposite side of the mold cavity. Sometimes the cores can be split between the two sides and interlocked when the mold is closed, allowing long through holes to be created. With through holes, the overall length of a given size core generally can be twice as long as that of a blind hole. Sometimes even longer cores are necessary. The tool can be designed to balance the hydraulic pressure on the core pin, thus limiting the deflection.

Fig 8.09 · Modifications to nominal wall to improve structural response

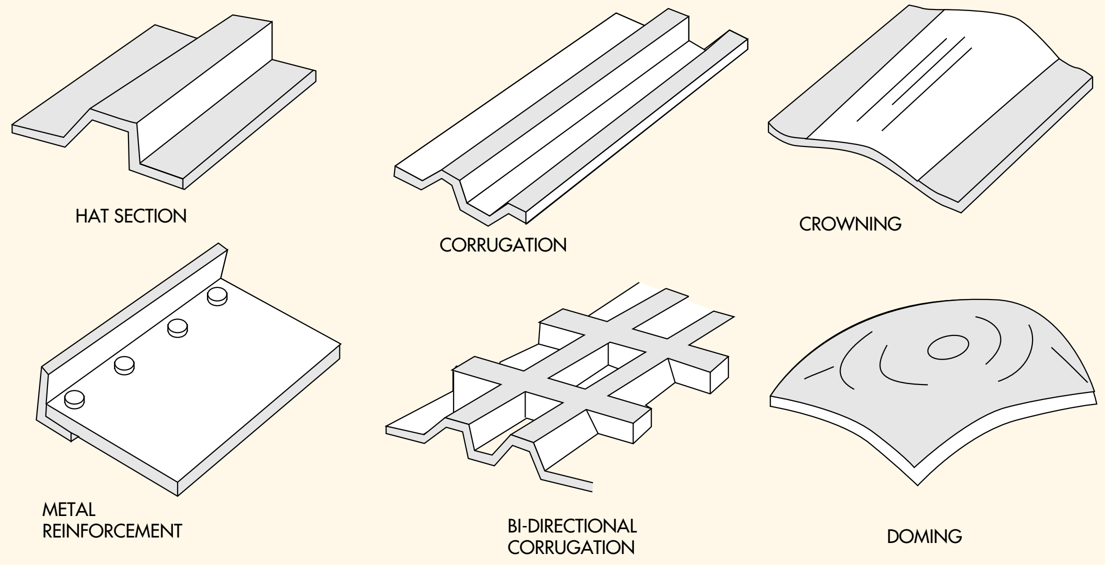


Fig 8.10 · Design of bosses

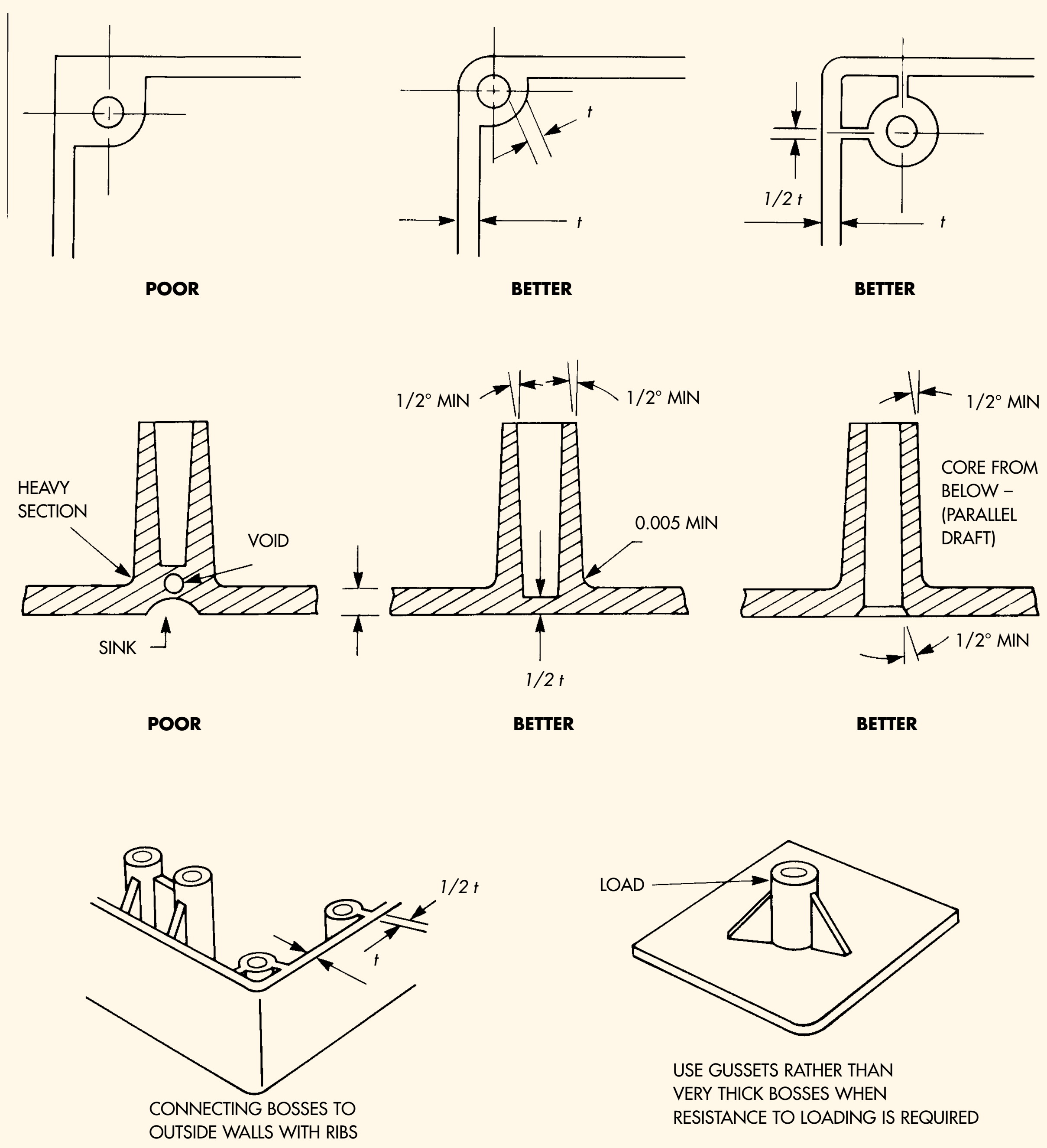
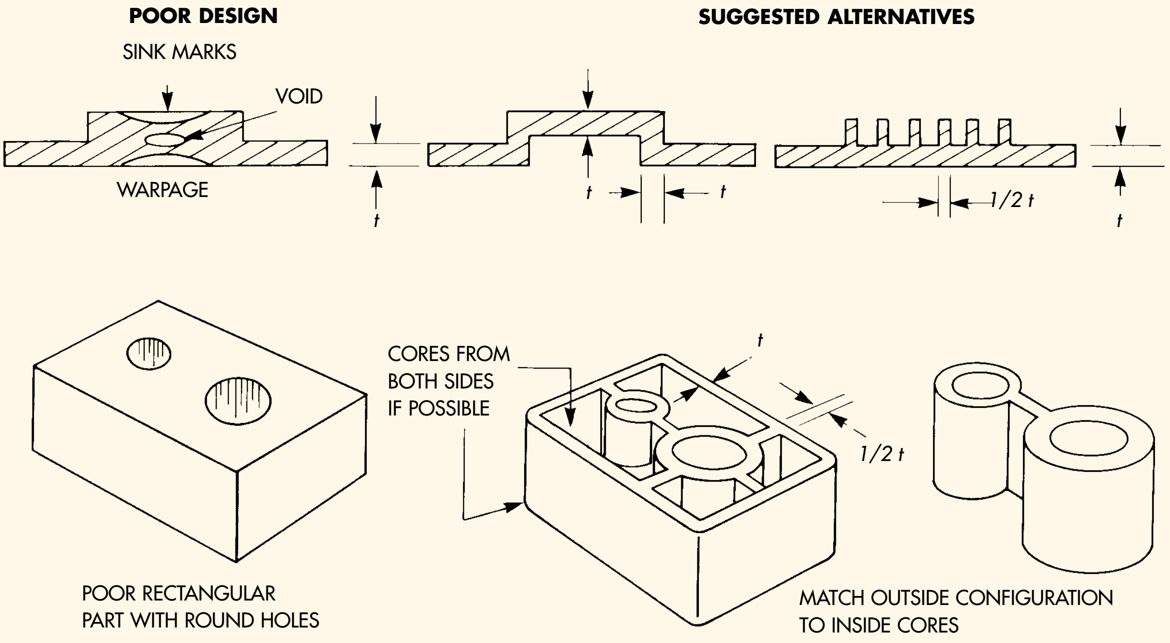


Fig 8.11 · Coring examples

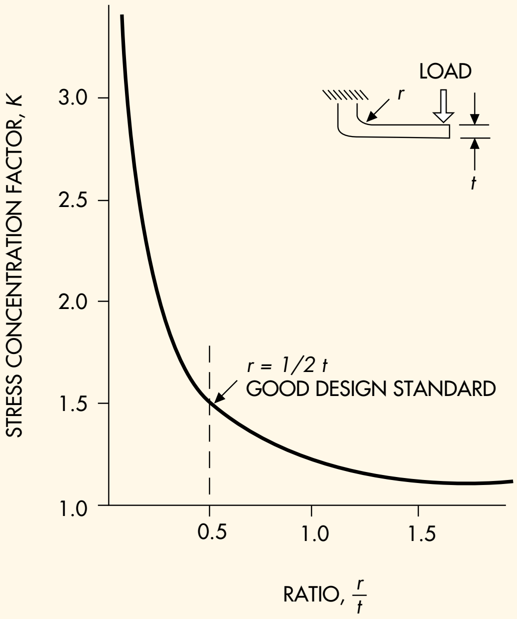


8.10 Fillets and Radii

In the design of injection-molded parts, sharp corners should always be avoided. Although sharp corner designs are common with sheet metal and machined parts, good design practice in any material dictates the use of generous radii to reduce stress concentrations. Metal parts often tolerate sharp corners. Either the stresses at the corners are very low compared to the strength of the material or localized yielding redistributes the load. Neither of these phenomena is reliable in injection-molded parts. Sharp corners, particularly inside corners, cause poor flow patterns, reduced mechanical properties, and increased tool wear, as well as severe molded-in stresses as the material shrinks onto the corner.

Besides molding problems, sharp corners are often the cause of premature failure in plastic parts due to the stress concentration. To avoid these problems, inside corner radii should be equal to half of the nominal wall thickness. A 0.020 in. radius is considered a minimum for parts subjected to stress, and a 0.005 in. minimum for stress-free regions of a part. Inside radii less than 0.005 in. are not recommended for most materials. Outside corners should have a radius equal to the inside corner plus the wall thickness. Figure 8.12 dramatically shows how the radius/thickness ratio affects stress concentration factors.

Fig 8.12 · Typical stress concentration factor



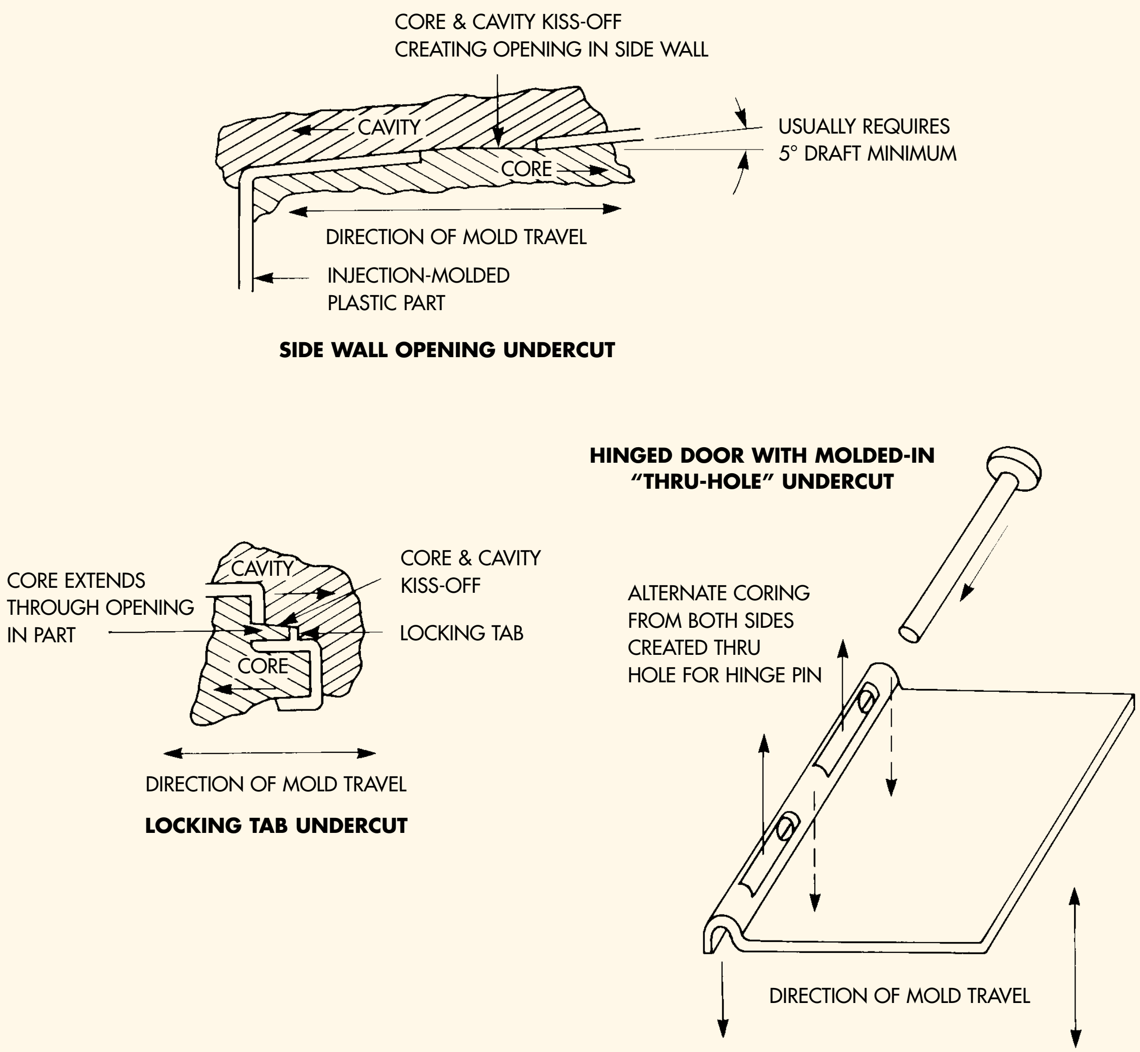
TO FIND STRESS DUE TO SMALL RADIUS, MULTIPLY CALCULATED BENDING STRESS BY *K*

With an inside radius equal to half of the nominal wall, a stress concentration of 1.5 is a reasonable assumption. For radii down to about 10% of the nominal wall, a stress concentration of 3.0 is a good first approximation. Standard tables of stress concentration factors should always be consulted for critical applications.

8.11 Undercuts

Ideally, plastic parts are designed so that the mold can open easily, and eject the molded part without any part of the tool needing to open in any direction other than parallel to the movement of the machine platen. Some complex parts require other mechanical movement known as side actions, side coring, cams, pullers, collapsing cores, loose cores, etc., but certain design techniques can achieve the desired geometry with simple tooling. Figure 8.13 shows some examples of these techniques.

Fig 8.13 · Creating "undercuts" with simple tooling



SIDE WALL OPENING UNDERCUT

HINGED DOOR WITH MOLDED-IN "THRU-HOLE" UNDERCUT

LOCKING TAB UNDERCUT

9. Assembly

One of the goals in plastic product design is to eliminate as much assembly as possible by combining components and building as much function as possible into the design. However, most applications for plastics do require some assembly, and many methods, which can be broken down into the following general categories, are available to the designer:

9.1 General Types of Assembly Systems

1. Molded-in Assembly Systems
Molded-in assembly systems are generally economical methods of assembly, since no additional fastener, adhesive, solvent, or special equipment is required. Examples are snap-fit, press-fit, pop-on, and molded-in threads. Key advantages of these methods are that assembly is fast and inexpensive, and does not require additional parts or substances. They also effectively minimize the chances of improper assembly, since the proper fits can be fine tuned into the tooling. The key disadvantage is that the tooling can be complex and expensive, and some of the methods may not be suitable for parts that need to be disassembled.

2. Chemical Bonding Systems
Chemical bonding systems require no additional fasteners, but they do require chemical substances, fixtures, and usually safety equipment. These methods use solvents and adhesives to create a joining of similar and dissimilar materials, and are well suited to applications where a liquid or gas seal is required and where the use of fasteners would create a problem. Furthermore, these joining methods generally do not create assembly stresses. Disadvantages of such systems are that adhesives or solvents could be toxic and dangerous, and must be properly matched to the particular grades of plastic or other materials being joined. In addition, preparation and cure times could be time consuming, depending on the system used.

3. Thermal Welding Methods
Thermal welding methods generally require no chemicals or joining materials, but do require specialized equipment. With the right equipment, assembly is fast, economical and generally considered safer than chemical methods. The most commonly used method is ultrasonic welding. Others include thermal welding methods such as hot plate, spin, vibration, induction, and radio frequency welding. All of these methods depend on the interface or bond line between the two parts melting sufficiently to create a weld between the two parts. These thermal methods are also used for staking, swaging, and with other methods using heat deformation to assemble components. A limitation of these methods is that the materials being welded must be compatible and have similar melting temperatures.

4. Assembly with Fasteners
Most of the mechanical fasteners used with metals can be successfully used with plastics. In addition, a multitude of fasteners are specifically designed for use with particular types of thermoplastics. Necessary equipment ranges from simple hand tools to sophisticated automatic machinery. Typical methods include bolted assemblies, self-tapping screws, rivets, threaded inserts, spring clips, and any other mechanical devices that join parts together. The key advantages of these mechanical fasteners is that they are readily available, easy to use, do not require complex tooling or special preparation, and most allow for simple nondestructive disassembly. Disadvantages are that extra parts must be stocked, and care must be taken to prevent the assembled parts from becoming overstressed. Furthermore, creep can result in loss of pre-load if poorly designed.

Many plastic assemblies employ a combination of methods. The most notable example is ultrasonic injection used to install a threaded insert that engages a machine screw. Other examples are the use of elastomeric adhesives to create an air-tight seal in a bolted assembly and solvents used to facilitate or strengthen a snap-fit or interference fit assembly. This section examines the various methods used with thermoplastics and presents specific guidelines for their use.

9.1.1 Molded In Assembly Systems

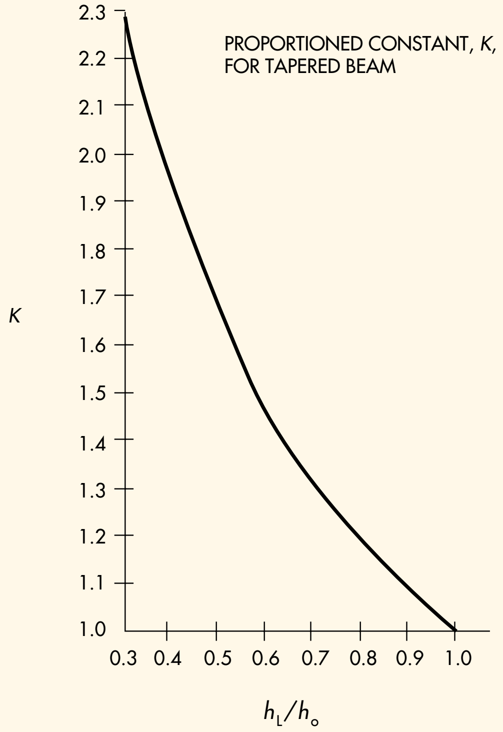
9.1.1.1 Snap-Fit Assembly

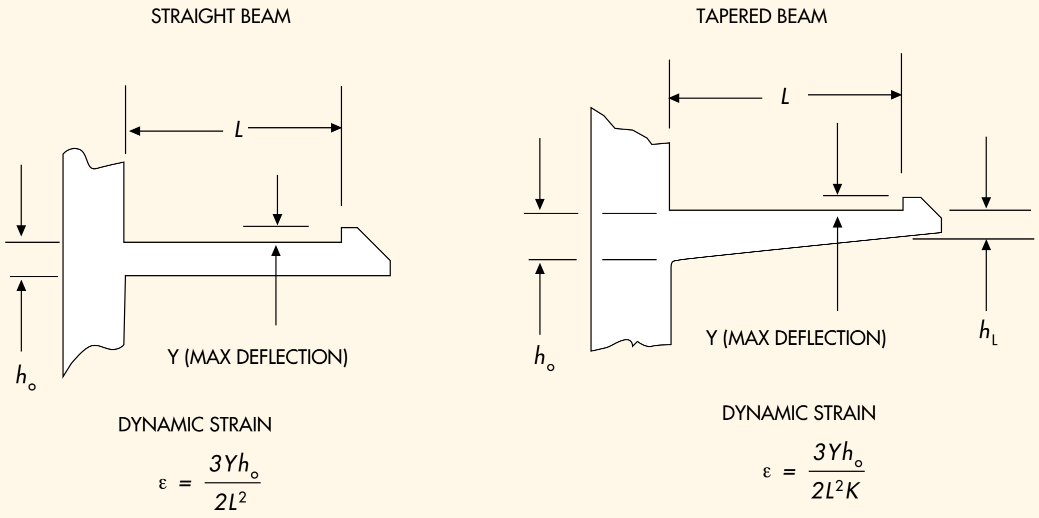
For high-volume production, molded-in snap-fit designs provide economical and rapid assembly. In many products, such as inexpensive housewares or hand-held appliances, snapfits are designed for only one assembly without any nondestructive means for disassembly. Where servicing is anticipated, provision is made to release the assembly with a tool. Other snap-fit designs, such as those used in battery compartment covers for calculators and radios, are designed for easy release and reassembly over hundreds or even thousands of cycles.

In all snap-fit designs, some portion of the molded part must flex like a spring, usually past a designed-in interference, and quickly return, or nearly return, to its original position to create an assembly between two or more parts. The key to successful snap-fit design is having sufficient holding power without exceeding the elastic or fatigue limits of the material.

Figure 9.01 shows a typical snap-fit design. Using the beam equations, we can calculate the maximum stress during assembly. If we stay below the yield point of the material, the flexing finger returns to its original position. However, for certain designs there is not enough holding power due to low forces or small deflections. With many plastic materials, the calculated bending stress can far exceed the yield point stress if the assembly occurs rapidly. In other words, the flexing finger just momentarily passes through its maximum deflection or strain, and the material does not respond as if the yield stress has been greatly exceeded. Thus, a common way to evaluate snap-fits is by calculating strain rather than stress. Compare this value with the allowable dynamic strain limit (if available) for the particular material. In designing the finger, it is extremely important to avoid any sharp corners or structural discontinuities, which can increase stress. A tapered finger provides a uniform stress distribution and is advisable where possible.

Fig 9.01 · Snap-fit design for cantilever beam with rectangular cross section





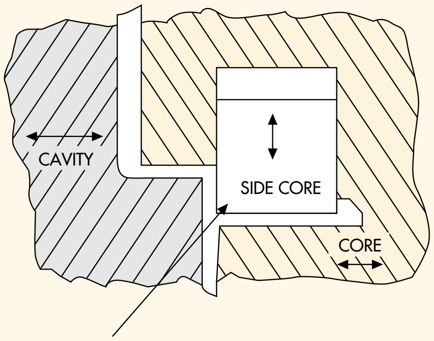
$$\varepsilon = \frac{3Yh_o}{2L^2}$$

$$\varepsilon = \frac{3Yh_o}{2L^2K}$$

Since the snap-fit generally requires an undercut, a mold with side action is frequently required, as shown in Figure 9.02A. Figure 9.02B shows an alternative that works well when an opening at the base of the flexing finger is acceptable. In certain cases, the snap-finger can simply be popped off the mold.

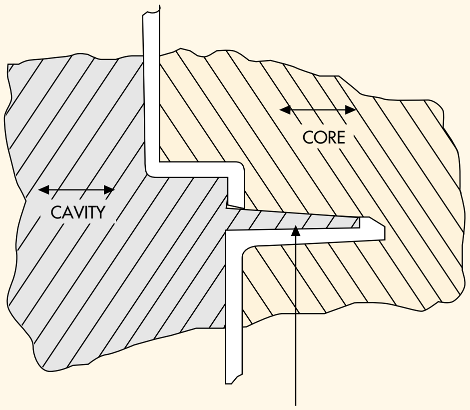
Another type of snap-fit assembly system, which can sometimes be molded into the part, is known as snap-on or snap-in. It is used most often on round parts. Often larger portions of the part or even the entire part flexes, but the deflections are usually very small. Figure 9.03 shows a typical example of a snap-on assembly.

Fig 9.02 · Tooling for snap-fit fingers



SIDE CORE MOVES DOWN TO MOLD UNDERCUT, AND IS ACTIVATED UP TO ALLOW MOLD TO OPEN

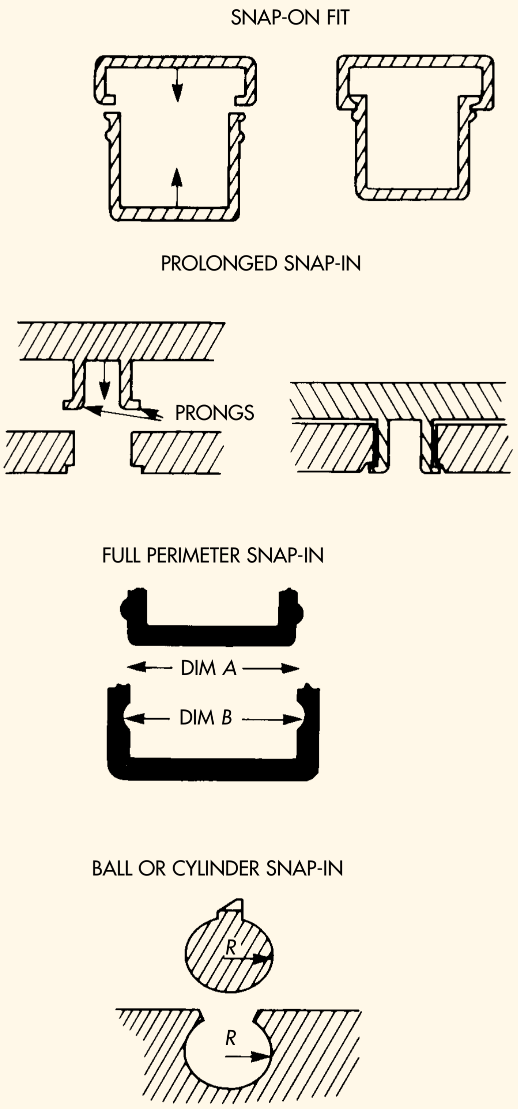
A) MOLDING SNAP-FIT FLEXING FINGER WITH MOLD USING SIDE CORE



PROJECTION FROM CAVITY, THROUGH PART, AND MATING WITH CORE FORMS UNDERCUT WITHOUT NEED FOR SIDE CORE. IT DOES, HOWEVER, LEAVE SMALL "WINDOW" OR OPENING IN MOLDED PART.

B) MOLDING SNAP-FIT FLEXING FINGER WITHOUT SIDE CORE

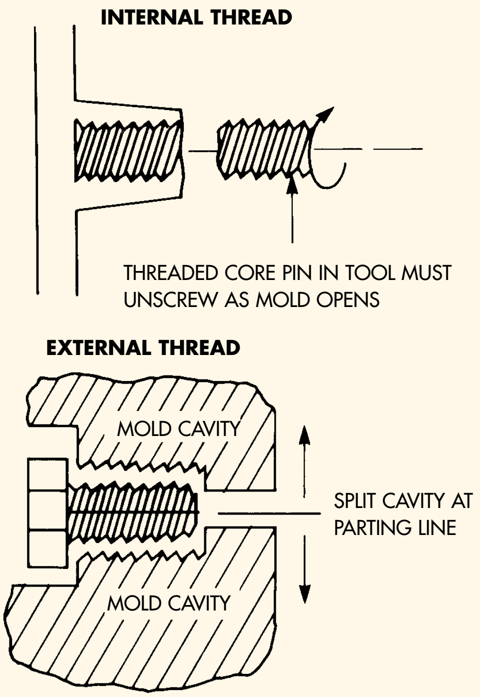
Fig 9.03 · Snap-on / Snap-in fits



9.1.1.2 Molded-in Threads

In this type of assembly, mating male and female threads are molded into the parts to be assembled (Figure 9.04). Molded internal threads usually require some type of unscrewing or collapsing mechanism, which complicates the tooling. Many external threads can be molded by splitting them across the parting line, as shown. The most common applications for molded threads are in containers and caps, molded plastic hardware, and liquid handling applications. Molding very fine threads, greater than 28 pitch, is usually not practical.

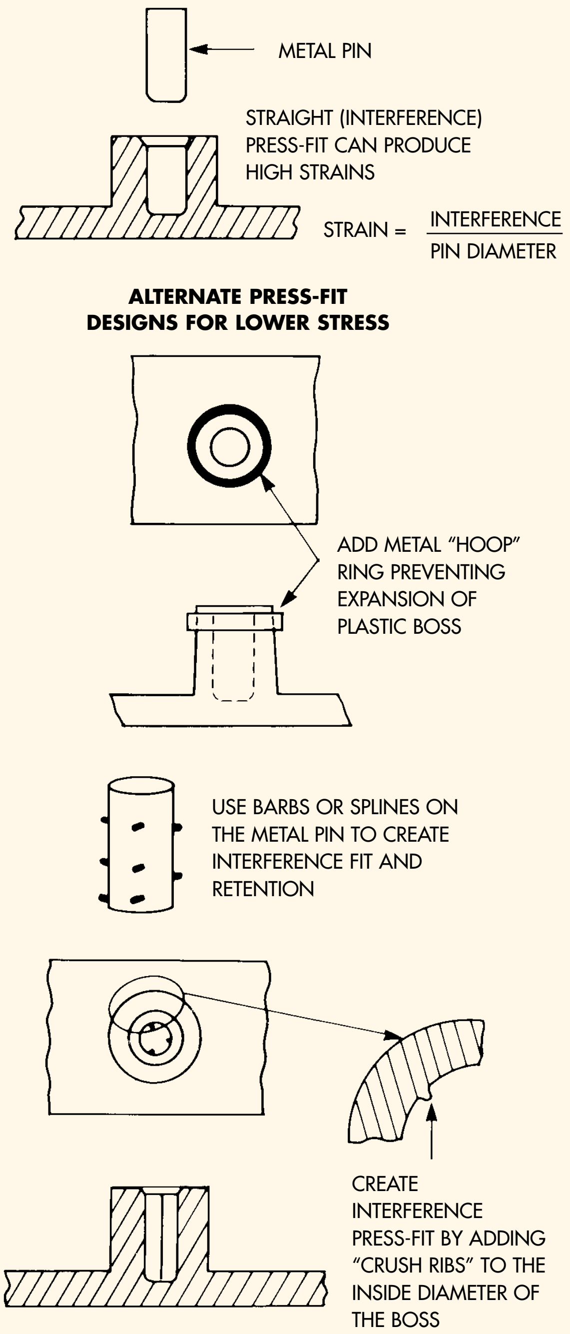
Fig 9.04 · Molded plastic threads



9.1.1.3 Press-Fits

In a press-fit assembly, parts or components of a material are assembled to a plastic part, using interference fits to maintain the assembly. The main advantage of this system is that the tooling is kept relatively simple, however the method can create very high stresses in the plastic part. The consequences of this stress depend on many factors, such as temperature during and after assembly, modulus of the mating material, type of stress, use environment, and probably most important, the type of material being used. Some materials creep or stress relax, while others fracture or craze if the strain is too high. Except for very light press-fits, this type of assembly can be very risky due to the hoop stress in the boss, which might already be weakened by a knit-line. Figure 9.05 presents alternative methods of designing press-fits that have a lower risk of failure.

Fig 9.05 · Alternative press-fit designs for metal pins in plastic hub



9.1.2 Chemical Bonding Systems

9.1.2.1 Solvent Welding

This is a fast and economical method for joining like or similar types of plastics. The principle involved is to apply a substance, usually a liquid solvent, to dissolve the surfaces of the joint areas sufficiently to allow the parts to be joined in a true weld after the solvent evaporates. The key advantages of this method are that it is inexpensive and requires little or no part preparation or special equipment.

Of course, the use of solvent bonding is limited to materials that are compatible and dissolve in the same solvent or combination of solvents. The chemical resistance of many plastic resins, particularly crystalline resins, limits the applicability of this method.

The key limitation of solvent welding, in applications where it is otherwise suitable, is the requirement for precautions in handling the solvents. Strict regulations must be observed regarding worker protection, ventilation, and solvent recovery.

9.1.2.2 Adhesive Bonding

This method differs from solvent welding in that a third substance, which has suitable adhesion to both parts being joined, is introduced at the interface of both parts. This third substance, called an adhesive, is capable of joining plastics together with other plastics, metals, rubber, ceramics, glass, wood, or any other bondable surface.

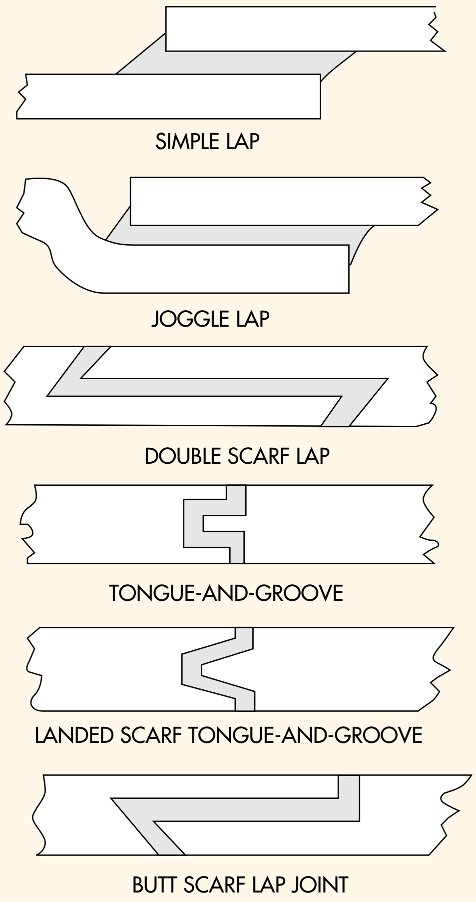
Adhesives frequently recommended for use with thermoplastics are epoxies, acrylics, polyurethanes, phenolics, rubbers, polyesters, vinyl, and many others, depending on the plastic being used. Because of their rapid adhesion to many materials, cyanoacrylates have become very popular in plastic assemblies. Specific adhesive recommendations can be obtained from both the plastic and adhesive suppliers. However, the designer must test the performance of the joint in the actual end-use environment.

Many adhesive systems also use solvents that partially dissolve the plastic surface, thus improving adhesion. It is important to check for compatibility since some adhesives can strongly attack certain plastics and lead to part deterioration and failure.

The key disadvantages of adhesive bonding are that it is generally slow, requires longer clamp times, often requires more fixtures, and sometimes special ovens or curing conditions are necessary. Furthermore, surface preparation can be critical since any contamination such as grease, oil, mold release, or even fingerprints can spoil a bond. With many hard to bond materials, the surfaces must be mechanically roughened or chemically etched to allow the adhesive to gain a firm grip.

Figure 9.06 shows typical joint designs used for both solvent and adhesive bonding.

Fig 9.06 · Typical joint designs for solvent and adhesive bonding



9.1.3 Thermal Welding Methods

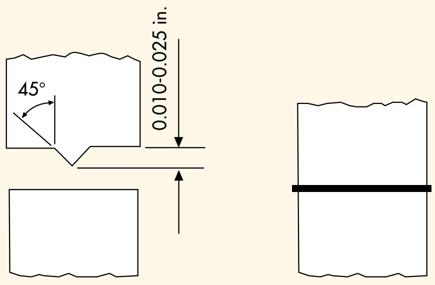
9.1.3.1 Ultrasonic Welding

Ultrasonic welding is an economical method for joining small- to medium-sized plastics parts to parts of the same or similar plastic material. This technique is very rapid and can be fully automated. Welding occurs when high-frequency (20-40 kHz) vibrational energy is directed to the interface between the two parts. This creates localized molecular excitation, causing the plastic to melt. Pressure is maintained between the two parts after vibrations stop, and the melted resin immediately solidifies. The entire welding process normally takes place in less than 2 seconds and has high strength, sometimes approaching the strength of the base material itself, provided the joint design is correct and equipment is properly set. Figure 9.07 illustrates typical ultrasonic welding equipment.

The principle involved in ultrasonic joint design is to concentrate the energy in an initial small contact area, creating rapid melting and melt flow, which progresses along the joint as the parts are pressed together. The bottom of the plastic part is held rigidly in a specially made nest. The top part is properly aligned with the bottom, usually by the joint design, but has freedom to couple acoustically when contacted by the horn, which transmits the ultrasonic energy.

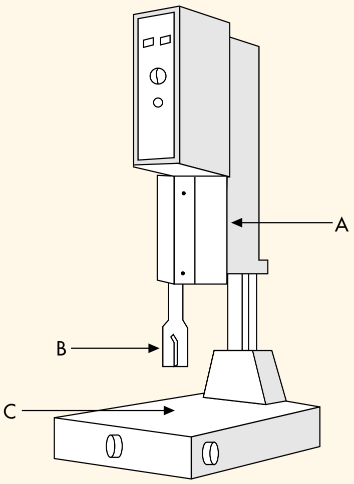
Figure 9.08 illustrates a basic shear/interference joint both before and after welding. Melting starts at the small initial contact area, and melt flow continues along the vertical wall as the parts telescope together, creating a continuous, leakproof joint whose strength often exceeds that of the parts being joined. This joint design is preferred with liquid crystal polymers and with crystalline materials such as nylon, acetal, and thermoplastic polyester and for any material where high strength and a hermetic seal are required.

Fig 9.09 · Basic energy director joint design



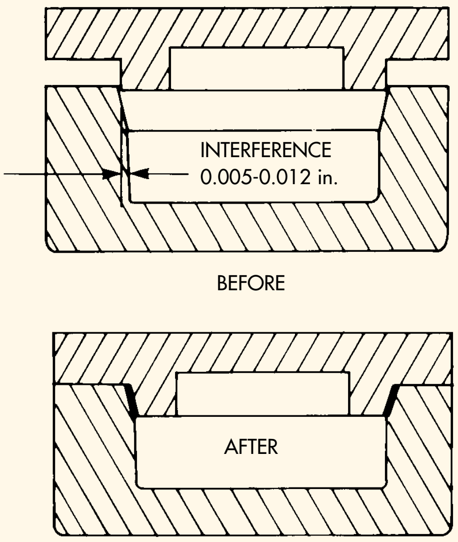
Before Weld
After Weld

Fig 9.07 · Typical ultrasonic welding equipment



(A) Ultrasonic assembly stand
(B) Horn
(C) Work piece area

Fig 9.08 · A basic shear/interference joint



The simple butt/energy director design that works very well with amorphous materials is shown in Figure 9.09 (also see Fig. 9. 10A). Before joining, a V-shaped projection, known as an energy director, concentrates the ultrasonic energy in a small area, which quickly melts and creates a melt flow as the parts are pressed together.

Figure 9.10 shows some typical joint designs commonly used with injection-molded thermoplastic parts. Exact dimensions vary with the material used, equipment available, and part requirements. Both plastic resin suppliers and ultrasonic equipment manufacturers offer literature and design assistance with equipment, fixtures, horns, part configuration, joint design settings, cycle times, and worker protection. They should be consulted during the part design process.

Fig 9.10A · Energy director

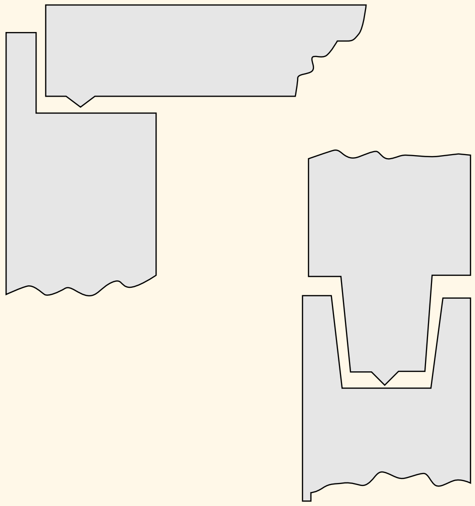
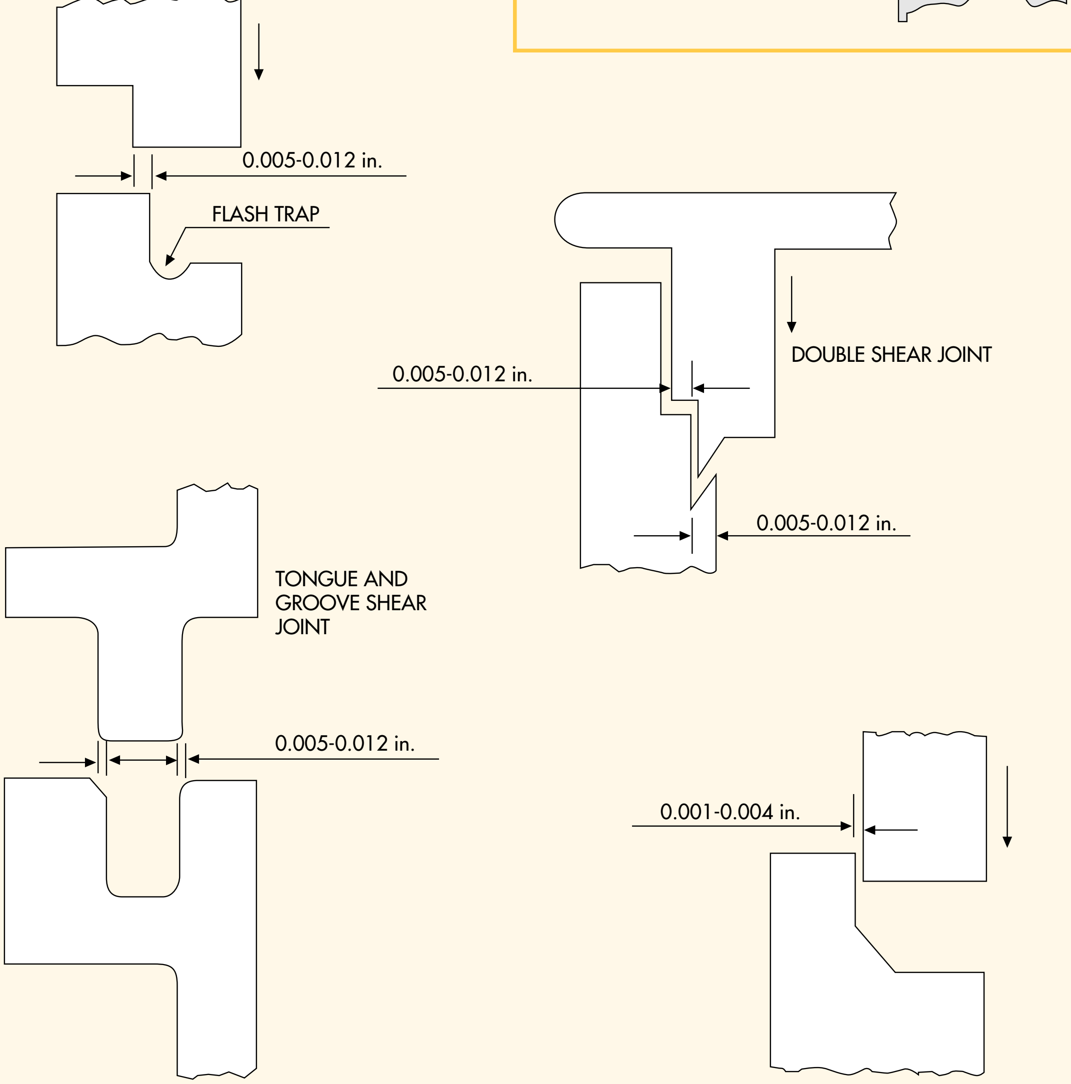


Fig 9.10B · Shear joints



With hygroscopic materials, it is best to weld the parts as soon as possible after molding, since the absorption of moisture can lead to weaker bonds. In some cases, the parts may require drying just prior to welding. Although ultrasonics provide a nearly ideal welding method, following are some drawbacks.

1 . Design and quality control of the parts along with maintenance and settings of equipment are critical in ensuring consistent high-strength welds.

2. Ultrasonic equipment is expensive and can become uneconomical with large parts due to the power required.

3. Parts to be joined must be made from the same or very similar material, and there are some limitations with filled and reinforced grades.

It should be noted that the operating frequencies of ultrasonic welding, 20-40 kHz, are above human hearing. However, sometimes a shrill sound is produced when a section of the part vibrates at a lower frequency. This can result in a need for acoustic enclosures or ear protection in the immediate area. There is seldom any sound when welding is performed at 40 kHz.

Finally, ultrasonic equipment can also be used for staking, swaging, and spot welding, as illustrated in Figure 9.11.

9.1.3.2 Vibration Welding

In vibration welding, two parts are rubbed together, producing frictional heat, which results in a melt at the interface of the two parts. The movement is in the form of high-amplitude, low-frequency, reciprocating motion. When vibration stops, the melt cools and the parts become permanently welded in the proper alignment. Typical frequencies are 120 and 240 Hz, and amplitudes range between 0.10 and 0.20 in. of linear displacement. Vibration welding equipment can also produce angular displacement when the geometry or assembly of the product prevents linear displacement.

Vibration welding, like ultrasonic welding, produces high-strength joints and is much better suited to large parts and irregular joint interfaces. Moisture in hygroscopic materials such as nylon usually has no adverse effect on the weld, as is the case with ultrasonics. Figure 9.12 illustrates typical joints used with vibration welding.

Fig 9.10C · Scarf joints

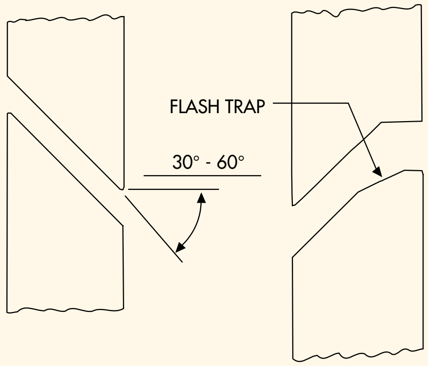


Fig 9.11 · Ultrasonic staking, swaging, and spot welding

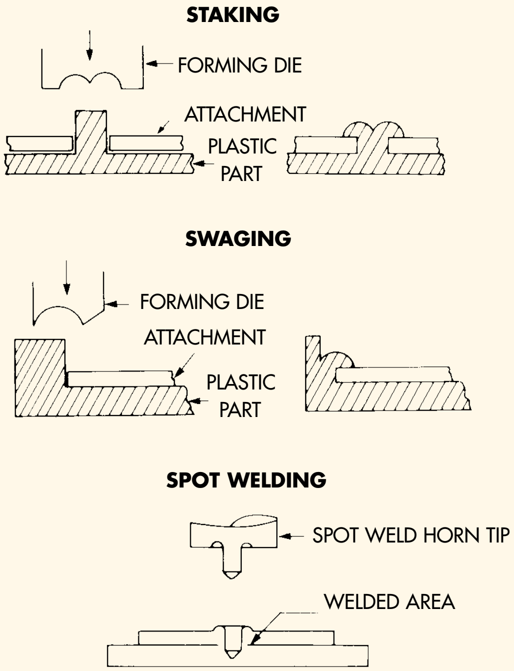
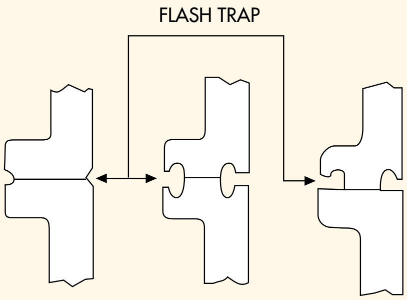


Fig 9.12 · Typical joints for vibration welding



9.1.3.3 Spin Welding

Spin welding is a rapid and economical method for joining parts with circular joint interfaces. As with vibration welding, frictional heat is generated, creating a melt and subsequent weld. While one part is held fixed, the rotating part contacts it with a specified pressure, generating frictional heating. After the melting occurs, rotation is halted, but pressure is maintained to create a weld when the interface solidifies. The entire process usually takes less than 3 seconds and can be easily automated. Compared to ultrasonic and vibration welding, the equipment is very simple, sometimes just a properly equipped drill press for low production runs.

9.1.3.4 Radio Frequency (RF) Welding

This joining method, often called heat sealing, is widely used with flexible thermoplastic films and sheets such as vinyl (plasticized PVC) and polyurethane. However, it can be used with injection-molded parts, most often in joining them to flexible films. With this process, welding occurs due to the heat created by the application of a strong radio frequency field to the selected joint region. The field is usually applied by a specially formed metal die in the shape of the desired joint, which also applies the clamping pressure needed to complete the weld. However, some plastics are transparent to radio frequency energy and cannot be welded by this method.

9.1.3.5 Electromagnetic or Induction Welding

Electromagnetic or induction welding uses the principle of inductive heating to generate fusion temperatures in thermoplastic materials. A radio frequency (RF) magnetic field is used to excite fine, magnetically sensitive particles, either metallic or ceramic, to welding temperatures. The particles can be incorporated into a gasket, preform, filament, ribbon, adhesives, coextruded film, or the molded part.

The most common electromagnetic welding involves an additional part added to the joint interface, as illustrated in Figure 9.13. The additional part is a “preform” containing the magnetically active particles. It is designed to provide a specific volume of material to the joint during fusion. The preform is placed at the joint interface and exposed to an electromagnetic field. Electromagnetically induced heat is conducted from the particles through the preform and to the part joint as the parts are pressed together. As shown in Figure 9.14, once fusion temperatures are achieved, the preform material, under pressure, flows through the joint interface and becomes an integral part of the weld.

A proper joint design is essential to the ultimate success of the weld. Figure 9.15 illustrates five basic joint designs. Since the preform material located at the joint interface becomes molten when activated, it flows under pressure into voids and irregular surfaces to produce a reliable weld. Ideally, the molten flow should be contained and subjected to an internal pressure against the abutting weld surface.

While the addition of the magnetic preform adds some cost to the piece price, this increase is often offset by lower reject rates and gains in weld reliability. Induction welding can produce structural, hermetic welds in most thermoplastic materials and can generally be automated for large volume production applications with greater latitude in joint size, configuration, tolerance requirements, and the ability to bond some dissimilar materials.

However, a significant disadvantage of the method is that no metal components should be present near the weld line during welding. Therefore, for example, if electromagnetic welding is used to seal the housing of a mechanism, either all internal components must be nonmetallic or all metallic components must be in a position so as not to be subjected to the RF field.

Fig 9.13 · Preform in place for electromagnetic welding

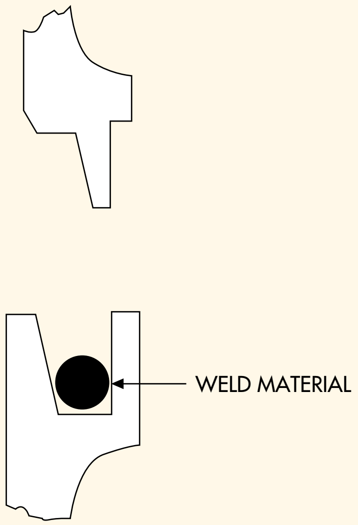


Fig 9.14 · The electromagnetic welding process

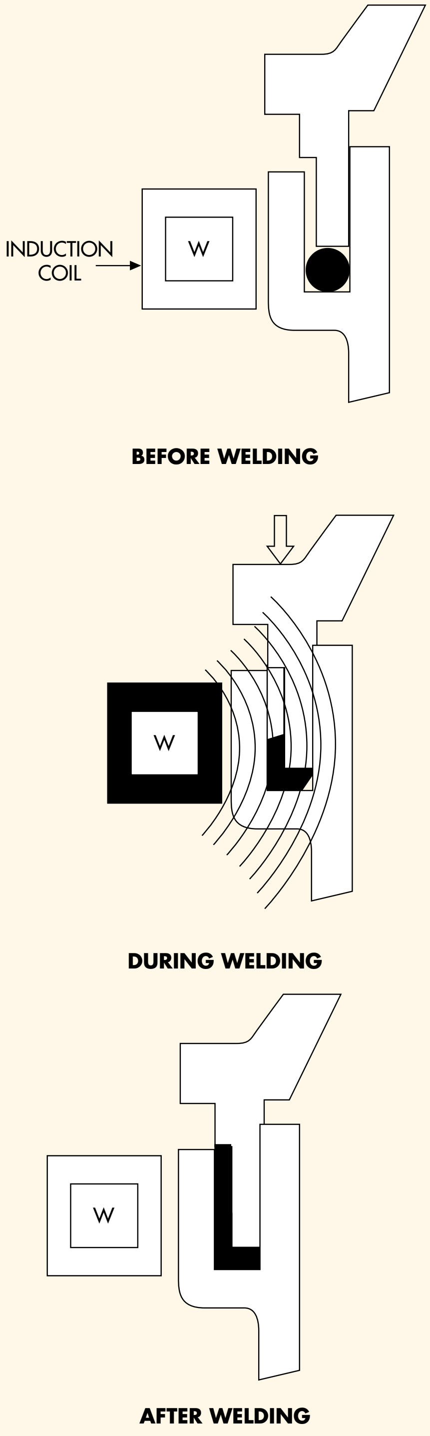
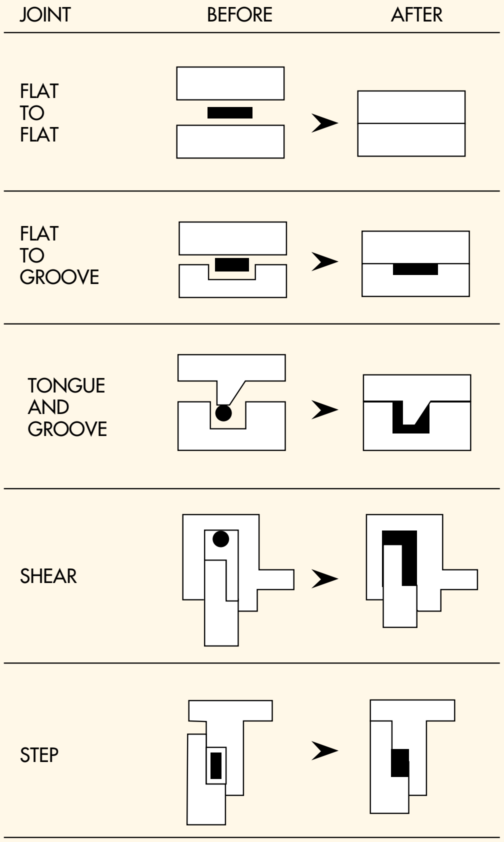


Fig 9.15 · Five basic joint designs for induction welding



9.1.4 Assembly with Fasteners

9.1.4.1 Bolted Assembly

Standard fasteners, screws, bolts, nuts, lock nuts, lock washers, and other specially designed products are used frequently with injection-molded plastic parts. Since these threaded fasteners are usually made from steel, brass, or other high-strength metal, the plastic parts being assembled can likely be overstressed well before these fasteners break or strip. Therefore, good design practice dictates that certain precautions be taken to prevent excessive stresses when bolted assemblies are used.

The most obvious method for preventing a high-stress assembly is to control carefully the tightening of all fasteners with properly adjusted torque-limiting drivers. This approach can work well when operations are confined to a factory assembly line, but field or customer assembly presents a difficult control problem. Even when torque can be controlled, sometimes a poorly designed bolted assembly has an impractically low assembly torque. In this case design modifications are called for.

Figure 9.16 presents common examples of high assembly stress problems that often occur with bolted assembly, along with some practical solutions.

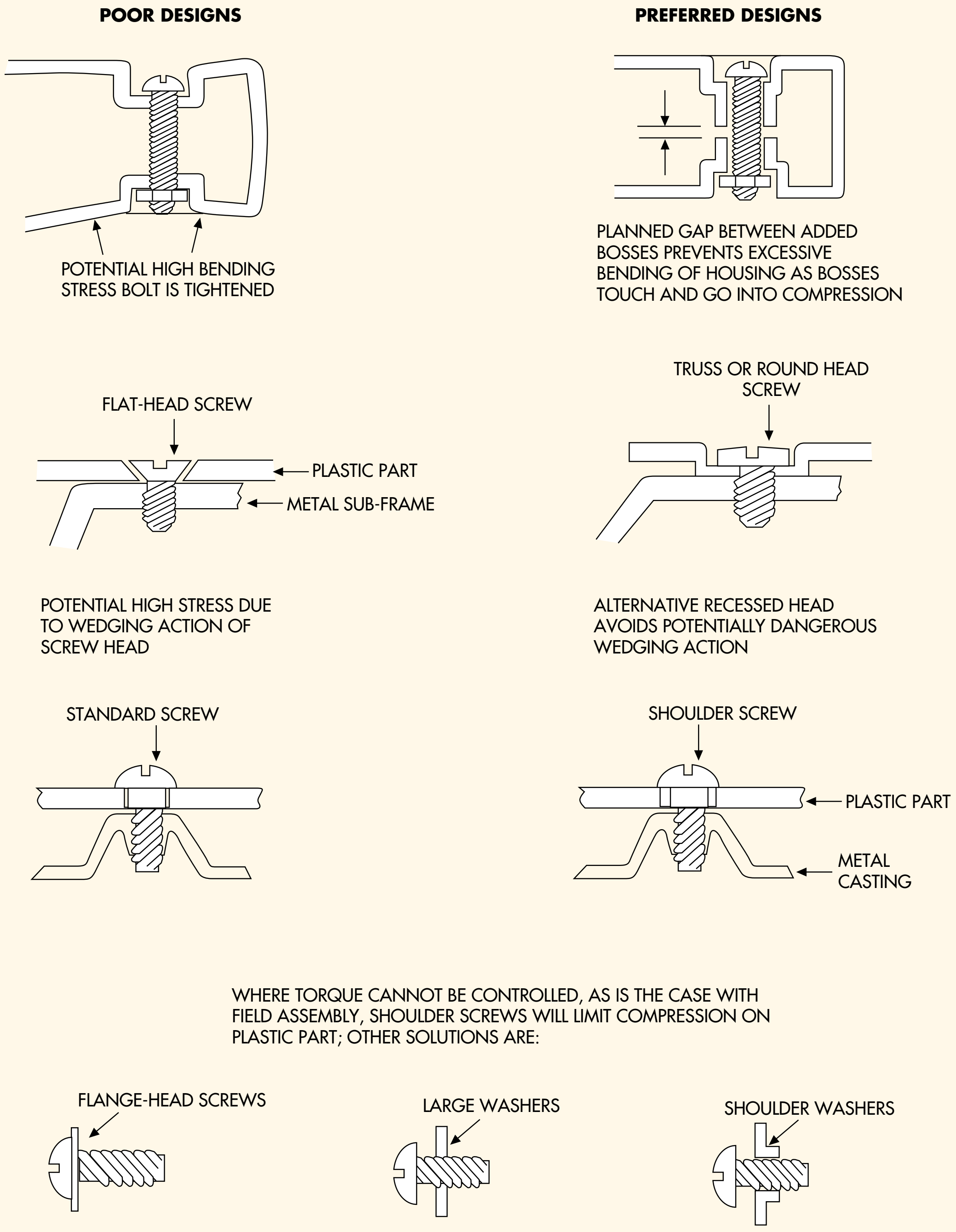


Fig 9.16 · Bolt assembly, stress problems and solutions

POOR DESIGNS

PREFERRED DESIGNS

POTENTIAL HIGH BENDING STRESS BOLT IS TIGHTENED

PLANNED GAP BETWEEN ADDED BOSSES PREVENTS EXCESSIVE BENDING OF HOUSING AS BOSSES TOUCH AND GO INTO COMPRESSION

POTENTIAL HIGH STRESS DUE TO WEDGING ACTION OF SCREW HEAD

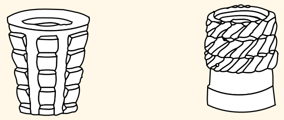
ALTERNATIVE RECESSED HEAD AVOIDS POTENTIALLY DANGEROUS WEDGING ACTION

WHERE TORQUE CANNOT BE CONTROLLED, AS IS THE CASE WITH FIELD ASSEMBLY, SHOULDER SCREWS WILL LIMIT COMPRESSION ON PLASTIC PART; OTHER SOLUTIONS ARE:

Fig 9.17 · Common threaded metal inserts

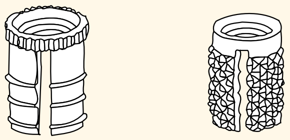
PUSH-IN TYPE INSERTS
ADVANTAGES — SPEED AND LOW EQUIPMENT COST

DISADVANTAGES — HIGH INDUCED STRESS AND ONLY FAIR HOLDING POWER



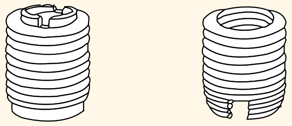
PUSH-IN TYPE INSERTS
ADVANTAGES — NO INSTALLATION EQUIPMENT

DISADVANTAGES — LOWER PERFORMANCE AND MODERATELY HIGH INDUCED STRESS



PUSH-IN TYPE INSERTS
ADVANTAGES — INSTALLED WITH MINIMAL EQUIPMENT

DISADVANTAGES — SLOW AND THEY CAN CREATE HIGH STRESS

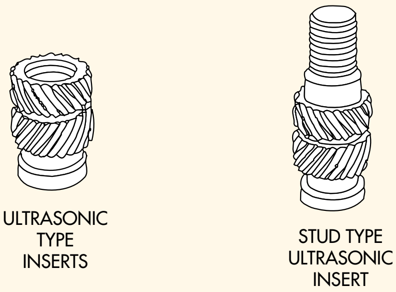


9.1.4.2 Threaded Metal Inserts

More common than bolted assemblies, threaded metal inserts provide metallic machine threads permanently installed in the plastic part. These inserts come in a wide variety of types and sizes and permit various installation methods. Inserts are typically installed in molded bosses whose internal diameter is specifically designed for the particular insert to be used. Some inserts are simply forced into the boss, while others are installed by methods that create stronger and lower stress installations. Figure 9.17 illustrates some of these inserts and the relative advantages and disadvantages of each. They all provide a permanent metallic machine thread, eliminating the need for a nut, allowing assembly with access to only one side of the product. In addition to female threads, inserts can provide threaded male studs, locating pins, and bushings. Follow insert supplier and resin manufacturer recommendations for suitability, boss dimensions, and installation procedures.

A very popular and preferred type of insert for just about any thermoplastic material is the ultrasonically installed type shown in Figure 9.18. This type of insert is installed with the same equipment used for ultrasonic welding. The resulting installation is strong and relatively free of stress compared to many other styles of inserts because the plastic melts around the insert as it is installed. Installation is fast, economical, and often performed by the operator at the molding machine.

Fig 9.18 · Ultrasonic inserts designed for installation with standard ultrasonic equipment



ADVANTAGES — EXCELLENT PERFORMANCE
VERY FAST (OFTEN DONE AT MOLDING MACHINE)
VERY LITTLE INDUCED STRESS

DISADVANTAGES— REQUIRES EXPENSIVE EQUIPMENT
SOMETIMES NOISY

9.1.4.3 Self-Tapping Screws

Screws that create their own threads are widely used with all thermoplastic parts. They are economical and require no extra operations or special unscrewing cores since the thread is cut or formed by the screw during normal assembly operations. A cutting screw actually removes material, like a thread-cutting tap, and works with most materials. The forming screw, as the name implies, actually displaces material and must be used with caution, since very high hoop stresses can be developed in attempting to form threads in high-modulus, low-creep materials. Some screw designs create the threads through a combination of cutting and forming. Figure 9.19 illustrates some of the many varieties of screws used with thermoplastics. Two recent designs that are very popular due to their excellent holding power and lower levels of induced stress are screws that are not round but have multiple lobes and screws with alternating thread heights. These are also illustrated in Figure 9.19. With all selftapping screws, certain guidelines should be followed:

1. The diameter of the molded hole in the plastic part must be properly sized for the screw design and grade of plastic material. An undersized hole can lead to excessive hoop stresses in the boss and eventual fracturing.

2. The depth of the molded hole should be sufficient to prevent bottoming of the leading edge of the screw. A planned clearance is usually recommended, especially for thread-cutting screws.

3. The wall section of the boss must be sufficient to resist the stresses created by the screw. As a general rule, the outside diameter of the boss should be at least twice the major diameter of the screw.

4. Avoid the use of thread-forming screws on glass-reinforced and other very high modulus thermoplastics.

5. To avoid stripping or high-stress assemblies, torque controlled drivers should be used on assembly lines.

9.1.4.4 Riveted Assembly

For fast, permanent assemblies, metal rivets are frequently used. Hollow aluminum rivets are often chosen. The major considerations in using rivets are 1) to use rivets with large heads to distribute the load, and 2) to form the rivet against the metal part of the assembly or against a properly sized metal washer if both parts being joined are plastic.

Fig 9.19 · Typical screws used with plastics

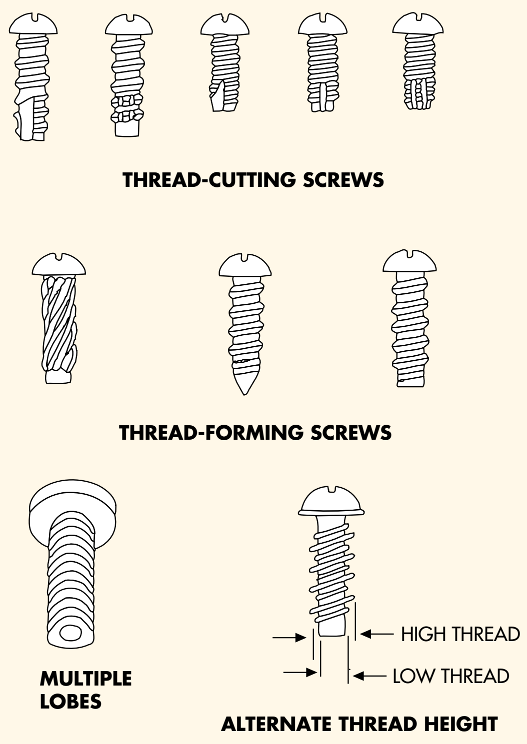
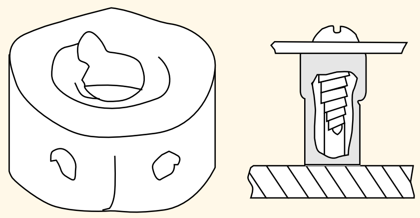


Fig 9.20 · A typical boss cap



9.1.4.5 Sheet Metal Nuts

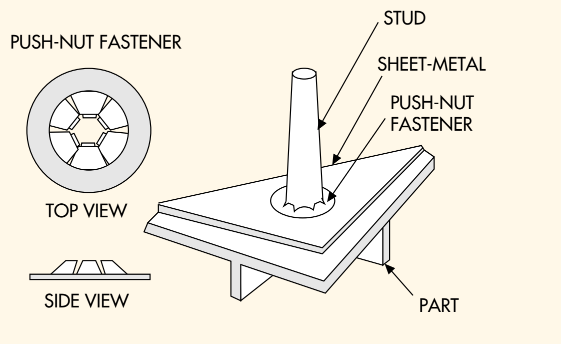
A wide variety of stamped sheet metal fasteners are available to provide light-duty threads or push-on type of assembly for thermoplastic parts. Boss caps, as illustrated in Figure 9.20, are cup-shaped parts that can simply be pushed onto a plastic boss. In addition to providing a partial metal thread, usually for a self-tapping or sheet metal screw, they also tend to reinforce the boss against expansion forces exerted by the screw.

Figure 9.21 illustrates a typical push-nut, which is usually used in permanent light-duty assemblies. Push nuts are similar to metal shaft retainers and are simply pushed on a plain, molded plastic stud or boss. They are easy to install, inexpensive, vibration-proof, and work with most plastics.

9.1.4.6 Specialty Plastic Fasteners

There are many varieties of molded plastic fasteners, which are satisfactory for many light-duty plastic assemblies. They are especially useful for attaching external appearance items such as trim, escutcheons, and faceplates where metal fasteners would be unsatisfactory. In addition to plastic screws and rivets, a wide variety of push-in plastic fasteners is also available.

Fig 9.21 · A typical push-nut assembly



10. Machining, Finishing, and Decorating

Ideally, injection-molded thermoplastic parts are finished as molded. For example, almost any type of texture or surface finish can be molded into the part, as can almost any geometric shape, hole, or projection. In some situations it is not possible, practical, or economical to have every feature or finish molded into the part. Typical examples where machining may be required are certain undercuts, complicated side coring, or places where parting line irregularity is unacceptable. Another common machining/finishing operation with plastics is the removal of the remnant of the sprue or gate if it is in an appearance area or critical tolerance region of the part.

Many plastic parts are decorated to make them multicolored, to add distinctive logos, or to allow them to imitate wood, metal, and other materials. Some plastic parts are painted since their as-molded appearance is not satisfactory, as may be the case with reinforced, filled, or foamed thermoplastics. Painting or coating is also used for part protection. This section discusses some of the secondary operations frequently used with thermoplastic materials. Since plastics vary widely in their ability to be machined and to accept finishes, this discussion is general in nature, with details left to other literature dealing with specific resins.

10.1 Machining

All thermoplastic materials can be shaped and finished with common equipment used for machining metals. In addition, many tools specifically used for woodworking, such as routers, shapers, and sanders, are well suited for thermoplastic materials. Since many materials are available in the form of sheets, blocks, slabs, rods, tubes, and other cast and extruded shapes, initial prototypes are frequently made entirely by machining.

The main problems encountered when machining thermoplastic materials are due to the heat built up by friction. As the resin and cutting tools begin to heat up, the plastic can distort or melt. This can produce a poor surface finish, tearing, localized melting, welding together of stacked parts, and jamming of cutters. It is important to prevent the part and cutting tool from heating up to the point where significant softening or melting occurs. Some plastic materials machine much easier and faster than others due to their physical and mechanical properties. Generally, a high melting point, inherent lubricity, and good hardness and rigidity are factors that improve machinability.

10.1.1 Drilling and Reaming

In addition to building prototype parts, drilling and reaming are often required to enlarge, deepen, or remove the draft from a molded hole. In some cases, secondary drilling is a more economical solution than side cores in a mold. Although specific requirements vary with material, the following guidelines apply to almost all thermoplastic resins:

1 . Standard drill presses, as well as other drilling equipment used for metals and wood, are appropriate for drilling and reaming thermoplastics. Speeds and feeds must be controlled to avoid heat buildup.

2. Wood and metal drill bits can usually be used, but best results are obtained with commercially available bits designed for plastics. These special drills usually have one or two highly polished or chrome-plated flutes, narrow lands, and large helix angles to quickly expel chips and minimize frictional heating. For holes in thin sections, circle cutters, which are drills that only cut the circumference and eject a round thin plug of material, are often preferred for production.

3. Table 10.01 gives the approximate drilling speed for thermoplastics. In practice, the drill speed and feed rate can be increased for maximum production provided that there is no melting, burning, discoloration, or poor surface finish For deep drilling, frequent withdrawal of the drill may be necessary for chip ejection.

4. Drill bits and reamers must be kept sharp and cool for good results. For high-volume production, carbide tools are sometimes preferred, especially with glass-reinforced materials. The first choice for cooling is clean, compressed air, since no part contamination occurs and chip removal is improved. If a liquid coolant lubricant is required for deep drilling, water or some aqueous solution can be used. Metal-cutting fluids and oils should be avoided since they may degrade or attack the plastic and create a cleaning problem.

5. Plastic parts must be firmly held, fixed, or clamped during drilling and reaming operations to prevent dangerous grabbing and spinning of the work.

Table 10.01 · Approximate drilling speed and feed rate for 1/4 – 3/8 in. hole in various thermoplastics

Material	Drill Speed (RPM)	Feeding Speed (Low, Med., High)	Comments
Polyethylene	1000 – 2000	H	Easy to machine
Polyvinyl Chloride	1000 – 2000	M	Tends to become gummy
Acrylic	500 – 1500	M – H	Easy to drill with lubricant
Polystyrene	500 – 1500	H	Must have coolant for good hole
ABS	500 – 1000	M – H	
Polytetra-fluoroethylene	1000	L – M	Easily drilled
Nylon 6/6	1000	H	Easy to drill
Polycarbonate	500 – 1500	M – H	Easy to drill, some gumming
Acetal	1000 – 2000	H	Easy to drill
Polypropylene	1000 – 2000	H	Easy to drill
Polyester (PET, PBT)	1000 – 1500	H	Easy to drill

10.1.2 Thread Tapping

Many plastic parts use self-tapping screws, threaded metal inserts, molded-in threads, or other fastener systems. When a machine thread must be added after molding, standard metal-cutting taps and dies may be used, provided the same precautions regarding heat, chip removal, tool maintenance, and lubrication discussed for drilling are observed. For production of high volumes or with filled resins, carbide taps are recommended. Drilled or molded holes should generally be larger than those specified for steel, and threads finer than 28 threads per inch should be avoided.

10.1.3 Sawing, Milling, Turning, Grinding, and Routing

These cutting operations are usually used only for machined prototypes or very low-volume production of simple shapes. High-speed routing is sometimes used for slotting or gate removal on injection-molded parts. Standard end mills (two-flute), circular cutters, tool bits, wood saw blades, router bits, files, rasps, and sandpaper can usually be used. As with drilling, tools must be kept sharp and cool, and feeds and speeds may be increased until overheating, gumming, or poor finish becomes a problem. All machining operations should provide for dust control, adequate ventilation, safety guards, and eye protection. Inquire about machining information for each specific resin.

10.2 Finishing and Decorating

Since most injection-molded plastic parts are attractive as well as inherently resistant to corrosion and rust, special paints, coatings, and other surface treatments are used mainly to enhance eye appeal. Many reinforced and filled resin parts, as well as structural foam molded parts, emerge from the mold with an uneven appearance, and paint may be necessary in critical appearance applications. Common decorative finishes applied to plastic parts are spray painting, vacuum metallizing, hot stamping, silk screening, metal plating, printing, and the application of self-adhesive labels, decals, and border stripping. In some cases the finish gives the part added protection from heat, ultraviolet radiation, chemicals, scratching, or abrasion.

Some conductive coatings are applied to the inside of the part for dissipation of static electricity and/or electromagnetic shielding. Such coatings are common in computer and other electronic equipment housings. With all coatings and finishes, a clean surface is essential for a good bond. Care must be used to avoid contamination. Common sources of contamination include oils, mold releases, the environment, and handling. In addition to cleaning with solvents and detergents, some plastics require primers, etching, sanding, or flame treatment to enhance adhesion. Following is a brief description of several widely used processes.

10.2.1 Painting

Most plastics can be painted, though some are much more difficult than others. Materials such as polyethylene, polypropylene, and acetal, which have waxy surfaces, or other crystalline resins that are very resistant to solvents, can be difficult to paint and require special primers or pretreatments for satisfactory adhesion. Many amorphous plastics easily accept a wide variety of coatings.

Although rolling and dipping are sometimes used, power spray painting is the usual method of paint application. Among the coatings used for plastics are polyurethane-, epoxy-, acrylic-, alkyd-, and vinyl-based paints. Since many paints are oven cured, materials must have sufficient heat resistance to survive this treatment without distortion.

10.2.2 Vacuum Metallizing and Sputter Plating

In these processes, a special base coat is applied to the surface of the plastic part to be metallized. The part is then placed in a vacuum chamber in which a metallic vapor is created and deposited on the part. A protective clear top coat is then applied over the thin metal layer for abrasion and environmental resistance. The simplest vacuum metallizing processes use resistance heating to melt and vaporize the metal. These processes are generally limited to pure metals, typically aluminum, but also silver, copper, and gold. A newer vacuum metallizing process uses an electron beam to vaporize the metal. The sputter plating process uses a plasma to produce the metallic vapor. Both the electron beam and plasma heating methods can be used satisfactorily with alloys such as brass, and are economical metallizing processes that can produce attractive high-gloss finish. However, the adhesion is generally low.

10.2.3 Electroplating

Many chromed automotive exterior parts are electroplated injection-molded plastic parts. After special pretreatments, specific grades of plastics can be put through electroplating processes similar to those used in plating metals. Electroplated plastic parts are very durable and provide lightweight replacements for die castings and sheet metal in demanding applications such as automotive grilles and wheel covers.

10.2.4 Flame Spraying/Arc Spraying

In these processes, specialized equipment actually deposits a fine spray of molten metal on the plastic surface. The relatively thick, rough surface is generally used in unseen internal surfaces for electromagnetic and radio frequency shielding, as well as static electricity dissipation.

10.2.5 Hot Stamping

This is a one-step economical process for selectively transferring a high-quality image to a plastic part. A heated die transfers the pattern from selected transfer tape to a flat plastic surface. Lettering of decorative designs can be transferred in pigmented, woodgrain, or metallic finishes.

10.2.6 Sublimation Printing

Sublimation (diffusion) printing is a textile process in which color patterns in dry dye crystals are transferred from a release film to the fabric under high heat and pressure. The process has been adapted to plastics. The equipment is very similar to that used for hot stamping. Under heat and pressure, the dye crystals sublime (go directly to the vapor phase from the solid phase without melting) and the vapor penetrates the plastic part. As a result, the decoration is very durable and resistant to wear. It is also cost competitive against other processes such as two-stage injection molding or silk screening. The process is generally limited to polyester and polyester-based alloys due to the availability of dye technology from the textile industry. However, new dyes are under development and the process is being applied to more plastics.

10.2.7 Printing

Lettering and decoration can be applied to most materials by using various printing methods. Offset printing, silk screening, and pad printing are among the methods adapted to plastics.

10.2.8 Decals and Labels

These are usually self-adhesive, precut, printed patterns on a substrate that simply adhere to the surface of a part. Decals generally use a transparent plastic film, while labels normally use an opaque plastic, metallic, multilayer sandwich base. When sufficiently thick, labels are useful for hiding occasionally unavoidable appearance problems, such as gate and sprue removal areas, sink marks, blush, splay, and knit lines.

List of Symbols

A – area
E – modulus of elasticity
E_{app} – apparent or creep modulus
E_c – modulus of elasticity in compression
E_m – modulus of elasticity in metal
E_p – modulus of elasticity in plastic
E_t – modulus of elasticity in tension
F – force or load
G – shear modulus
H – drop height
I – area moment of inertia
J – polar moment of inertia
K – stress concentration factor or proportionality constant
L – length
M – bending moment
P – pressure
Q – shear force
R – square of the ratio of inside to outside diameter
T – torque, temperature
T_g – glass transition temperature
Y – deflection
W – weight
Z – section modulus, a geometric property
Z^I – section modulus, unsymmetrical beam
b – dimension
c – distance from axis or neutral surface to maximum stress
d – diameter or dimension
d_i – inside diameter
d_o – outside diameter
d_s – shaft diameter
h – dimension
h_o – height of tapered cantilever beam at fixed end
h_L – height of tapered cantilever beam at free end
i – diametrical interference
i_a – allowable interference
na – neutral axis
r – fillet radius
s – dimension
t – nominal wall thickness, section thickness
t_r – rib thickness
y_i – impact deflection
y_s – static deflection
Γ – geometry factor for press-fits
ΔL – change in length
ΔL_{rel} – relative change in length
Δb – change in width
Δd – change in depth
ΔT – change in temperature
α – coefficient of linear thermal expansion
α_m – coefficient of linear thermal expansion of metal
α_p – coefficient of linear thermal expansion of plastic
γ – shear strain
ε – normal strain
ε_c – creep strain
ε_T – thermal strain
θ – angle of twist in torsion
μ – coefficient of friction
ν – Poisson's ratio
σ – normal or direct stress
σ_a – allowable stress
σ_i – impact stress
σ_s – static stress
σ_T – thermal stress
τ – shear stress

NOTICE TO USERS: This design manual was written to serve as a general purpose reference source for the experienced plastic product designer as well as the design engineer new to plastics. It should also be of interest to nondesigners and management personnel who need a general overview of the concepts and critical issues related to the world of plastics. Although the manual is not a guide to injection molding, many of the design considerations are based upon molding criteria, so those involved in the manufacturing and processing of plastic parts should also find it useful.

Most design manuals deal with a specific family of plastic resins, and present properties, design criteria, assembly, and other information related to these resins. The product line of Ticona includes crystalline, amorphous, liquid crystalline, and elasto-meric polymers. Due to this diversity, this manual deals with issues common to all injection-moldable thermoplastic resins. Tables, figures, and other descriptive methods are used to help illustrate significant design differences.

The first part, Chapters 1 through 6, introduces the nature of plastic materials, their properties and testing methods. Key advantages, as well as limitations, of certain thermoplastics are discussed. Where appropriate, we compare the properties of various engineering thermoplastics, often including the properties of metals or other structural materials. However, our goal is to review fundamental concepts rather than list the various testing methods.

Discussion of specific testing methods from the numerous governmental, industrial, and standards organizations involved with testing is beyond the scope of this manual.

The second part, Chapters 7 through 10, deals with the actual design of parts. It starts with structural analysis and injection molding considerations and concludes with assembly, finishing, and decorating techniques. This part of the manual will serve as both a general reference and a "how-to" guide for those new to plastic design.

For further information on design-related topics, the reader is urged to consult the following individual product brochures: Designing with Celcon® Acetal Copolymer (CE-10), Designing with Fortron® Polyphenylene Sulfide (FN-10), Vectra® Liquid Crystal Polymers Global Brochure (VC-7) and Designing with Celanex, Vandar®, Impet®, & Riteflex® Thermoplastic Polyesters (PE-10). These may be obtained by calling the Ticona Product Information Services Department at (800) 833-4882. Additional design information on Celcon® Acetal Copolymer and Celanese® Nylon 6/6.

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