

PLASTICS

Properties of Plastics

Characteristics of Important Plastics Families

ABS (acrylonitrile-butadiene-styrene)	Rigid, low-cost thermoplastic, easily machined and thermo-formed.
Acetal	Engineering thermoplastic with good strength, wear resistance, and dimensional stability. More dimensionally stable than nylon under wet and humid conditions.
Acrylic	Clear, transparent, strong, break-resistant thermoplastic with excellent chemical resistance and weatherability.
CPVC (chlorinated PVC)	Thermoplastic with properties similar to PVC, but operates to a 40-60°F higher temperature.
Fiberglass	Thermosetting composite with high strength-to-weight ratio, excellent dielectric properties, and unaffected by corrosion.
Nylon	Thermoplastic with excellent impact resistance, ideal for wear applications such as bearings and gears, self-lubricating under some circumstances.
PEEK (polyetheretherketone)	Engineering thermoplastic, excellent temperature resistance, suitable for continuous use above 500°F, excellent flexural and tensile properties.
PET (polyethylene-terephthalate)	Dimensionally stable thermoplastic with superior machining characteristics compared to acetal.
Phenolic	Thermosetting family of plastics with minimal thermal expansion, high compressive strength, excellent wear and abrasion resistance, and a low coefficient of friction. Used for bearing applications and molded parts.
Polycarbonate	Transparent tough thermoplastic with high impact strength, excellent chemical resistance and electrical properties, and good dimensional stability.
Polypropylene	Good chemical resistance combined with low moisture absorption and excellent electrical properties, retains strength up to 250°F.
Polysulfone	Durable thermoplastic, good electrical properties, operates at temperatures in excess of 300°F.
Polyurethane	Thermoplastic, excellent impact and abrasion resistance, resists sunlight and weathering.
PTFE (polytetrafluoroethylene)	Thermoplastic, low coefficient of friction, withstands up to 500°F, inert to chemicals and solvents, self-lubricating with a low thermal-expansion rate.
PVC (polyvinyl chloride)	Thermoplastic, resists corrosive solutions and gases both acid and alkaline, good stiffness.
PVDF (polyvinylidene-fluoride)	Thermoplastic, outstanding chemical resistance, excellent substitute for PVC or polypropylene. Good mechanical strength and dielectric properties.

Plastics Materials.—Plastics materials, often called resins, are made up of many repeating groups of atoms or molecules linked in long chains (called polymers) that combine such elements as oxygen, hydrogen, nitrogen, carbon, silicon, fluorine, and sulfur. Both the lengths of the chains and the mechanisms that bond the links of the chains together are related directly to the mechanical and physical properties of the materials. There are two main groups: thermoplastics and thermosets.

Thermoplastic materials become soft and moldable when heated, and change back to solids when allowed to cool. Examples of thermoplastics are acetal, acrylic, cellulose acetate, nylon, polyethylene, polystyrene, vinyl, and nylon. Thermoplastic materials that are flexible even when cool are known as thermoplastic elastomers or TPEs. When thermoplastic materials are heated, the linked chains of molecules can move relative to each other, allowing the mass to flow into a different shape. Cooling prevents further flow. Although the heating/cooling cycle can be repeated, recycling reduces mechanical properties and appearance.

Thermoset plastics such as amino, epoxy, phenolic, and unsaturated polyesters, are so named because they are changed chemically during processing and become hard solids. Although the structures of thermoset materials are similar to those of thermoplastic materials, processing develops cross-links between adjacent molecules, forming complex networks that prevent relative movement between the chains at any temperature. Many rubbers that are processed by vulcanizing, such as butyl, latex, neoprene, nitrile, polyurethane, and silicone, also are classified as thermosets. Heating a thermoset degrades the material so that it cannot be reprocessed satisfactorily.

Elastomers are flexible materials that can be stretched up to about double their length at room temperature and can return to their original length when released. Thermoplastic elastomers are often used in place of rubber, and may also be used as additives to improve the impact strength of rigid thermoplastics.

Structures.—Thermoplastics can be classified by their structures into categories such as amorphous (noncrystalline), crystalline, and liquid crystalline polymers (LCP). Amorphous thermoplastics include polycarbonate, polystyrene, ABS (acrylonitrile-butadienestyrene), SAN (styrene-acrylonitrile), and PVC (polyvinylchloride). Crystalline thermoplastics have polymer chains that are packed together in an organized way, as distinct from the unorganized structures of amorphous plastics, and include acetal, nylon, polyethylene, polypropylene, and polyester. The organized regions in crystalline thermoplastics are joined by noncrystalline (amorphous) zones, and the structures are such that the materials are stronger and stiffer, though less resistant to impact, than completely noncrystalline materials. Crystalline thermoplastics have higher melting temperatures and higher shrinkage and warpage factors than amorphous plastics. Liquid crystalline plastics are polymers with highly ordered rod-like structures and have high mechanical property values, good dimensional stability and chemical resistance, and are easy to process, with melting temperatures similar to those of crystalline plastics. Unlike amorphous and crystalline plastics, liquid crystalline plastics retain significant order in the melt phase. As a result, they have the lowest shrinkage and warpage of the three types of thermoplastics.

Mixtures.—Characteristics of plastics materials can be changed by mixing or combining different types of polymers and by adding nonplastics materials. Particulate fillers such as wood flour, silica, sand, ceramic and carbon powder, tiny glass balls, and powdered metal are added to increase modulus and electrical conductivity, to improve resistance to heat or ultraviolet light, and to reduce cost, for example. Plasticizers may be added to decrease modulus and increase flexibility. Other additives may be used to increase resistance to effects of ultraviolet light and heat or to prevent oxidation, and for a variety of other purposes.

Reinforcing fibers of glass, carbon, or Aramid (aromatic polyamide fibers having high tensile strength, a range of moduli, good toughness, and stress-strain behavior similar to

that of metals) are added to improve mechanical properties. Careful design and process selection must be used to position the fibers so that they will provide the required strength where it is needed. Continuous fiber may be positioned carefully in either a thermoplastics or thermoset matrix to produce basic parts generally called composites, which have the highest mechanical properties and cost of the reinforced plastics.

Copolymers embody two or more different polymers and may have properties that are completely different from those of the individual polymers (homopolymers) from which they are made. An approach known as alloying consists of pure mechanical blending of two or more different polymers, often with special additives to make them compatible. These "alloys" are compounded so as to retain the most desirable characteristics of each constituent, especially in impact strength and flame resistance. However, properties usually are intermediate between those of the constituent materials.

Physical Properties.—Almost all proposed uses of plastics require some knowledge of the physical properties of the materials, and this information is generally readily available from manufacturers. Properties such as density, ductility, elasticity and plasticity, homogeneity, uniformity of composition, shrinkage during cooling from the molding temperature, transmittal of light, toughness (resistance to impact), brittleness, notch sensitivity, isotropy (properties that are the same when measured in any direction) and anisotropy (properties that vary when measured in different directions), and lubricity (load-bearing characteristics under relative motion) may all need consideration when a material suitable for a specific application is to be specified.

Most of the terms used to describe the physical characteristics of metals, such as density, ductility, brittleness, elasticity, notch sensitivity, specific gravity, and toughness, have similar meanings when they are applied to plastics, but different measures are often used with plastics. Like cast metals, many plastics are isotropic so that their characteristics are the same measured in any direction. Properties of rolled metals and extruded plastics vary when measured in the longitudinal and transverse directions, so these materials are anisotropic.

Density is a measure of the mass per unit volume, usually expressed in lb/in.³ or g/cm³ at a temperature of 73.4 degrees F (23 degrees C). Density information is used mainly to calculate the amount of material required to make a part of a given volume, the volume being calculated from drawing dimensions.

Specific gravity is the ratio of the mass of a given volume of a material to the mass of the same volume of water, both measured at 73.4 degrees F (23 degrees C). The ratio is dimensionless so is useful for comparing different materials, and is used in cost estimating and quality control.

Shrinkage is the ratio of the dimension of the plastics molding to the corresponding dimension of the mold, expressed in in./in. or cm/cm, both at room temperature. As with a die casting die, the moldmaker uses this ratio to determine mold cavity measurements that will produce a part of the required dimensions. Shrinkage in a given material can vary with wall thickness, direction of flow of the plastics in the mold, and molding conditions. Amorphous and liquid crystalline thermoplastics have lower shrinkage ratios than crystalline thermoplastics. Glass-reinforced and filled materials have lower shrinkage than unfilled materials.

Water absorption is the amount of increase in weight of a material due to absorption of water, expressed as a percentage of the original weight. Standard test specimens are first dried for 24 hr, then weighed before and after immersion in water at 73.4 degrees F (23 degrees C) for various lengths of time. Water absorption affects both mechanical and electrical properties and part dimensions. Parts made from materials with low water absorption rates tend to have greater dimensional stability.

Opacity (or transparency) is a measure of the amount of light transmitted through a given material under specific conditions. Measures are expressed in terms of haze and

luminous transmittance. Haze measurements indicate the percentage of light transmitted through a test specimen that is scattered more than 2.5 degrees from the incident beam. Luminous transmittance is the ratio of transmitted light to incident light.

Elasticity is the ability of a material to return to its original size and shape after being deformed. Most plastics have limited elasticity, although rubber and materials classified as thermoplastic elastomers (TPEs) have excellent elasticity.

Plasticity is the inverse of elasticity, and a material that tends to stay in the shape or size to which it has been deformed has high plasticity. Some plastics can be formed cold by being stressed beyond the yield point and such plastics then exhibit plasticity. When thermoplastics are heated to their softening temperature, they have almost perfect plasticity.

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

Toughness is a measure of the ability of a material to absorb mechanical energy without cracking or breaking. Tough material can absorb mechanical energy with either elastic or plastic deformation. High-impact unfilled plastics generally have excellent toughness, and low- or moderate-impact materials may also be tough if their ultimate strength is high enough (see *Typical Stress–Strain Curves* on page 573). The area under the stress–strain curve is often used as the measure of toughness for a particular plastics material.

Brittleness is the lack of toughness. Brittle plastics frequently have low impact and high stiffness properties. Many glass-reinforced and mineral-filled materials are brittle.

Notch sensitivity is a measure of the ease with which a crack progresses through a material from an existing notch, crack, or sharp corner.

Lubricity describes the load-bearing characteristics of a material under relative motion. Plastics with good lubricity have low coefficients of friction with other materials (or sometimes with themselves) and no tendency to gall.

Homogeneous means uniform. The degree of homogeneity indicates the uniformity of composition of a material throughout its mass. In a completely homogeneous body, the smallest sample has the same physical properties as the body. An unfilled thermoplastics is a reasonably homogeneous material.

Heterogeneous means varying. In a heterogeneous body, for example, a glass-reinforced material, the composition varies from point to point. Many heterogeneous materials are treated as homogeneous for design purposes because a small sample of the material has the same properties as the body.

Isotropy means that the properties at any point in a body are the same, regardless of the direction in which they are measured.

Anisotropy means that the physical properties of a material depend on the direction of measurement. Various degrees of anisotropy exist, depending on the amount of symmetry of the material or component shape. For example, cast metals and plastics tend to be isotropic so that samples cut in any direction within a cast body tend to have the same physical properties. However, rolled metals tend to develop crystal orientation in the direction of rolling so that they have different mechanical properties in the rolling and transverse-to-rolling directions.

Extruded plastics film also may have different properties in the extruding and transverse directions so that these materials are oriented biaxially and are anisotropic. Composite materials that have fiber reinforcements carefully oriented in the direction of applied loads, surrounded by a plastics matrix, have a high degree of property orientation with direction at various points in the structure and are anisotropic.

As another example, wood page 375 is an anisotropic material with distinct properties in three directions and is very stiff and strong in the direction of growth. Fair properties are also found in one direction perpendicular to the growth direction, but in a third direction at right angles to the other two directions, the mechanical properties are much lower.

The preceding examples involve mechanical properties, but anisotropy is also used in referring to the way a material shrinks in the mold. Anisotropic shrinkage is important in molding crystalline and glass-fiber-reinforced materials for which shrinkage values are usually listed for the flow direction and the cross-flow direction. These values are of most concern to the tool designer and molder, but the existence of anisotropy and its severity must be considered when a material is chosen for a part having tight tolerances.

Significance of Elasticity, Homogeneity, and Isotropy: Structural analysis during design of components uses two independent constants, Young's modulus (E) and Poisson's ratio (ν), but two constants are sufficient only for elastic, isotropic materials that respond linearly to loads (when load is proportional to deformation). Designers often use the same values for these constants everywhere in the structure, which is correct only if the structure is homogeneous.

Assumptions of linear elasticity, isotropy, and homogeneity are reasonable for many analyses and are a good starting point, but use of these assumptions can lead to significant design errors with plastics, particularly with glass-reinforced and liquid crystalline polymers, which are highly anisotropic. In the following, plastics are assumed to be linearly elastic, homogeneous, and isotropic to allow a simpler presentation of mechanical properties in line with the data provided in plastics manufacturers' marketing data sheets. The standard equations of structural analysis (bending, torsion, pressure in a pipe, etc.) also require these assumptions.

As the degree of anisotropy increases, the number of constants or moduli required to describe the material also increases, up to a maximum of 21. Uncertainty about material properties and the questionable applicability of the simple analysis techniques employed point to the need for extensive end-use testing of plastics parts before approval of a particular application. A partial solution to this problem lies in the use of finite-element-analysis (FEA) methods. The applicability of FEA methods requires good understanding of the anisotropic nature of plastics materials.

Mechanical Properties.—Almost all end-use applications involve some degree of loading, so mechanical properties are of prime importance in designing with plastics. Material selection is usually based on manufacturers' marketing data sheets listing tensile strength, modulus of elasticity (E), elongation, impact strength, stress and strain behavior, and shear strength. Suppliers' data often are generated under standard test conditions so may not be directly transferable to the components produced. Because of the somewhat lower modulus of elasticity of plastics materials (10^5 for plastics compared with 10^6 lb_f/in² for metals), different units of measure are used to express the results.

Determination of the true meaning of mechanical properties and their relation to end-use requirements is of vital importance in design. In practical applications, materials are seldom subjected to steady deformation without the influence of other factors such as environment and temperature. A thorough understanding of mechanical properties and tests used to determine such properties, and the effects of adverse or beneficial conditions on mechanical properties over long time periods, is extremely important. Some manufacturers offer design and technical advice to customers who do not possess this understanding.

Stress: A three-dimensional body having a balanced system of external forces F_1 through F_5 acting on it, such that the body is at rest, is shown in Fig. 1. Such a body develops internal forces to transfer and distribute the external loads. If the body is cut at an arbitrary cross-section and one part is removed, as shown at the right in Fig. 1, a new system of

forces acting on the cut surface is developed to balance the remaining external forces. Similar forces (stresses) exist within the uncut body.

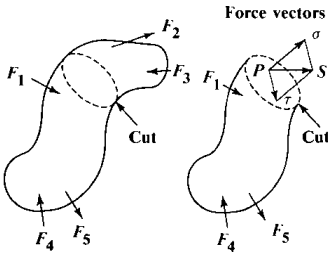


Fig. 1. Internal Forces and Stresses in a Body

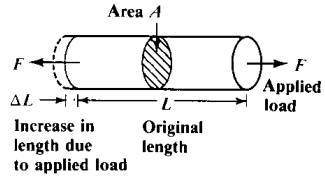


Fig. 2. Simple Tension Load

Stresses must be defined with both magnitude and direction. The stress S acting in the direction shown in Fig. 1, on the point P of the cut surface, has two stress components. One of these components, σ , acts perpendicular to the surface and is called a normal or direct stress. The other stress, τ , acts parallel to the surface and is called a shear stress.

Normal stress is illustrated by the simple tension test shown in Fig. 2, where the direct stress is the ratio of applied load to the original cross-sectional area in lb_f/in^2 . In the Système International (SI or metric system, see pages 2520, *Metric Conversion Factors* starting on page 2525, and 2548) the stress, σ , is expressed in newtons/meter² (N/m^2).

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} \text{ or } \sigma = \frac{F}{A} \quad (1)$$

If the load is applied as shown in Fig. 2, the test piece is in tension, and if reversed, it is in compression.

Normal strain is also illustrated by the diagram in Fig. 2, where the load or stress applied to the test piece causes it to change its length. If the bar has an original length L , and changes its length by ΔL , the strain, ϵ , is defined as

$$\text{Strain} = \frac{\text{Change of Length}}{\text{Original Length}} \text{ or } \epsilon = \frac{\Delta L}{L} \quad (2)$$

Strain is the ratio between the amount of deformation of the material and its original length and is a dimensionless quantity. Extensions of most materials under load are generally very small. Strain ($\mu\epsilon$ or microstrain in most metals) is measured and expressed in microinches (millionths of an inch) per inch, or 10^{-6} in./in. (10^{-6} cm/cm). Alternatively, strain is expressed as a percentage. The three methods compare as follows:

$$\begin{aligned} 1000\mu\epsilon &= 0.001 = 0.1 \text{ per cent strain} \\ 10000\mu\epsilon &= 0.010 = 1 \text{ per cent strain} \end{aligned}$$

Modulus of Elasticity: Most metals and plastics have deformations that are proportional to the imposed loads over a range of loads. Stress is proportional to load and strain is proportional to deformation, so stress is proportional to strain and is expressed by Hooke's law:

$$\frac{\text{Stress}}{\text{Strain}} = \text{Constant} = E \quad (3)$$

The constant E is called the modulus of elasticity, Young's modulus, or, in the plastics industry, tensile modulus. Referring to Fig. 2, tensile modulus is given by the formula:

$$E = \frac{\sigma}{\epsilon} = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L} \quad (4)$$

Thus, the modulus is the slope of the initial portion of the stress–strain curve. An elastic material does not necessarily obey Hooke's law, since it is possible for a material to return to its original shape without the stress being proportional to the strain. If a material does obey Hooke's law, however, it is elastic.

The straight portion of the stress–strain curve for many plastics is difficult to locate, and it is necessary to construct a straight line tangent to the initial portion of the curve to use as a modulus. The shape of a line so obtained is called the initial modulus. In some plastics, the initial modulus can be misleading, owing to the nonlinear elasticity of the material. Some suppliers therefore provide the so-called 1 per cent secant modulus, which is the ratio of stress to strain at 1 per cent strain on the stress–strain curve. In the illustration of typical stress–strain curves in Fig. 3, the secant modulus at the point *E* is the slope of the line *OE*.

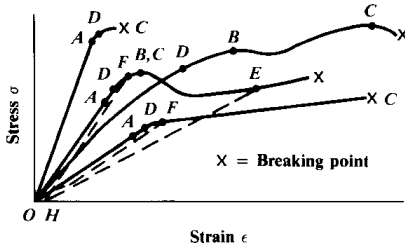


Fig. 3. Typical Stress–Strain Curves

For metals, Young's modulus is expressed in terms of 10^6 lb_f/in.², N/m², or Pa, as convenient (see starting on page 2525). For plastics, tensile modulus is expressed as 10^5 lb_f/in.² or in GPa (1 GPa = 145,000 lb_f/in.²).

Secant modulus is the ratio of stress to corresponding strain at any point on the stress–strain curve (see *Modulus of Elasticity*).

Proportional limit is the greatest stress at which a material is capable of sustaining the applied load without losing the proportionality of stress to strain. This limit is the point on the stress–strain curve where the slope begins to change, as shown at *A* on each of the curves in Fig. 3. Proportional limit is expressed in lb_f/in.² (MPa or GPa).

Yield point is the first point on the stress–strain curve where an increase in strain occurs without an increase in stress, and is indicated by *B* on some of the curves in Fig. 3. The slope of the curve is zero at this point; however, some materials do not have a yield point.

Ultimate strength is the maximum stress a material withstands when subjected to a load, and is indicated by *C* in Fig. 3. Ultimate strength is expressed in lb_f/in.² (MPa or GPa).

Elastic limit is indicated by the point *D* on the stress–strain curve in Fig. 3, and is the level beyond which the material is permanently deformed when the load is removed. Although many materials can be loaded beyond their proportional limit and still return to zero strain when the load is removed, some plastics have no proportional limit in that no region exists where the stress is proportional to strain (i.e., where the material obeys Hooke's law).

Yield strength is the stress at which a material shows a specified deviation from stress to strain proportionality. Some materials do not show a yield strength clearly, and it may be desirable to choose an arbitrary stress level beyond the elastic limit, especially with plas-

tics that have a very high strain at the yield point, to establish a realistic yield strength. Such a point is seen at F on some of the curves in Fig. 3, and is defined by constructing a line parallel to OA at a specified offset strain, H . The stress at the intersection of the line with the stress-strain curve at F would be the yield strength at H offset. If H were at 2 per cent strain, F would be described as the yield strength at a 2 per cent strain offset.

Poisson's ratio is defined on page 196. Under a tensile load, a rectangular bar of length L , with sides of widths b and d , lengthens by an amount ΔL , producing a longitudinal strain of

$$\epsilon = \frac{\Delta L}{L} \quad (5)$$

The bar is reduced in its lateral dimensions and the associated lateral strains will be opposite in sign, resulting in

$$\epsilon = -\frac{\Delta b}{b} = -\frac{\Delta d}{d} \quad (6)$$

If the deformation is within the elastic range, the ratio (Poisson's ratio ν) of the lateral to the longitudinal strains will be constant. The formula is:

$$\nu = \frac{\text{Lateral Strain}}{\text{Longitudinal Strain}} = \frac{\Delta d/d}{\Delta L/L} \quad (7)$$

Values of ν for most engineering materials lie between 0.20 and 0.40, and these values hold for unfilled rigid thermoplastics. Values of ν for filled or reinforced rigid thermoplastics fall between 0.10 and 0.40 and for structural foam between 0.30 and 0.40. Rigid thermoset plastics have Poisson's ratios between 0.20 and 0.40, whether filled or unfilled, and elastomers can approach 0.5.

Shear stress is treated on page 207. Any block of material is subject to a set of equal and opposite shearing forces Q . If the block is envisaged as an infinite number of infinitesimally thin layers as shown diagrammatically in Fig. 4, it is easy to imagine a tendency for one layer subject to a force to slide over the next layer, producing a shear form of deformation or failure. The shear stress τ is defined as

$$\tau = \frac{\text{Shear Load}}{\text{Area Resisting Load}} = \frac{Q}{A} \quad (8)$$

Shear stress is always tangential to the area on which it acts. Shearing strain is the angle of deformation γ and is measured in radians.

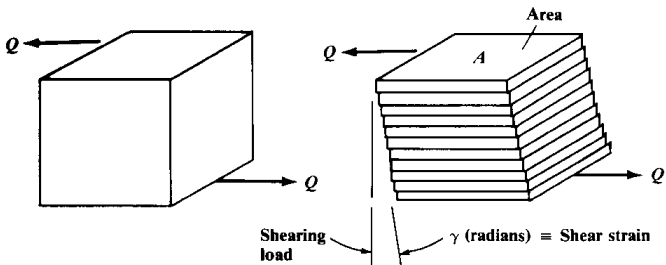


Fig. 4. Shear Stress is Visualized as a Force Q Causing Infinitely Thin Layers of a Component to Slide Past Each Other, Producing a Shear Form of Failure

Shear modulus is a constant G , otherwise called the modulus of rigidity, and, for materials that behave according to Hooke's law, is directly comparable to the modulus of elasticity used in direct stress calculations. The constant is derived from

$$G = \frac{\text{Shear Stress}}{\text{Shear Strain}} = \frac{\tau}{\gamma} \quad (9)$$

Relating Material Constants: Although only two material constants are required to characterize a material that is linearly elastic, homogeneous, and isotropic, three such constants have been introduced here. These three constants are tensile modulus E , Poisson's ratio ν , and shear modulus G , and they are related by the following equation, based on elasticity principles:

$$\frac{E}{G} = 2(1 + \nu) \quad (10)$$

This relationship holds for most metals and is generally applicable to injection-moldable thermoplastics. It must be remembered, however, that most plastics, and particularly fiber-reinforced and liquid crystalline materials, are inherently either nonlinear, or anisotropic, or both.

Direct shear refers to a shear strength test much used in the plastics industry with a setup similar to that shown in Fig. 5, and the results of such tests are often described in manufacturers' marketing data sheets as the shear strength of the material. The shear strength reported from such a test is not a pure shear strength because a considerable part of the load is transferred by bending or compressing, or both, rather than by pure shear, and results can be affected by the susceptibility of the material to the sharpness of the load faces in the test apparatus. Thus, the test cannot be used to develop shear stress–strain curves or to determine the shear modulus.

When analyzing plastics in a pure shear situation or when the maximum shear stress is calculated in a complex stress environment, designers often use a shear strength value of about half the tensile strength, or the direct shear strength obtained from the test referred to above, whichever is least.

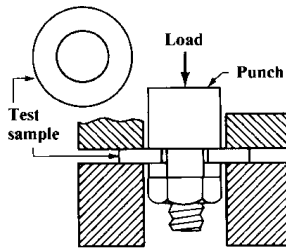


Fig. 5. Direct Shear Test Used in the Plastics Industry

True stress and true strain are terms not in frequent use. In Fig. 2, the stress, sometimes called the engineering stress, is calculated from an increasing load F , acting over a constant area A . Because the cross-sectional area is reduced with most materials, use of that smaller cross-sectional area in the calculation yields what is called the "true stress." In addition, the direct strain referred to earlier, that is, the total change in length divided by the original length, is often called the "engineering strain." The true strain would be the instantaneous deformation divided by the instantaneous length. Therefore, the shape of such a stress–strain curve would not be the same as a simple stress–strain curve. Modulus values and stress–strain curves are almost universally based on engineering stress and strain.

Other Measures of Strength and Modulus.—Tensile and compression properties of many engineering materials, which are treated as linearly elastic, homogeneous, and isotropic, are often considered to be identical, so as to eliminate the need to measure properties in compression. Also, if tension and compression properties are identical, under standard beam bending theory, there is no need to measure the properties in bending. In a concession to the nonlinear, anisotropic nature of most plastics, these properties, particularly flexural properties, are often reported on manufacturers' marketing data sheets.

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. For design purposes it often is necessary to know the stress–strain relationship for compression loading. With most elastic materials at low stress levels, the tensile and compressive stress–strain curves are nearly equivalent. At higher stress levels, the compressive strain is less than the tensile strain. Unlike tensile loading, which usually results in a clear-cut failure, stressing in compression produces a slow and indefinite yielding that seldom leads to failure. Because of this phenomenon, compressive strength is customarily expressed as the stress in $\text{lb}_f/\text{in.}^2$ (Pa) required to deform a standard plastics test specimen to a certain strain. Compression modulus is not always reported, because defining a stress at a given strain is equivalent to reporting a secant modulus. If a compression modulus is given, it is usually an initial modulus.

Bending Strength and Modulus: When material of rectangular cross-section is bent, it is apparent that one surface is stretched in tension and the other side is compressed. Within the material is a line or plane of zero stress called the neutral axis. Simple beam bending theory makes the following assumptions: that the beam is initially straight, unstressed, and symmetric; the material is linearly elastic, homogeneous, and isotropic; the proportional limit is not exceeded; Young's modulus for the material is the same in tension and compression; and all deflections are small so that planar cross-sections remain planar before and after bending.

In these conditions, the formula for bending stress σ is

$$\sigma = \frac{3FL}{2bh^2} \quad (11)$$

the formula for bending or flexural modulus E is

$$E = \frac{FL^3}{4bh^3Y} \quad (12)$$

and the formula for deflection Y is

$$Y = \frac{FL^3}{4Ebh^3} \quad (13)$$

where F , the force in pounds, is centered between the specimen support points, L is the distance in inches between the support points, b and h are the width and thickness of the test specimen in inches, and Y is the deflection in inches at the central load point.

Using the preceding relationships, the flexural strength and flexural modulus (of elasticity) for any material can be determined in the laboratory. The flexural modulus reported is usually the initial modulus from the load deflection curve. Most plastics parts must be analyzed in bending, so use of flexural values should give more accurate results than corresponding tensile values.

Rate Dependence of Mechanical Properties: Tensile and flexural data in manufacturers' literature are measured at specific displacement rates. These rates are usually not consistent with the loading environment encountered in use of the product. The same plastics material, under differing rates or in other environmental conditions, can produce different stress–strain curves. Designers should be aware of the loading rates in specific applica-

tions and request the appropriate data. End-use testing must always be considered, but particularly when adequate data are not available.

Time-Related Mechanical Properties.—Mechanical properties discussed previously were related to loads applied gradually and applied for short periods. Long-term and very short-term loading may give somewhat different results. With high-performance thermoplastics it is important to consider creep, impact, fatigue, and related issues. Even the best laboratory test methods do not always predict structural response of production parts accurately, and other factors may also affect results.

Creep is defined as increasing strain over time in the presence of a constant stress when deformation continues without increases in load or stress. The rate of creep for a given material depends on applied stress, temperature, and time.

Creep behavior of a material is important, and a crucial issue with plastics, where parts are to be subjected to loads for extended periods and where the maximum deflection is critical. To determine the creep behavior, test samples may be loaded in tension, compression, or flexure in a constant-temperature environment. Under constant loads, deflection is recorded at regular intervals over suitable periods. Results are generally obtained for four or more stress levels and recorded as creep curves of strain versus time on a logarithmic scale. In general, crystalline materials have lower creep rates than amorphous plastics. Glass reinforcement generally improves the creep resistance.

Apparent or Creep Modulus: If the deflection of a part subjected to continuous loading is calculated by using the modulus of elasticity E , results are likely to be inaccurate because the effects of creep have not been considered. If the stress level and temperature are known and creep curves are available for the temperature in question, an apparent or creep modulus E_{app} can be calculated from the creep curves by the formula: $E_{app} = \sigma/\epsilon_c$, where σ is the calculated stress level and ϵ_c is the strain from the creep curve at the expected time and temperature.

This value E_{app} can be used instead of E in predicting the maximum deflection, using the methods described subsequently (page 577).

Manufacturers' data often include curves of creep modulus (or log creep modulus) versus log time at either constant stress or constant strain, derived from creep data. This information may also be provided as tables of values at constant stress and temperature for various time periods. Some manufacturers provide creep data in the form of creep modulus figures rather than curves.

Creep rupture data are obtained in the same manner as creep data except that higher stresses are used and time is measured to failure. Such failures may be brittle or ductile with some degree of necking. Results are generally plotted as log stress versus log time to failure.

Stress relaxation occurs when plastics parts are assembled into a permanent deflected condition, as in a press fit, a bolted assembly, or some plastics springs. Under constant strain over a period of time, the stress level decreases due to the same internal molecular movement that produces creep. Stress relaxation is important with such applications as bolt preloading and springs, where loading must be maintained. The relaxation can be assessed by applying a fixed strain to a sample and measuring the load over time. A relaxation modulus similar to the creep modulus can be derived from the relaxation data. Relaxation data are not as readily available as creep data, but the decrease in load due to stress relaxation can be approximated by using the creep modulus E_{app} calculated from the creep curves.

Plastics parts often fail due to imposition of excessive fixed strains over extended periods of time, for example, a plastics tube that is a press fit over a steel shaft. No relaxation rupture equivalent to creep rupture exists, so for initial design purposes a strain limit of 20 per cent of the strain at the yield point or yield strength is suggested for high-elongation plas-

tics. For low-elongation brittle plastics that have no yield point, 20 per cent of the elongation at break is also recommended. These figures should be regarded only as guidelines for development of initial design concepts; prototype parts should be thoroughly tested under end-use conditions to confirm the suitability of the design. Higher or lower property limits may also be indicated in manufacturers' data on specific materials.

Extrapolating creep and relaxation data must be done with caution. When creep and relaxation data are plotted as log property against log time, the curves are generally less pronounced, facilitating extrapolation. This procedure is common practice, particularly with creep modulus and creep rupture data. Extrapolation should not exceed one unit of log time, and the strain limit of 20 per cent of the yield or ultimate strength mentioned above should not be exceeded.

Impact loading describes a situation in which a load is imposed rapidly. Any moving body has kinetic energy and when the motion is stopped by a collision, the energy is dissipated. Ability of a plastics part to absorb energy is determined by the shape, size, thickness, and type of material. Impact testing methods now available do not provide designers with information that can be used analytically. The tests can be used for comparing relative notch sensitivity or relative impact resistance, so can be useful in choosing a series of materials to be evaluated for an application or in grading materials within a series.

Impact testing by the Izod and Charpy methods, in which a pendulum arm is swung from a certain height to impact a notched test specimen, is the most widely used for measuring impact strength. Impact with the test specimen reduces the energy remaining in the arm, and this energy loss is recorded in ft-lb (J). The value of such tests is that they permit comparison of the relative notch toughness of two or more materials under specific conditions.

Tensile impact tests mount the test specimen on the swinging arm. Attached to the test specimen is a cross piece that is arrested by a notched anvil as the bar swings down, allowing the energy stored in the arm to break the specimen under tension as it passes through the notch. Another impact test used for plastics allows a weighted, round-ended cylindrical "dart" to fall on a flat disk of the plastics to be tested. This test is good for ranking materials because it represents conditions that are encountered by actual parts in certain applications.

Fatigue tests are designed to measure the relative ability of plastics materials to withstand repeated stresses or other cyclic phenomena. For example, a snap-action, or snap-fit latch that is continually opened and closed, a gear tooth, a bearing, a structural component subject to vibration or to repeated impacts. Cyclic loading can cause mechanical deterioration and progressive fracture, leading to failure in service. Typical fatigue tests are carried out on machines designed to subject a cantilever test piece to reversing flexural loading cycles at different stress levels. Numbers of cycles before failure are recorded for each stress level. Data are normally presented in plots of log stress versus log cycles called *S-N* curves for specific cycle rates and environmental temperatures. With thermoplastics materials there is the added complication that heat built up by the frequency of the cyclic stress may contribute to failure. Significantly different *S-N* curves can be produced for the same materials by testing at different frequencies, mean stresses, waveforms, and methods, such as testing in tension rather than in bending. Testing usually cannot reproduce the conditions under which components will work. Only tests on the end product can determine whether the design is suitable for the purpose to be served.

Thermal Properties.—Melting temperatures of crystalline thermoplastics are sharp and clearly defined, but amorphous and liquid crystalline materials soften and become more fluid over wider temperature ranges. Melting points have greater significance in molding and assembly operations than in product design, which usually deals with the product's temperatures.

Glass transition temperature is a level at which a plastics material undergoes a significant change in properties. Below this temperature T_g , the material has a stiff, glassy, brittle response to loads. Above T_g the material has a more ductile, rubbery response.

Vicat softening point is the temperature at which a small, circular, lightly gravity-loaded, heated probe penetrates a specific distance into a thermoplastics test specimen. This test measures the ability of a thermoplastics material to withstand a short-term contact with a heated surface, and is most useful for crystalline plastics. Amorphous thermoplastics materials tend to creep during the test, which reduces its usefulness for such materials.

Deflection temperature under load (DTUL) is the temperature at which a test bar of 0.5 in. thickness, loaded to a specified bending stress, will deflect by 0.010 in. This test is run at bending stresses of 66 lb_f/in.² or 264 lb_f/in.² or both. The value obtained is sometimes referred to as the heat distortion temperature (HDT), and is an indication of the ability of the material to perform at elevated temperatures under load. Both stress and deflection for a specific design of test bar are given so the test may be regarded as establishing the temperature at which the flexural modulus is reduced to particular values, 35,200 lb_f/in.² at 66 lb_f/in.² stress, and 140,000 lb_f/in.² at 264 lb_f/in.² stress.

Table 1. Typical Values of Coefficient of Linear Thermal Expansion for Thermoplastics and Other Commonly Used Materials

Material ^a	in./in./deg F × 10 ⁻⁵	cm/cm/deg C × 10 ⁻⁵	Material ^b	in./in./deg F × 10 ⁻⁵	cm/cm/deg C × 10 ⁻⁵
Liquid Crystal—GR	0.3	0.6	ABS—GR	1.7	3.1
Glass	0.4	0.7	Polypropylene—GR	1.8	3.2
Steel	0.6	1.1	Epoxy—GR	2.0	3.6
Concrete	0.8	1.4	Polyphenylene sulfide—GR	2.0	3.6
Copper	0.9	1.6	Acetal—GR	2.2	4.0
Bronze	1.0	1.8	Epoxy	3.0	5.4
Brass	1.0	1.8	Polycarbonate	3.6	6.5
Aluminum	1.2	2.2	Acrylic	3.8	6.8
Polycarbonate—GR	1.2	2.2	ABS	4.0	7.2
Nylon—GR	1.3	2.3	Nylon	4.5	8.1
TP polyester—GR	1.4	2.5	Acetal	4.8	8.5
Magnesium	1.4	2.5	Polypropylene	4.8	8.6
Zinc	1.7	3.1	TP Polyester	6.9	12.4
ABS—GR	1.7	3.1	Polyethylene	7.2	13.0

^a GR = Typical glass fiber-reinforced material. Other plastics materials shown are unfilled.

^b GR = Typical glass fiber-reinforced material. Other plastics materials shown are unfilled.

Linear thermal expansion: Like metals, thermoplastic materials expand when heated and contract when cooled. For a given temperature range, most plastics change dimensions much more than metals. The coefficient of linear thermal expansion (CLTE) is the ratio of the change in a linear dimension to the original dimension for a unit change of temperature and is expressed as in./in./degree F, or cm/cm/degree C. Typical average values for common materials are shown in Table 1. These values do not take account of grades, molding conditions, wall thickness, or direction of flow in molding.

Thermal conductivity is the rate at which a material conducts heat energy along its length or through its thickness.

Aging at elevated temperatures may affect physical, mechanical, electrical, or thermal properties of plastics materials. Data from tests on specimens stored at specific tempera-

tures for suitable periods are presented as plots of properties versus aging time at various temperatures, and may be used as an indication of thermal stability of the material.

Temperature index is a rating by Underwriters Laboratories (UL) of electrical and mechanical properties (with and without effects of impacts) of plastics materials used in electrical equipment for certain continuous operating conditions.

Flammability ratings also are produced by Underwriters Laboratories. UL tests measure the ability to continue burning after a flame is removed, and the percentage of oxygen needed for the material to continue burning. Other tests measure combustibility, ignition temperatures, and smoke generation.

Effect of Temperature on Mechanical Properties.—The inverse relationship between strain rate and temperature must be kept in mind when designing with plastics materials. Stress/strain curves for tests performed with one strain rate at several temperatures are similar to those for tests with one temperature and several strain rates. Therefore, very high strain rates and very low temperatures produce similar responses in materials. Conversely, the effects of very low strain rates, that is, creep effects, can be determined more quickly by testing at elevated temperatures. Testing at temperatures near or above the highest values expected in everyday use of a product helps the designer estimate long-term performance of components.

Strength, modulus, and elongation behavior are similar for tensile, compressive, flexural, and shear properties. Generally, strength and modulus decrease with increasing temperature. The effect of temperature increases is shown by the curves in Fig. 6 for crystalline and amorphous materials, where a gradual drop in modulus is seen as the glass transition temperature T_g is approached. Above the glass transition temperature, amorphous materials have a rapid loss of modulus, and even with glass-fiber reinforcement they display a rapid drop in modulus above the glass transition temperature. Crystalline materials maintain a significant usable modulus at temperatures approaching the crystalline melting point, and glass-fiber reinforcement can significantly improve the modulus of crystalline materials between the glass transition and melting temperatures. Generally, strength versus temperature curves are similar to modulus curves and elongation increases with rising temperatures.

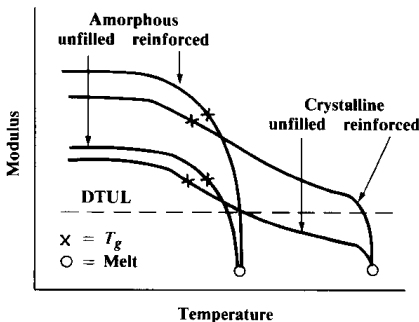


Fig. 6. Modulus Behavior of Crystalline and Amorphous Plastics Showing T_g and Melt Temperatures and the Effect of Reinforcement on Deflection Temperature Under Load (DTUL)

Isochronous stress and isometric stress curves are taken from measurements made at fixed temperatures, although sometimes curves are available for other-than-ambient temperatures. Creep rupture and apparent modulus curves also are often plotted against the log

of time, with temperature as a parameter. Refer to sections on creep, creep modulus, and creep rupture beginning on page 577.

As temperatures drop significantly below ambient, most plastics materials lose much of their room temperature impact strength, although a few materials show only a gradual decrease. Plastics reinforced with long glass fibers have relatively high Izod impact values at room temperature, and retain these values at -40 degrees F (-40 degrees C).

Electrical Properties.—The most notable electrical property of plastics is that they are good insulators, but there are many other electrical properties that must be considered in plastics part design.

Conductivity in solids depends on the availability and mobility of movable charge carriers within the material. Metals are good conductors because the metal atom has a loosely held, outermost electron, and the close proximity of the atoms allows these outer electrons to break free and move within the lattice structure. These free electrons give metals the ability to conduct large currents, even at low voltages. Outer electrons in materials such as glass, porcelain, and plastics are tightly bound to the atoms or molecules so there are no free electrons. Electrical current cannot be conducted and the materials act as insulators.

Volume resistivity is the electrical resistance of a material when a current is applied to it. The resistance is measured in ohm-cm. Materials having values above 10^8 ohm-cm are considered to be insulators, and materials with values between 10^8 and 10^3 ohm-cm are considered to be partial conductors. Most plastics have volume resistivity in the range of 10^{12} to 10^{18} ohm-cm.

Surface resistivity is a measure of the susceptibility of a material to surface contamination, particularly moisture. The tests use electrodes that are placed on the same side of the material.

Dielectric strength is a measure of the voltage required to cause an insulator to break down and allow an electric current to pass and is expressed in volts per 0.001 in. of thickness. Variables that may affect test results include temperature, sample thickness and condition, rate of voltage increase and duration of test, sample contamination, and internal voids.

Dielectric constant or permittivity is a dimensionless constant that indicates how easily a material can become polarized by imposition of an electrical field on an insulator. Reversal of the direction of flow of the current results in reversal of the polarization. The dielectric constant is the ratio of the permittivity of the material in normal ambient conditions to the permittivity of a vacuum. Permittivity is important when plastics are used as insulating materials in high-frequency electrical apparatus. Changes in temperature, moisture levels, electrical frequency, and part thickness may affect the dielectric constant.

Heat dissipation factor is a measure of heat energy dissipated by rapidly repeated reversals of polarization, as with an alternating current. The dissipation factor may also be thought of as the ratio of heat energy lost compared to that transmitted at a given frequency, often 1 MHz (10^6 cycles/sec). Some dielectric constants and heat dissipation factor values are shown in Table 2.

Arc resistance is the length of time required for an electric arc imposed on the surface of an insulating material to develop a conductive path. Materials that resist such a development are preferred for parts of switchgear and other high-voltage apparatus. Tests are used mostly for thermosetting materials because conductive paths can be formed on such materials from the decomposition products resulting from heating by an electric arc.

Table 2. Typical Values of Dielectric Constants and Heat Dissipation Factors for Various Thermoplastics at Room Temperature

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

Comparative tracking index (CTI) is another UL test that is similar to the arc resistance test except that the surface to be tested is precoated with an ammonium chloride electrolyte. The test measures the voltage required to cause a conductive path to form between the electrodes, and indicates the arc resistance of a contaminated surface, often found in electrical and electronic equipment.

End-Use Environmental Considerations.—The environment that will be encountered by the product is a prime consideration at the design stage. Problems with cracking, crazing, discoloration, loss of properties, melting, or dissolving can be encountered in the presence of high or low temperatures, chemical substances, energy sources, and radiation. Plastics components also are often subjected to processing, assembly, finishing, and cleaning operations before reaching their ultimate environment.

The stress level in the plastics product greatly affects performance. Generally, increased stress levels resulting from injection molding, forming, assembly work, and end-use forces reduce resistance to environmental factors. Although many plastics are hygroscopic and absorption of water results in dimensional and property changes, plastics are widely accepted because of their relative compatibility with the environment compared with metals. Some chemicals attack the polymer chain directly by reaction, resulting in a progressive lowering of the molecular weight of the polymer and changes in the short-term mechanical properties. Others dissolve the material, although high-molecular-weight plastics dissolve very slowly. Swelling, changes in weight and dimensions, and loss of properties are evidence of solvation.

Plasticization may result if the chemical is miscible with the polymer, resulting in loss of strength, stiffness, and creep resistance, and increased impact resistance. The material may swell and warp due to relaxation of molded-in stresses. Environmental stress cracking may cause catastrophic failure when plastics are stressed, even when the product appears to be unaffected by exposure to a chemical.

Chemical compatibility data are obtained from standard test bars exposed to or placed in the chemical of study and tested as previously described for such properties as tensile strength, flexural modulus, dimensional change, weight, and discoloration. Chemical resistance from some commonly used thermoplastics materials are shown in Table 3, but are only general guidelines and cannot substitute for tests on the end product. More extensive tests expose samples to a chemical in the presence of fixed stress or fixed strain distribution along its length, followed by examination for the stress or strain location at which damage begins.

The preceding tests may provide data about chemical compatibility but do not generate reliable information on performance properties for design purposes. The only test that provides such information is the creep rupture test, conducted at appropriate temperatures in the environment that will be encountered by the product, preferably on prototype parts. Plastics are degraded to varying degrees by ultraviolet light, which causes fading, chalking, and embrittlement. Plastics that will resist the action of ultraviolet rays are available on the market.

Table 3. Chemical Resistance of Various Materials by Chemical Classes

	Polyarylate								Polycarbonate								
	Polyphenylene Sulfide* x x x x x x x x								Polysulfone*								
	Liquid Crystal Polymer* x x x x x x x x								Modified Polyphenylene Oxide								
	Polyester Elastomer x x x x x x x x								Polypropylene								
	Thermoplastic Polyester (PET) x x x x x x x x								ABS								
	Thermoplastic Polyester (PBT) x x x x x x x x								316 Stainless Steel								
	Nylon 6/6 x x x x x x x x								Carbon Steel								
	Acetal Homopolymer x x x x x x x x								Aluminum								
	Acetal Copolymer x x x x x x x x																
ACIDS AND BASES																	
Acids, weak	A	B	C	A	A	A	A	A	A	B	A	A	A	A	C	Dilute mineral acids	
Acids, strong	C	C	C	B	—	C	B	A	—	C	C	—	A	A	B	C	Concentrated mineral acids
Bases, weak	A	C	A	B	B	A	B	A	—	C	A	A	A	A	B	C	Dilute sodium hydroxide
Bases, strong	A	C	C	—	—	B	C	A	—	C	A	—	A	A	B	C	Concentrated sodium hydroxide
Acids, organic, weak	A	B	C	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	Trichloroacetic acid
AUTOMOTIVE																	
Automotive, fuel	A	A	A	A	A	A	A	A	C	A	C	C	A	A	A	A	
Automotive, lubricants	A	A	A	A	A	A	A	A	C	A	A	A	A	A	B	A	
Automotive, hydraulic	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	B	C	A	A	A	A	Heptane, hexane
Aliphatic hydrocarbons, halogenated	A	B	C	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	B	Ethanol, cyclohexanol
Aldehydes	A	A	A	A	B	A	A	A	—	C	B	—	A	—	A	B	Acetaldehyde, formaldehyde
Amines	—	—	—	—	—	—	C	B	—	C	C	—	A	—	A	B	Aniline, triethanolamine
Aromatic hydrocarbons	A	B	A	A	B	B	A	A	C	C	C	C	C	A	A	A	Toluene, xylene, naphtha
Aromatic hydrocarbons, halogenated	—	—	—	—	—	C	—	A	C	C	C	—	—	A	A	A	Chlorobenzene
Aromatic, hydroxy	C	C	C	C	—	C	A	A	—	C	C	—	A	—	B	C	Phenol
Esters	B	B	A	B	B	A	A	A	C	C	C	—	C	—	B	B	Ethyl acetate, dioctyl phthalate
Ethers	B	—	A	A	—	—	—	A	—	A	B	—	C	—	A	A	Butyl ether, diethyl ether
Ketones	B	B	A	B	B	B	A	A	C	C	C	—	B	C	A	A	Methyl ethyl ketone, acetone
MISCELLANEOUS																	
Detergents	A	—	A	—	B	—	—	A	A	A	—	B	A	—	A	A	Laundry and dishwashing detergents, soaps
Inorganic salts	B	B	B	—	A	—	—	A	—	A	—	—	A	A	B	B	Zinc chloride, cupric sulfate
Oxidizing agents, strong	C	C	C	—	C	—	B	B	—	C	—	—	A	—	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	C	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. Furthermore, 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 on one plastics of various chemicals in the same category ranged from essentially no effect to total dissolution. Therefore, an "A" rating for a particular plastics 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 "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 for hot water, steam, and materials marked with a * ≅ 200°. Generally, extended exposure (more than a week) data were used.

DESIGN ANALYSIS

Structural Analysis.—Even the simplest plastics parts may be subjected to stresses caused by assembly, handling, temperature variations, and other environmental effects. Simple analysis using information in *Calculating Moment of Inertia* starting on page 217 and *Beam Calculations* on page 236 can be used to make sure that newly designed parts can withstand these stresses. These methods may also be used for product improvement, cost reduction, and failure analysis of existing parts.

Safety Factors: In setting safety factors for plastics parts there are no hard and fast rules. The most important consideration is 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 not cause much concern, but the failure of a pressure vessel or water valve might have serious safety or product liability implications. Tests should be run on actual parts at the most extreme operating conditions that could possibly be encountered before any product is marketed. For example, maximum working load should be applied at the maximum temperature and in the presence of any chemicals that might be encountered in service. Loads, temperatures, and chemicals to which a product may be exposed prior to its end use also should be investigated. Impact loading tests should be performed at the lowest temperature expected, including during assembly and shipping. Effects of variations in resin lots and molding conditions must also be considered.

Failures in testing of preproduction lots often can be corrected by increasing the wall thickness, using ribs or gussets, and eliminating stress concentrations. Changing the material to another grade of the same resin or to a different plastics with more suitable mechanical properties is another possible solution. Reviews of product data and discussions with experienced engineers suggest the design stresses shown in Table 4 are suitable for use with the structural analysis information indicated above and the equations presented here, for preliminary design analysis and evaluating general product dimensions. Products designed under these guidelines must be thoroughly tested before being marketed.

Table 4. Design Stresses for Preliminary Part Designs Expressed as a Percentage of Manufacturers' Data Sheet Strength Values

	Failure Not Critical	Failure Critical
Intermittent (Nonfatigue) loading	25–50	10–25
Continuous loading	10–25	5–10

Failure Criteria: Setting of failure criteria is beyond the scope of this section, which is intended to give only basic general information on plastics. Designers who wish to rationalize complex stress states and analyses might investigate the maximum shear theory of failure (otherwise known as Coulomb or Tresca theory). It is further suggested that the shear strength be taken as the manufacturer's published shear strength, or half the tensile strength, whichever is lower. Better still, use half the stress at the elastic limit, if known.

Pressure Vessels: The most common plastics pressure vessel takes the form of a tube with internal pressure. In selecting a wall thickness for the tube, it is convenient to use the thin-wall hoop stress equation:

$$\text{hoop stress } \sigma = \frac{Pd}{2t} \quad (14)$$

where P = the uniform internal pressure in the tube, d = inside diameter of the tube, and t = the tube wall thickness. This equation is reasonably accurate for tubes where the wall thickness is less than 0.1 of the inside diameter of the tube. As the wall thickness increases, the error becomes quite large.

For thick-walled tubes the maximum hoop stress on the wall surface inside the tube can be calculated from

$$\text{hoop stress } \sigma = P \frac{1+R}{1-R} \quad (15)$$

where $R = (d_i/d_o)^2$, and d_i and d_o are the inside and outside diameters of the tube, respectively.

Press Fits: Press fits are used widely in assembly work for speed and convenience, although they sometimes are unsatisfactory with thermoplastics parts. Common applications are to a plastics hub or boss accepting a plastics or metal shaft or pin. Forcing the pin into the hole expands the hub, creating a tensile or hoop stress.

If the interference is too great, very high strain and stress develop and the plastics part will J) fail immediately by developing a crack parallel to the hub axis to relieve the stress, a typical hoop stress failure; K) survive assembly but fail prematurely due to creep rupture caused by the high induced-stress levels; and L) undergo stress relaxation sufficient to reduce the stress to a level that can be sustained.

For a typical press fit, the allowable design stress depends on the particular plastics material, temperature, and other environmental considerations. Hoop stress equations for such a design make use of a geometry factor γ :

$$\gamma = \frac{1 + (d_s/d_o)^2}{1 - (d_s/d_o)^2} \quad (16)$$

where d_s = diameter of the pin to be inserted and d_o = outside diameter of the boss.

When both the shaft and the hub are of the same, or essentially the same, materials, the hoop stress σ , given the diametral interference, $i = d_s - d_i$, is

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + 1} \quad (17)$$

and the allowable interference i_a , given the permissible design stress σ_a , is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + 1}{\gamma} \quad (18)$$

When the shaft is metal and the hub is plastics, the hoop stress, given i , is obtained from

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + \nu_p} \quad (19)$$

and the allowable interference i_a , given the permissible design stress for plastics σ_a , is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + \nu_p}{\gamma} \quad (20)$$

where E_p = modulus of elasticity of plastics and ν_p = Poisson's ratio for plastics.

Pipe Threads: Pipe threads on plastics pipes and other parts used in plastics plumbing and pneumatic assemblies require only hand tight assembly to effect a good seat, especially if a compatible sealant tape or compound is used. Assembling a tapered male pipe thread into a mating female thread in a plastics part is analogous to driving a cone into a round hole and may result in a split boss. Sometimes straight threads and an O-ring seal can avoid the need for pipe threads. When pipe threads must be used, torque control is essential.

When mating metal to plastics pipe threads, the threaded plastics component should be the male member, so that the plastics are in compression. If torque can be controlled during assembly, use fluoroplastics tape on female plastics pipe threads. If torque cannot be controlled, consider using an external hoop ring, either pressed on or molded in. Do not design

flats into plastics parts for assembly purposes, because they will encourage overtightening. If some provision for improved gripping must be made, use wings or a textured surface. An approximate formula for the hoop stress σ produced in a plastics boss with internal pipe threads is

$$\sigma = \frac{3T}{tdL} \quad (21)$$

where T = torque in in.-lb, t = wall thickness of the plastics boss in in., d = pipe outside diameter in in., and L = length of thread engagement in in.

This equation assumes certain geometric relationships and a coefficient of friction of 0.15. If compatible thread lubricants are used during assembly, the torque must be reduced. To ensure safety and reliability, all threaded assemblies must be subjected to long-term testing under operating pressures, temperatures, and stresses caused by installation procedures exceeding those likely to be encountered in service.

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 potential for thermal stress to exist. Typical examples are joining of nonreinforced thermoplastics parts with materials such as metals, glass, or ceramics that usually have much lower coefficients of thermal expansion. The basic relationship for thermal expansion is

$$\Delta L = \alpha L \Delta T \quad (22)$$

where ΔL = change in length, α = coefficient of thermal expansion (see Table 4), L = linear dimension under consideration (including hole diameters), and ΔT = temperature change.

If the plastics component is constrained so that it cannot expand or contract, the strain ϵ_T , induced by a temperature change, is calculated by

$$\epsilon_T = \frac{\Delta L}{L} = \alpha \Delta T \quad (23)$$

The stress can then be calculated by multiplying the strain ϵ_T by the tensile modulus of the material at the temperature involved. A typical example is of a plastics part to be mounted to a metal part, such as a window in a housing. Both components expand with changes in temperature. The plastics imposes insignificant load to the metal but considerable stress is generated in the plastics. For such an example, the approximate thermal stress σ_T in the plastics is given by

$$\sigma_T = (\alpha_m - \alpha_p) E_p \Delta T \quad (24)$$

where α_m = coefficient of thermal expansion of the metal, α_p = coefficient of thermal expansion of the plastics, and E_p = tensile modulus of the plastics at the temperature involved.

Other equations for thermal expansion in various situations are shown in Fig. 7.

Most plastics expand more than metals with temperature increases and their modulus drops. The result is a compressive load in the plastics that often results in buckling. Conversely, as the temperature drops, the plastics shrinks more than the metal and develops an increased tensile modulus. These conditions can cause tensile rupture of the plastics part. Clearances around fasteners, warpage, creep, or failure, or yield of adhesives tend to relieve the thermal stress. Allowances must be made for temperature changes, especially with large parts subjected to wide variations. Provision is often made for relative motion ΔL_{rel} , between two materials, as illustrated in Fig. 7:

$$\Delta L_{rel} = (\alpha_p - \alpha_m) L \Delta T \quad (25)$$

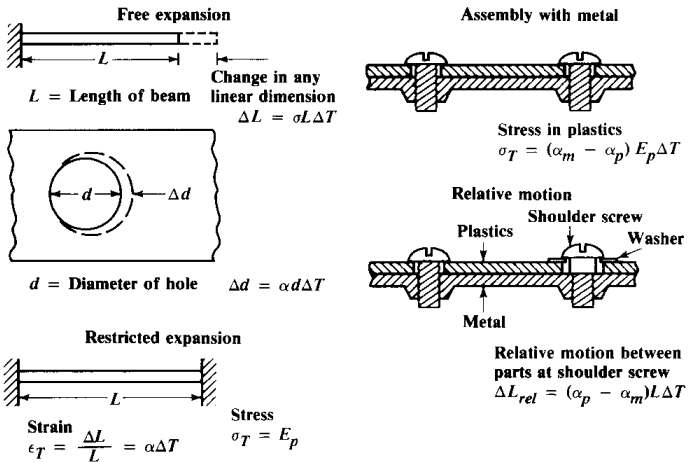


Fig. 7. Thermal Expansion Equations for Various Combinations of Materials and Situations

Design for Injection Moldings.—Injection molding uses equipment similar to that for die casting, in that a precision steel mold is clamped shut, and melted material (here, plasticized plastics) is forced into the cavity between the mold components. The pelletized plastics material is fed into a heated chamber, or barrel, by a large, slowly rotating screw, and is melted. When a sufficient quantity to fill the cavity has been prepared, the screw is moved axially under high pressure to force the material into the cavity. The mold has channels through which coolant is circulated to remove heat and to chill the plastics. When the plastics has cooled sufficiently, the mold is unclamped and opened, and the molding is forced out by strategically located ejectors. During cooling and removal, material for the next part is plasticized within the barrel, ready for the cycle to be repeated.

Product analysis provides a good approach to design for plastics molding. A basic principle of plastics molding design, when moldings are being substituted for parts made by other means, is to incorporate as many functions into the molding as possible, especially those requiring nuts, bolts, and washers, for instance. Material should be selected that fulfills the maximum requirements, such as the functions mentioned, as well as insulation from the passage of heat or electricity, and allows use of the minimum amount of material.

Important material selection criteria include ability to withstand the heat of assembly, finishing, shipping, operating, and heat from internal sources. Effects of chemicals in the environment and approvals of government and other agencies also should be checked. Many such approvals specify wall thicknesses, color additives, fillers, and operating temperatures. Plans for assembly by bonding may dictate use of certain materials, and the question of painting, plating, or other surface coatings must be considered. Cost of candidate materials compared with the alternatives must be weighed, using the formula for cost per in.³ = 0.0361 × specific gravity × material cost per lb. Material cost required for a part is obtained by multiplying the cost per in.³ by the part volume. A rough estimate of likely part cost is double the cost of material for the part.

Wall Thicknesses: The thickness of material used in a plastics molding is of the greatest importance, and should be settled before the mold is made, since modifications are costly. In general, wall thicknesses should be kept as thin as practical and as uniform as possible.

Ideally, the flow of molding material should be so arranged that it moves through thicker sections into thinner ones rather than the reverse. Geometric, structural, or functional needs may prevent ideal design, but examination of alternatives can often prevent problems from arising. Most injection-molded plastics parts range in thickness from $\frac{1}{32}$ to $\frac{3}{16}$ in. (0.8 to 4.8 mm) with the dimensions within that range related to the total size of the part.

Impact Resistance: The impact resistance of a plastics part is directly related to its ability to absorb mechanical energy without fracture or deformation, and this ability depends on the material properties and the part geometry. Increasing wall thickness may improve the impact resistance but may also hurt impact resistance by making the part too stiff so that it is unable to deflect and distribute the force.

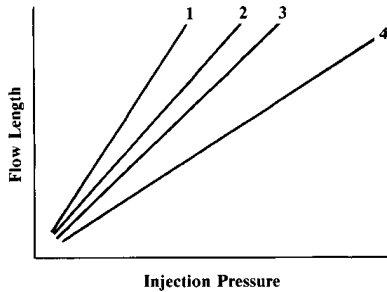


Fig. 8. Typical Spiral-Flow Curves for (1) Nylon 6/6, (2) Polyester Thermoplastics PBT, Liquid-Crystal-Glass-Reinforced, and Polyphenylene-Sulfide-Glass-Reinforced, (3) Acetal Copolymer, and (4) PBT-Glass-Reinforced Plastics Materials

Design engineers must also have some knowledge of mold design and, in determining wall thickness, should consider the ability of plastics to flow into the narrow mold channels. This flowability depends on temperature and pressure to some extent, but varies for different materials, as shown in Fig. 8.

Table 5 shows some typical nominal wall thicknesses for various types of thermoplastics.

Table 5. Typical Nominal Wall Thicknesses for Various Classes of Thermoplastics

Thermoplastics Group	Typical Working Range (in.)
Acrylonitrile-butadiene-styrene (ABS)	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
Polyvinyl chloride (PVC)	0.040–0.150
Styrene-acrylonitrile (SAN)	0.035–0.150

If the plastics part is to carry loads, load-bearing areas should be analyzed for stress and deflection. When stress or deflection is too high, solutions are to use ribs or contours to increase section modulus; to use a higher-strength, higher-modulus (fiber-reinforced) material; or to increase the wall thickness if it is not already too thick. Where space allows, adding or thickening ribs can increase structural integrity without thickening walls.

Equations (11), (12), and (13) can be related to formulas using the section modulus and moment of inertia on page 237, where Case 2, for (i), stress at the beam center is given by $\sigma = -W/4Z$.

On page 236, note that $Z = I \div$ distance from neutral axis to extreme fiber ($h \div 2$ in the plastics example). The rectangular beam section diagrammed on page 219 gives the equivalent of $I = bh^3/12$ for the rectangular section in the plastics example. Therefore,

$$Z = \frac{I}{h/2} = \frac{bh^3}{12} \times \frac{2}{h} = \frac{bh^2}{6}$$

In $\sigma = -W/4Z$, the $(-)$ sign indicates that the beam is supported at the ends, so that the upper fibers are in compression and the lower fibers are in tension. Also, $W = F$ and $l = L$ in the respective equations, so that stress, $\sigma = FL/4(bh^2)/6$, and $\sigma = 3FL/2bh^2$.

To calculate (ii) maximum deflection Y at load, use $Y = Wl^3/48EI$ from page 237, where $W = F$, $l = L$, $E = E$, from Equation (12) and $I = bh^3/12$. Therefore,

$$Y = \frac{FL^3}{48E(bh^2/12)} = \frac{FL^3}{4Ebh^3}$$

As an example, assume that a beam as described in connection with Equations (11), (12), and (13) is 0.75 in. wide, with a constant wall thickness of 0.080 in., so that the cross-sectional area is 0.060 in.², and there is a central load W of 5 lb. Based on a bending or flexural modulus of 300,000 lb/in.², the maximum stress is calculated at 6250 lb/in.² and the maximum deflection at 0.694 in. Both the stress and the deflection are too high, so a decision is made to add a rib measuring 0.040 in. thick by 0.400 in. deep, with a small draft of $\frac{1}{2}$ degree per side, to reinforce the structure.

The equations on page 237, the drawing page representing the ribbed section (neglecting radii), and the accompanying formulas, permit calculation of the maximum stress and deflection for the ribbed section.

With the new cross-sectional area only slightly larger at 0.0746 in.², the calculated stress is reduced to 2270 lb/in.², and the deflection goes down to 0.026 in., which is acceptable for both the material and the application. To achieve the same result from a heavier beam would require a thickness of 0.239 in., tripling the weight of the beam and increasing molding difficulties. The rib adds only 25 percent to the total section weight.

Use of ribs allows the structural characteristics of a part to be tailored to suit its function, but ribs can cause warping and appearance problems, so are best avoided if they are not structurally necessary. If the first parts produced require strengthening, ribs can be added or thickened without high cost after the tool is finished because the work consists only of removing steel from the mold. In general, ribs should have a base thickness of about half the thickness of the adjacent wall, and be kept as thin as possible where they are positioned near faces that need to have a good appearance.

Where structural strength is more important than appearance, or when using materials that have low shrinkage, ribs can be made 75 or 100 per cent of the wall thickness. However, where the rib base joins the main molding there is an increase in thickness forming a heavy mass of material. Shrinkage of this mass can produce a cavity or void, a hollow area or sink, or can distort the molding. If the mass is very large, cooling time may be prolonged, leading to low output from the machine. Large masses of material in other parts of a molding are also best avoided. These problems can usually be addressed by good mold design.

Ribs need not be of constant height or width, and are often varied in proportions to suit the stress distribution in the part. All ribs should have a minimum of $\frac{1}{2}$ degree of draft per side for ease of removal from the mold, and a minimum radius of 0.005 in. at the base to avoid stress-raising corners. Draft and thickness requirements will usually limit the height of the rib, which can be from 1.5 to 5 times the base thickness, and several evenly spaced ribs are generally preferred to a single large one. Smooth transitions should be made to other structural features such as bosses, walls, and pads.

Other ways to improve section properties include use of top-hat and corrugated sections, crowning or doming of some areas, and reinforcement with metal or other inserts that are placed in the mold before it is closed. To keep molded parts uniform in wall thickness, cores or projections may be provided in the mold to prevent a space being filled with molding material. Blind holes can be cored by pins that are supported on only one side of the mold and through holes by pins that pass through both sides. The length to width ratio should be kept as low as possible to prevent bending or breakage under the high pressures used in the injection molding process.

Agency approvals for resistance to flammability or heat, electrical properties, or other characteristics are usually based on specific wall thicknesses. These restrictions sometimes necessitate thicker walls than are required for structural strength purposes.

Table 6. Dimensional Changes for Various Combinations of Draft Angles and Draw Depths (Values to Nearest 0.001 in.)

Draw Depth (in)	Draft Angle (degrees)								
	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	2	3	4	5	
1	0.002	0.004	0.009	0.017	0.035	0.052	0.070	0.080	
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	0.088	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	0.349	0.524	0.699	0.875	

Draft: Most molded parts have features that must be cut into the mold perpendicular to the parting line. Removal of these parts from the mold is easier if they are tapered in the direction of mold opening. This taper is called draft in the line of draw or mold movement, and it allows the part to break free of the mold by creating a clearance as soon as the mold starts to open. Plastics materials shrink as they cool, so they grip mold projections very tightly and ejection can be difficult without sufficient draft. A draft of $\frac{1}{2}$ degree on each side of a projection on the part is generally considered as a minimum, although up to 3 degrees per side is often used. Draft angles in degrees for various draw depths, and the resulting dimensional changes per side in inches (rounded to three decimal places), between the dimensions at the base and at the top of a projection are shown in Table 6. A

rule of thumb is that 1 degree of draft yields 0.017 in. of difference in dimension per inch of draw length. Where a minimum of variation in wall thickness is needed to produce walls that are perpendicular to the direction of draw, the mold sometimes can be designed to produce parallel draft, as seen at the left in Table 6. The amount of draft required also depends on the surface finish of the mold walls. Any surface texture will increase the draft requirement by at least 1 degree per side for every 0.001 in. of texture depth.

Fillets, Radii, and Undercuts: Sharp corners are always to be avoided in injection-molded part designs because they represent points of stress concentration. Sharp corners in metal parts often are less important because the stresses are low compared with the strength of the material or because local yielding redistributes the loads. Sharp inside corners are particularly to be avoided in moldings because severe molded-in stresses are generated as the material shrinks onto the mold corner. Sharp corners also cause poor material flow patterns, reduced mechanical properties, and increased tool wear. Therefore, inside corner radii should be made equal to half the nominal wall thickness, with a minimum of 0.020 in. for parts subject to stress and 0.005 in. radius for stress-free parts. Outside corners should have a radius equal to the inside corner radius plus the wall thickness.

With an inside radius of half the wall thickness, a stress concentration of 1.5 is a reasonable assumption, and for radii down to 0.1 times the wall thickness, a stress concentration of 3 is likely. More information on stress concentrations is found in *Working Stress* on page 200, *Stress Concentration Factors* on page 200, and in the charts pages 201 through 204. A suitable value for q in Equation (8) on page 200, for plastics materials, is 1. Most plastics parts are so designed that they can be ejected parallel with the direction of mold parting. Complex parts with undercuts may require mold designs with cavity-forming projections that must move at an angle to the direction of opening. Between these two extremes lie such items as "windows," or simple openings in the side of a molding, which can be produced by the normal interaction of the two main parts of the mold.

Design for Assembly.—An advantage of the flexibility of plastics parts is that they can often be designed for assembly by means of molded-in snap-fit, press-fit, pop-on, and thread fasteners, so that no additional fasteners, adhesives, solvents, or special equipment is required. Improper assembly can be minimized, but tooling is often made more complex and disassembly may be difficult with these methods.

Chemical bonding involves fixtures, substances, and safety equipment, is suited to applications that must be leak-tight, and does not create stresses. However, adhesives and solvents can be dangerous and preparation and cure times can be prolonged.

Thermal welding methods include ultrasonic, hot-plate, spin, induction, and radio-frequency energy and require special equipment. Thermal methods are also used for staking, swaging, and other heat deformation procedures. Materials must be compatible and have similar melting temperatures.

Mechanical fasteners designed for metals are generally usable with plastics, and there are many other fasteners designed specifically for plastics. Typical are bolts, self-tapping and thread-forming screws, rivets, threaded inserts, and spring clips. Care must be taken to avoid overstressing the parts. Creep can result in loss of preload in poorly designed systems.

Snap-fit designs are widely used, a typical application being to battery compartment covers. All snap-fit designs have a molded part that must flex like a spring, usually past a designed-in interference, then return to its unflexed position to hold the parts together. There must be sufficient holding power without exceeding the elastic or fatigue limits of the material. With the typical snap-fit designs in Fig. 9, beam equations can be used to calculate the maximum strain during assembly. If the stress is kept below the yield point of the material, the flexing finger returns to its original position.

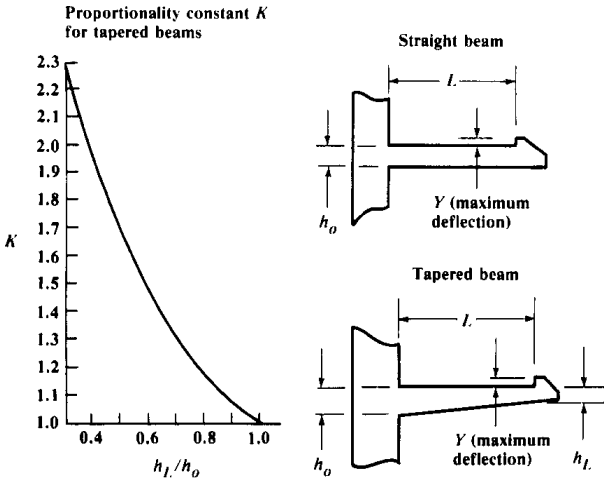


Fig. 9. Snap-fit Designs for Cantilever Beams with Rectangular Cross Sections

With some materials the calculated bending stress can exceed the yield point stress considerably if the movement is done rapidly. In other words, the flexing finger passes through its maximum deflection or strain and the material does not respond as it should if the yield stress has been greatly exceeded. It is common to evaluate snap-ins by calculating strain instead of stress.

Dynamic strain ϵ , for the straight beam, is calculated from

$$\epsilon = \frac{3Yh_0}{2L^2} \quad (26)$$

and for the tapered beam, from

$$\epsilon = \frac{3Yh_0}{2L^2K} \quad (27)$$

The derived values should be compared with the permissible dynamic strain limits for the material in question, if known. A tapered finger provides more-uniform stress distribution and is recommended where possible. Sharp corners or structural discontinuities that will cause stress concentrations on fingers such as those shown must be avoided.

Snap-in arrangements usually require undercuts produced by a sliding core in the mold as shown in Fig. 10a. Sometimes the snap finger can be simply popped off when the mold is opened. An alternative to the sliding core is shown in Fig. 10b, which requires an opening in the molding at the base of the flexing finger. Other snap-in assembly techniques that take advantage of the flexibility of plastics are shown in Fig. 11.

Molded-in threads in holes usually are formed by cores that require some type of unscrewing or collapsing mechanism leading to tooling complications. External threads can often be molded by positioning them across the parting plane of the mold. Molding of threads finer than 28 to the inch is generally not practical.

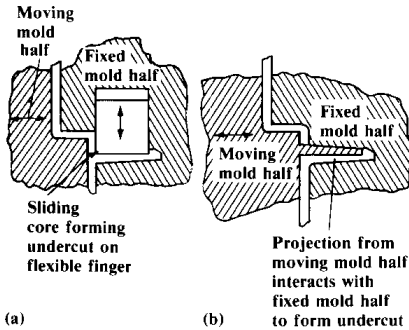


Fig. 10. (left) (a) Arrangement for Molding an Undercut on the End of a Flexible Finger Using a Sliding Core; (b) With the Undercut Formed by a Mold Projection, the Sliding Core is Eliminated.

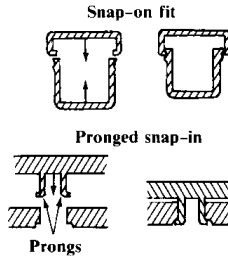


Fig. 11. (right) Examples of Snap-In and Snap-On Arrangements

Chemical bonding may use solvents or adhesives. Use of solvents is limited to compatible materials that can be dissolved by the same solvent. Chemical resistance of many plastics, especially crystalline materials, limits the use of this method. Safety precautions must also be considered in handling the solvents to protect workers and for solvent recovery. With adhesive bonding, a third adhesive substance is introduced at the interface between the parts to be joined. Adhesives can join plastics, metals, ceramics, glass, wood, or other bondable substances.

Typical adhesives used for thermoplastics are epoxies, acrylics, polyurethanes, phenolics, rubbers, polyesters, and vinyls. Cyanoacrylates are often used because of their rapid adhesion to many materials. Manufacturers' recommendations should be sought because many adhesives contain solvents that partially dissolve the plastics surfaces, giving improved adhesion. However, some adhesives can attack certain plastics, leading to deterioration and failure. The main disadvantages of adhesives are that they are slow, use long clamp times, require fixtures, and may involve special ovens or curing conditions. Surface preparation also may be difficult because the presence of grease, oil, mold-release material, or even a fingerprint can spoil a bond. Some materials may need surface preparation such as chemical etching or mechanical roughening to improve joint strength.

Ultrasonic welding is frequently used for joining parts of similar material, of small and medium size, is rapid, and can be automated. High-frequency (20–40 kHz) vibrational energy is directed to the interfaces to be joined, creating localized molecular excitation that causes the plastics to melt. With proper joint designs, welds can be made in only 2 seconds

that are as strong as the base materials. When the energy is switched off, the plastics solidifies immediately. Parts to be welded ultrasonically must be so designed that the energy is concentrated in an initially small contact area, creating rapid melting and melt flow that progresses along the joint as the parts are pressed together. The lower part of the assembly is supported in a rigid nest fixture and the upper part is aligned, usually by the joint design. This upper part has freedom to couple acoustically when it is in contact with the horn through which the ultrasonic energy is transmitted.

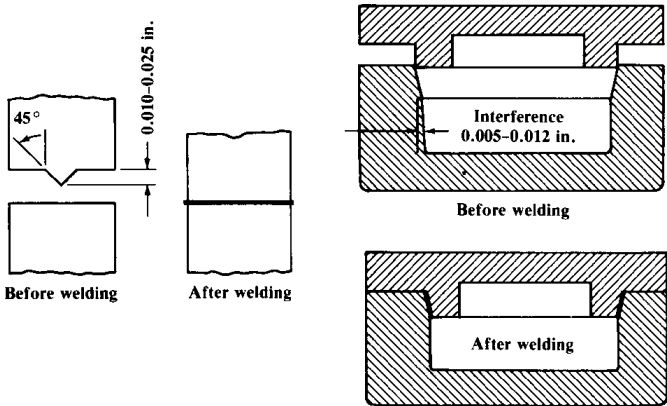


Fig. 12. (left) Energy Director Types of Ultrasonic Weld Joint Designs for Assembly of Plastics Moldings, and (right) Typical Shear Interference

Typical joint designs are shown in Fig. 12, where the example at the left is of a simple butt-type energy director design that works well with amorphous materials. The inverted V-projection, known as an energy director, concentrates the energy in a small area on both sides of the joint. This area melts quickly and the material flows as the parts are pressed together. A basic shear interference joint is seen at the right in Fig. 12. Melting of both components starts at the small initial contact area and flow continues along the near-vertical wall as the parts are pressed together, creating a continuous, leakproof joint with a strength that often exceeds that of the parts joined.

This design is preferred with liquid crystal polymers and crystalline materials such as nylon, acetal, and thermoplastics polyester, and for any application of these materials where high strength and a hermetic seal are required. Many variations of these basic designs are possible and manufacturers of materials and ultrasonic equipment offer literature and design assistance. Ultrasonic vibrations may also be used for staking, swaging, and spot-welding in assembly of plastics parts.

With hygroscopic materials, welding should be completed as soon as possible after molding because moisture can cause weaker bonds. Drying may be advisable immediately before welding. Drawbacks with ultrasonic welding are that design, quality control, equipment maintenance, and settings are of critical importance for consistent, high-strength welds; the equipment is costly; the process uses large amounts of electric power especially with large parts; and parts to be joined must be of the same or similar materials. Filled and reinforced materials also present difficulties with compatibility.

Operating frequencies used in ultrasonic welding are in the range of 20–40 kHz, above the range detectable by the ear. However, discomforting sounds may be generated when plastics parts vibrate at lower frequencies, and may make sound-proofing necessary.

Vibration welding resembles ultrasonic welding except that the parts to be joined are rubbed together to produce heat to melt the joint faces by friction. The energy is transferred in the form of high-amplitude, low-frequency, reciprocating motion. When the vibration stops, the weld area cools and the parts remain joined in the alignment provided by the welding fixture. Typical frequencies used are 120–240 Hz and amplitudes range between 0.10 and 0.20 in. of linear displacement. When the geometry or assembly design prevents linear movement, vibration-welding equipment can be designed to produce angular displacement of parts.

Like ultrasonic welding, vibration welding produces high-strength joints and is better suited to large parts and irregular joint faces. Moisture in hygroscopic materials such as nylon has less effect on the joint strength than it does with ultrasonic methods.

Spin welding is a rapid and economical method of joining parts that have circular joint interfaces. The process usually is completed in about 3 seconds and can be automated easily. Frictional heat for welding is generated by rotating one part against the other (usually fixed) with a controlled pressure. When the rotation is stopped, pressure is maintained during cooling and solidification of the melted material. Simple equipment such as a drill press is often sufficient for this process.

Radio-frequency welding, often called heat sealing, is widely used with flexible thermoplastics films and sheets of materials such as vinyl (plasticized PVC) and polyurethane, and for joining injection-molded parts, usually to film. Heat for welding is generated by a strong radio-frequency field to the joint region through a metal die formed to suit the joint shape. The die also applies the pressure required to complete the weld. Some plastics are transparent to radio frequency, so cannot be welded by this method.

Electromagnetic or induction welding uses inductive heating to generate fusion temperatures in thermoplastics materials as shown at the top in Fig. 13. Fine, magnetizable particles embedded in a gasket, preform, filament, ribbon, adhesive, coextruded film, or molded part are excited by the radio frequency and are thus heated to welding temperatures. The heated parts are pressed together, and as the temperature rises, the material of the particle carrier flows under pressure through the joint interface, filling voids and cavities and becoming an integral part of the weld. Ideally, the melted material should be contained and subjected to an internal pressure by the surrounding component surfaces. Proper joint design is essential to successful welding and some basic designs are also shown in Fig. 13.

Requirements of the preform often add cost to this welding method but the cost is offset by low reject rates resulting from good reliability of the welds. Structural, hermetic welds can be produced in most thermoplastics materials and automation can be used for large-volume production. The process also offers great latitude in joint size, configuration, tolerance requirements, and ability to bond some dissimilar materials. A disadvantage is that no metal can be near the joint line during energization of the inductor coil. All components of an assembly to be induction-welded must therefore be nonmetallic, or metallic components must be placed where they will not be subjected to the radio-frequency field from the inductor.

Assembly with Fasteners.—Metal fasteners of high strength can overstress plastics parts, so torque-controlled tightening or special design provisions are needed. Examples of poor and preferred designs are shown in Fig. 14. Where torque cannot be controlled, even with a shoulder screw, various types of washers can be used to spread the compression force over wider areas.

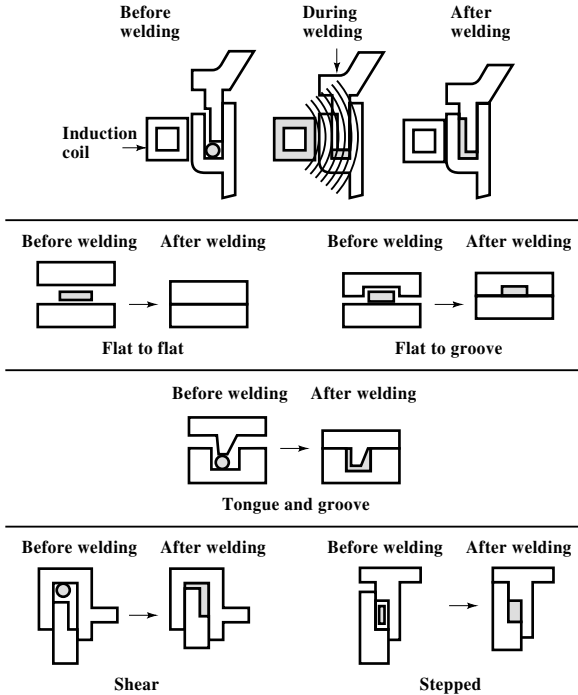


Fig. 13. Typical Joint Designs Used in Induction Welding of Plastics Materials

Metal inserts are available in a wide range of shapes and sizes for permanent installation of metal threads or bushings in plastics parts. Inserts are typically installed in molded bosses, designed with holes to suit the insert to be used. Some inserts are pressed into place and others are installed by methods designed to limit stress and increase strength. Generally, the outside of the insert is provided with projections of various configurations that penetrate the plastics and prevent movement under normal forces exerted during assembly. Inserts can also be installed with equipment similar to that used for ultrasonic welding, the plastics being melted to enhance contact with the metal and reduce insertion stresses.

Thread-cutting and -forming screws are widely used with plastics parts. Information on standard self-threading screws is found in *SELF-THREADING SCREWS* starting on page 1620. Thread-forming screws must be used carefully with high-modulus, low-creep materials, as high hoop stresses can be generated during insertion. Screws with multiple lobes and screws with alternating low and high threads have excellent holding power in plastics. Molded holes must have sufficient depth to prevent bottoming, and boss walls must be thick enough to resist stresses. A rule of thumb is that the outside diameter of the boss should be double the major diameter of the screw.

Hollow aluminum or other metal rivets are often used in plastics assembly, as are stamped sheet metal components, especially push-on or -in designs. Molded plastics fasteners also are frequently used.

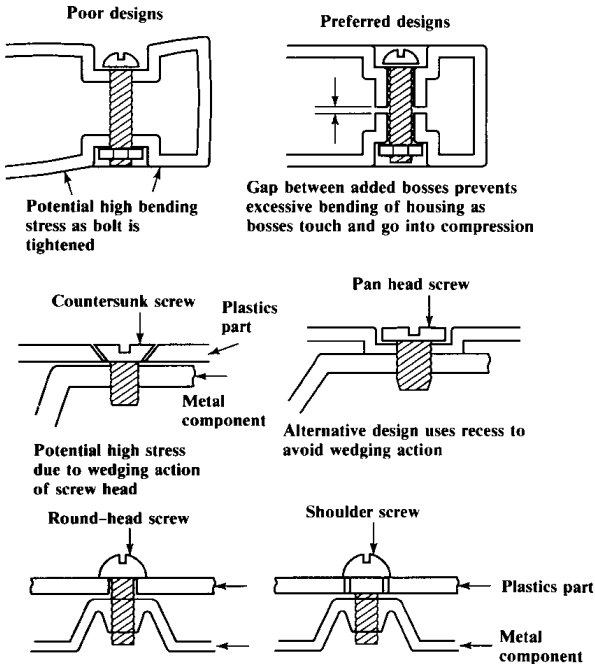


Fig. 14. Examples of Poor and Good Designs Used for Assembly of Plastics Parts with Metal Fasteners

Machining Plastics.—Plastics can be molded into complex shapes so do not usually need to be machined. However, machining is sometimes more cost-effective than making a complex tool, especially when requirements are for prototype development, low-volume production, undercuts, angular holes, or other openings that are difficult to produce in a mold. Specialized methods for development of prototypes are discussed later. All machining of plastics requires dust control, adequate ventilation, safety guards, and eye protection.

Like some metals, plastics may need to be annealed before machining to avoid warpage. Specific annealing instructions can be obtained from plastics suppliers. The modulus of elasticity of plastics is 10–60 times smaller than for metals, and this resilience permits much greater deflection of the work material during cutting. Thermoplastics materials must be held and supported firmly to prevent distortion, and sharp tools are essential to keep cutting forces to a minimum.

Plastics recover elastically during and after machining so that drilled or tapped holes often end up tapered or of smaller diameter than the tool. Turned diameters also can end up larger than the dimensions measured immediately after the finishing cut. The low thermal

conductivity of plastics causes most of the heat generated in cutting to be absorbed by the tool. Heat in the plastics tends to stay at the surface. The heat must be removed by an air blast or a liquid coolant for good results in machining.

Plastics have thermal expansion coefficients some 10 times higher than those of metals, so that more heat is generated during machining than with metals. Adequate tool clearances must be provided to minimize heating. Compared with metals, temperatures at which plastics soften, deform and degrade are quite low. Allowing frictional heat to build up causes gumming, discoloration, poor tolerance control, and rough finishes. These effects are more pronounced with plastics such as polystyrene and polyvinyl chloride, having low melting points, than with plastics having higher melting points such as nylon, fluoroplastics, and polyphenylene sulfide. Sufficient clearances must be provided on cutting tools to prevent rubbing contact between the tool and the work. Tool surfaces that will come into contact with plastics during machining must be polished to reduce frictional drag and resulting temperature increases. Proper rake angles depend on depth of cut, cutting speed, and type of plastics being cut. Large rake angles should be used to produce continuous-type cuttings, but they should not be so large as to cause brittle fracture of the work, and resulting discontinuous chips. A discussion of machining techniques follows.

Turning and Cutting Off: High speed steel and carbide tools are commonly used with cutting speeds of 200–500 and 500–800 ft/min, respectively. Water-soluble coolants can be used to keep down temperatures at the shear zone and improve the finish, except when they react with the work material. Chatter may result from the low modulus of elasticity and can be reduced by close chucking and follow rests. Box tools are good for long, thin parts. Tools for cutting off plastics require greater front and side clearances than are needed for metal. Cutting speeds should be about half those used for turning operations.

Drilling: Chip flow in drilling is poor, the rake angles are insufficient and cutting speeds vary from the center to the periphery of the drill, so that drilling imposes severe loading on the workpiece. Drills of high speed steel or premium high speed steel (T15, M33, or M41–M47) are recommended, with low helix angles, point angles of 70–120 deg, and wide, highly polished flutes to ease chip exit. Normal feed rates are in the range of 0.001–0.012 in./rev for holes of $\frac{1}{16}$ to 2 in. diameter, with speeds of 100–250 ft/min, using lower speeds for deep and blind holes. Point angles of 60–90 deg (included) are used for many plastics, but an angle of 120 deg should be used for rigid polyvinyl chloride and acrylic (polymethyl methacrylate).

Clearance angles of 9–15 deg are usually sufficient to prevent the drill flanks from rubbing in the bottom of the hole, but acrylic materials require angles of 12–20 deg. Tests may be needed to determine the drill diameter for accurately sized holes, taking thermal expansion and elastic recovery into account. Reaming may be used to size holes accurately, but diameters produced may also be affected by thermal expansion of the plastics. Close-fitting bushings in drill jigs may increase friction on the drill and cause chips to plug up the drill flutes. For positioning accuracy, removable templates may be used to spot the hole position, then removed for the drilling to be completed. Pilot holes are not necessary, except when the hole is to be reamed or counterbored. Peck feeds to remove chips and compressed air cooling may be needed, especially for deep holes.

Drilling and reaming speed and feed recommendations for various materials are shown in Table 7.

These speeds and feeds can be increased where there is no melting, burning, discoloration, or poor surface finish. Drilling is best done with commercially available drills designed for plastics, usually having large helix angles, narrow lands, and highly polished or chromium-plated flutes to expel chips rapidly and minimize frictional heating. Circle cutters are often preferred for holes in thin materials. Deep holes may require peck feeds. Drills must be kept sharp and cool, and carbide tools may be needed in high production, especially with glass-reinforced materials. Cool with clean compressed air to avoid con-

tamination. Use aqueous solutions for deep drilling because metalcutting fluids and oils may degrade or attack the plastics and may cause a cleaning problem. Hold plastics parts firmly during drilling to counter the tendency for the tooling to grab and spin the work.

Table 7. Speeds and Feeds for Drilling Holes of 0.25 to 0.375 in. Diameter in Various Thermoplastics

Material	Speed (rpm)	Feed ^a	Comments
Polyethylene	1,000–2,000	H	Easy to machine
Polyvinyl chloride	1,000–2,000	M	Tends to become gummy
Acrylic	500–1,500	M–H	Easy to drill with lubricant
Polystyrene	500–1,500	H	Must have coolant
ABS	500–1,000	M–H	
Polytetrafluoroethylene	1,000	L–M	Easy to drill
Nylon 6/6	1,000	H	Easy to drill
Polycarbonate	500–1,500	M–H	Easy to drill, some gumming
Acetal	1,000–2,000	H	Easy to drill
Polypropylene	1,000–2,000	H	Easy to drill
Polyester	1,000–1,500	H	Easy to drill

^aH = high; M = medium; L = low.

Tapping and Threading of Plastics: Many different threaded fasteners can be used with plastics, including thread-tapping and -forming screws, threaded metal inserts, and molded-in threads, but threads must sometimes be machined after molding. For tapping of through-holes in thin cast, molded, or extruded thermoplastics and thermosets, a speed of 50 ft/min is appropriate. Tapping of filled materials is done at 25 ft/min. These speeds should be reduced for deep or blind holes, and when the percentage of thread is greater than 65–75 per cent. Taps should be of M10, M7, or M1, molybdenum high-speed steel, with finish-ground and -polished flutes. Two-flute taps are recommended for holes up to 0.125 in. diameter. Oversize taps may be required to make up for elastic recovery of the plastics. The danger of retapping on the return stroke can be reduced by blunting the withdrawal edges of the tool.

Sawing Thermoset Cast or Molded Plastics: Circular or band saws may be used for sawing. Circular saws provide smoother cut faces than band saws, but band saws run cooler so are often preferred even for straight cuts. Projection of the circular saw above the table should be minimized. Saws should have skip teeth or buttress teeth with zero front rake and a raker set. Precision-tooth saw blades should be used for thicknesses up to 1 in., and saws with buttress teeth are recommended for thicknesses above 1 in. Dull edges to the teeth cause chipping of the plastics and may cause breakage of the saw. Sawing speeds and other recommendations for using blades of high-carbon steel are shown in the accompanying table.

Speeds and Numbers of Teeth for Sawing Plastics Materials with High-Carbon Steel Saw Blades

Material Thickness (in.)	Number of Teeth on Blade	Peripheral Speed (ft/min)	
		Thermoset Cast or Molded Plastics	Thermoplastics (and Epoxy, Melamine, Phenolic and Allyl Thermosets)
0–0.5	8–14	2000–3000	4000–5000
0.5–1	6–8	1800–2200	3500–4300
1–3	3	1500–2200	3000–3500
>3	>3	1200–1800	2500–3000

Milling of Plastics: Peripheral cutting with end mills is used for edge preparation, slotting and similar milling operations, and end cutting can also be used for facing operations. Speeds for milling range from 800 to 1400 ft/min for peripheral end milling of many thermoplastics and from 400 to 800 ft/min for many thermosets. However, slower speeds are generally used for other milling operations, with some thermoplastics being machined at 300–500 ft/min, and some thermosets at 150–300 ft/min. Adequate support and suitable feed rates are very important. A table feed that is too low will generate excessive heat and cause surface cracks, loss of dimensional accuracy, and poor surface finish. Too high a feed rate will produce a rough surface. High-speed steel tools (M2, M3, M7, or T15) are generally used, but for glass-reinforced nylon, silicone, polyimide, and allyl, carbide (C2) is recommended.

New Techniques: Lasers can be used for machining plastics, especially sheet laminates, although their use may generate internal stresses. Ultrasonic machining has no thermal, chemical, or electrical reaction with the workpiece and can produce holes down to 0.003 in. diameter, tight tolerances (0.0005 in.), and very smooth finishes (0.15 μ in. with No. 600 boron carbide abrasive powder). Water-jet cutting using pressures up to 60,000 lb/in.² is widely used for plastics and does not introduce stresses into the material. Tolerances of \pm 0.004 in. can be held, depending on the equipment available. Process variables, pressures, feed rates, and the nozzle diameter depend on the material being cut. This method does not work with hollow parts unless they can be filled with a solid core.

Development of Prototypes.—Prototypes are made for testing of properties such as stress and fatigue resistance, to find ways to improve quality and reliability, to improve tooling, and to reduce time to market. Prototyping may answer questions about finish, sink marks that result from contraction, witness lines from mold joints, ejector pin marks, knit or weld lines, texturing, moldability, shrinkage, mechanical strength, pull-out resistance of inserts, electrical properties, and problems of mating with other parts.

Prototypes of moldings are made in five major steps including design; refining the design; making a model (physical or computer); making a mold; and producing parts. The model may be made from wood, plaster, plastics (by machining), or a metal. Some 90 per cent of prototypes are made by modern CAD/CAM methods that allow holding of dimensional tolerances of 2–3 per cent of drawing specifications.

Prototypes can also be made by a process called stereo lithography that uses a tank of photosensitive liquid polymer, an *x-y* scanning, ultraviolet laser with a beam diameter of 0.010 in., a *z*-axis elevator platform, and a controlling computer. The platform height is adjusted so that a suitable thickness of liquid polymer covers its surface. The laser beam is focused on the liquid surface and hardens the polymer at this point by heating.

The CAD representation of the prototype is described by a model in which thin (0.005–0.020 in.) cross sections can be isolated. Data representing the lowest level of the prototype are used to move the platform so that a layer of the polymer corresponding to the lowest “slice” is hardened. The platform is then lowered, the liquid polymer flows over the hardened layer, and the platform is again raised, less an amount equal to the next “slice.” The process is repeated for successive “slices” of the prototype, which is thus built up gradually to form a hollow, three-dimensional shape corresponding to the model in the CAD program. The part thus produced is fairly brittle but can be used for visual examination, design verification, and marketing evaluation, and can be replicated from other materials such as plastics or metals by casting or other methods.

Finishing and decorating methods used for plastics parts include spray painting, vacuum metallizing, hot stamping, silk screening, and plating. Conductive coatings may be applied to inside surfaces, usually by flame- or arc-spraying, to dissipate static electricity and provide electromagnetic shielding. Thorough cleaning is essential. Materials such as polyethylene, polypropylene, and acetal have waxlike surfaces that may not be painted easily or may need pretreatment or special primers. Many amorphous plastics are easy to paint.

Suitable coatings include polyurethane-, epoxy-, acrylic-, alkyd-, and vinyl-based paints. Oven curing may distort parts made from non-heat-resistant materials.

Vacuum metallizing and sputter-plating require application of a special base coat and a protective clear top coat before and after treatment. Resistance heating or an electron beam can be used to melt the metallizing materials such as aluminum, silver, copper, and gold, which usually are pure elements. Sputter plating uses a plasma to produce the metallic vapor and can use brass as well as the metals mentioned. Chromium plating requires etched surfaces to ensure good adhesion.

Plastics may be polished by buffing methods similar to those used on metals, but experiments to determine the effect of frictional heat are recommended. Surfaces can be heated to 300–400 deg. F by buffing, and some plastics soften and melt at these temperatures. Heating sometimes causes plastics to give off toxic gases, so masks should be worn to filter out such gases and dust. Parting lines, imperfections, scratches, saw lines, imperfections and scars resulting from fabrication can be treated with abrasives prior to buffing. Wet or dry abrasives such as silicon carbide or aluminum oxide are generally used, in grain sizes of 60 to as fine as 320. Some buffing compounds are ineffective on plastics. Scratch lines should be presented at a slight angle to the buff surface for best results. Light, tallow-free grease will help keep the abrasive surface free from buildup, and speeds of 5,000 to 6,000 surface feet per minute are recommended.

For low-melting point plastics, soft cotton buffs are best, with surface speeds of 4,000 to 5,000 feet per minute, using a wet or greasy tripoli or silica compound. For finishing, only rouge may be needed for a satisfactory finish. If a cleaning solvent is used it should be checked to see that it does not dissolve the plastics, and it should be used only in a well-ventilated area. Acrylics such as Acrylite or Plexiglass may also be 'flame polished,' under advice from the materials supplier.

Plastics Gearing.—Plastics gears may be cut from blanks, as with metal gears, or molded to shape in an injection-molding machine, for lower production costs, though tooling may cost more. Cut plastics gears may be of similar design to their metal counterparts, but molded gears are usually of modified form to suit the material characteristics. Plastics materials also may be preferred for gears because of superior sliding properties with reduced noise and need for lubrication, chemical or electrical properties, or resistance to wear. However, plastics gear teeth slide more smoothly and easily against metal teeth than do plastics against plastics, and wear is less. For power transmission, plastics gear teeth are usually of involute form. See also *Non-metallic Gearing* on page 2119.

Most plastics gears are made from nylons and acetals, although acrylonitrile-butadiene-styrenes (ABS), polycarbonates, polysulfones, phenylene oxides, poly-urethanes, and thermoplastic polyesters can also be used. Additives used in plastics gears include glass fiber for added strength, and fibers, beads, and powders for reduced thermal expansion and improved dimensional stability. Other materials, such as molybdenum disulfide, tetrafluoroethylene (TFE), and silicones, may be added as lubricants to improve wear resistance.

Choice of plastics gear material depends on requirements for size and nature of loads to be transmitted, speeds, required life, working environment, type of cooling, lubrication, and operating precision. Because of cost, plastics gears are sometimes not enclosed in sealed housings, so are often given only a single coating of lubricant grease. Overloading of lubricated plastics gear teeth will usually cause tooth fracture, and unlubricated teeth often suffer excessive wear. Thermoplastics strength varies with temperature, with higher temperatures reducing root stress and permitting tooth deformation. In calculating power to be transmitted by spur, helical, and straight bevel gearing, the following formulas should be used with the factors given in Tables 2, 3 and 1.

For internal and external spur gears,

$$HP = \frac{S_s F Y V}{55(600 + V) P C_s}$$

For internal and external helical gears,

$$HP = \frac{S_s F Y V}{423(78 + \sqrt{V}) P_n C_s}$$

For straight bevel gears,

$$HP = \frac{S_s F Y V (C - F)}{55(600 + V) P C_s}$$

where S_s = safe stress in bending (from Table 2); F = face width in inches; Y = tooth form factor (from Table 1); C = pitch cone distance in inches; C_s = service factor (from Table 3); P = diametral pitch; P_n = normal diametral pitch; and V = velocity at pitch circle diameter in ft/min.

Table 1. Tooth Form Factors Y for Plastics Gears

Number of Teeth	14½-deg Involute or Cycloidal	20-deg Full Depth Involute	20-deg Stub Tooth Involute	20-deg Internal Full Depth	
				Pinion	Gear
12	0.210	0.245	0.311	0.327	...
13	0.220	0.261	0.324	0.327	...
14	0.226	0.276	0.339	0.330	...
15	0.236	0.289	0.348	0.330	...
16	0.242	0.259	0.361	0.333	...
17	0.251	0.302	0.367	0.342	...
18	0.261	0.308	0.377	0.349	...
19	0.273	0.314	0.386	0.358	...
20	0.283	0.320	0.393	0.364	...
21	0.289	0.327	0.399	0.371	...
22	0.292	0.330	0.405	0.374	...
24	0.298	0.336	0.415	0.383	...
26	0.307	0.346	0.424	0.393	...
28	0.314	0.352	0.430	0.399	0.691
30	0.320	0.358	0.437	0.405	0.679
34	0.327	0.371	0.446	0.415	0.660
38	0.336	0.383	0.456	0.424	0.644
43	0.346	0.396	0.462	0.430	0.628
50	0.352	0.480	0.474	0.437	0.613
60	0.358	0.421	0.484	0.446	0.597
75	0.364	0.434	0.496	0.452	0.581
100	0.371	0.446	0.506	0.462	0.565
150	0.377	0.459	0.518	0.468	0.550
300	0.383	0.471	0.534	0.478	0.534
Rack	0.390	0.484	0.550

These values assume a moderate temperature increase and some initial lubrication. With bevel gearing, divide the number of teeth by the cosine of the pitch angle and use the data in the table. For example, if a 20-deg PA bevel gear has 40 teeth and a pitch angle of 58 deg, 40 divided by the cosine of 58 deg = 40 ÷ 0.529919 = 75, and $Y = 0.434$.

Table 2. Safe Bending Stress (lb/in²) Values for Plastics Gears

Plastics Type	Safe Stress	
	Unfilled	Glass-filled
ABS	3,000	6,000
Acetal	5,000	7,000
Nylon	6,000	12,000
Polycarbonate	6,000	9,000
Polyester	3,500	8,000
Polyurethane	2,500	...

Table 3. Service Factors for Plastics Gears

Type of Load	8–10 Hr/Day	24 Hr/Day	Intermittent, 3 Hr/Day	Occasional, ½ Hr/Day
Steady	1.00	1.25	0.80	0.50
Light shock	1.25	1.5	1.00	0.80
Medium shock	1.5	1.75	1.25	1.00
Heavy shock	1.75	2.00	1.5	1.25

As an example, assume that a material is to be selected for a spur gear that must transmit $\frac{1}{8}$ hp at 350 rpm, for 8 hrs/day under a steady load. The gear is to have 75 teeth, 32 diametral pitch, 20 deg pressure angle, 0.375 in. face width, and a pitch diameter of 2.3438 in. Using the first formula above,

$$HP = \frac{S_s FYV}{55(600 + V)PC_s} \quad \text{or} \quad S_s = \frac{55(600 + V)PC_s HP}{FYV}$$

$$\text{hp} = 0.125, \quad Y = 0.434 \quad \text{and}$$

$$V = \frac{rpm \times \pi \times D}{12} = \frac{350 \times 3.1416 \times 2.3438}{12} = 215 \text{ ft/min}$$

therefore,

$$S_s = \frac{55(600 + 215)32 \times 1.00 \times 0.125}{0.375 \times 0.434 \times 215} = 5,124 \text{ lb/in.}^2$$

From Table 2 it is apparent that the gear could be molded from several materials. Available physical and chemical characteristics must now be considered in relation to the operating environment for the gear. Strengths of plastics materials decrease with increasing temperatures and not all plastics resist the effects of some liquids, including some lubricants. Some plastics deteriorate when in sunlight for long periods; some are more dimensionally stable than others; and wear resistance varies from one to another. Manufacturers' data sheets will answer some of these questions.

Backlash: Plastics gears should be so dimensioned that they will provide sufficient backlash at the highest temperatures likely to be encountered in service. Dimensional allowances must also be made for gears made of hygroscopic plastics that may be exposed to damp service conditions. Teeth of heavily loaded gears usually have tip relief to reduce effects of deflection, and have full fillet radii to reduce stress concentrations. Such modifications to tooth form are also desirable in plastics gears. If the pinion in a pair of gears has a small number of teeth, undercutting may result. Undercutting weakens teeth, causes undue wear, and may affect continuity of action. The undercutting can be reduced by using the long-short addendum system, which involves increasing the addendum of the pinion teeth and reducing that of the gear teeth. The modified addendum method will also reduce the amount of initial wear that takes place during the initial stages of contact between the teeth.

Accuracy: The Gear Handbook, AGMA 390-03a-1980, Part 2, Gear Classification, provides a system whereby results of gear accuracy measurements are expressed in terms of maximum tooth-to-tooth and composite tolerances. This system uses AGMA quality numbers related to maximum tolerances, by pitch and diameter, and is equally applicable to plastics gears as to metal gears. AGMA quality numbers must be chosen for a pair of mating gears early in the design process, and the finished gears must be inspected by being run in close mesh with a master gear in a center-distance measuring instrument to make sure that the errors do not exceed the specified tolerances.

To prevent failure from fatigue and wear caused by excessive flexing of the teeth, plastics gears must be made to the same standards of accuracy as metal gears. Solidification shrinkage of plastics requires that dimensions of molds for gears be larger than the dimensions of the parts to be produced from them. The amount of the shrinkage is usually added to the mold dimension (with the mold at operating temperature). However, this procedure cannot be followed for the tooth profile as it would introduce large errors in the pressure angle. Increases in pressure angle cause gear teeth to become wider at the root and more pointed. Sliding conditions are improved and the teeth are stronger, so that higher loading values can be used.

Shrinkage allowances have the greatest effect on the accuracy of the molded gears, so tooth profiles must be calculated extremely carefully in terms of mold profile. If a tooth is merely made larger by using a standard hobbing cutter to cut the tool whereby the teeth in the mold are electroeroded, differential shrinkage caused by the molded tooth being thicker at the root than at the tip will distort the shape of the molded tooth, making it thinner at the tip and thicker at the root. With two mating gears, these faulty shapes will affect the pressure angle resulting in binding, wear, and general malfunction. If the tooth thickness limits for a molded gear are to be held to +0.000 in., -0.001 in., the outside diameter must be permitted to vary up to 0.0027 in. for 20-deg, and 0.0039 in. for 14½-deg pressure angle gears. All high-accuracy gears should be specified with AGMA quality numbers and inspected with center-distance measuring machines if the required accuracy is to be achieved.