

Table 10. Mechanical Properties of Wrought Titanium Alloys

Nominal Composition (%)	Condition	Tensile Strength (ksi)	Room Temperature		Reduction in Area (%)
			Yield Strength (ksi)	Elongation (%)	
Commercially Pure					
99.5 Ti	Annealed	48	35	30	55
99.2 Ti	Annealed	63	50	28	50
99.1 Ti	Annealed	75	65	25	45
99.0 Ti	Annealed	96	85	20	40
99.2 Ti ^a	Annealed	63	50	28	50
98.9 Ti ^b	Annealed	75	65	25	42
Alpha Alloys					
5 Al, 2.5 Sn	Annealed	125	117	16	40
5 Al, 2.5 Sn (low O ₂)	Annealed	117	108	16	
Near Alpha Alloys					
8 Al, 1 Mo, 1 V	Duplex annealed	145	138	15	28
11 Sn, 1 Mo, 2.25 Al, 5.0 Zr, 1 Mo, 0.2 Si	Duplex annealed	160	144	15	35
6 Al, 2 Sn, 4 Zr, 2 Mo	Duplex annealed	142	130	15	35
5 Al, 5 Sn, 2 Zr, 2 Mo, 0.25 Si	975°C (1785°F) (½ h), AC 595°C (1100°F)(2 h), AC	152	140	13	
6 Al, 2 Nb, 1 Ta, 1 Mo	As rolled 2.5 cm (1 in.) plate	124	110	13	34
6 Al, 2 Sn, 1.5 Zr, 1 Mo, 0.35 Bi, 0.1 Si	Beta forge + duplex anneal	147	137	11	
Alpha-Beta Alloys					
8 Mn	Annealed	137	125	15	32
3 Al, 2.5 V	Annealed	100	85	20	
6 Al, 4 V	Annealed	144	134	14	30
	Solution + age	170	160	10	25
6 Al, 4 V (low O ₂)	Annealed	130	120	15	35
6 Al, 6 V, 2 Sn	Annealed	155	145	14	30
	Solution + age	185	170	10	20
7 Al, 4 Mo	Solution + age	160	150	16	22
6 Al, 2 Sn, 4 Zr, 6 Mo	Solution + age	184	170	10	23
6 Al, 2 Sn, 2 Zr, 2 Mo, 2 Cr, 0.25 Si	Solution + age	185	165	11	33
10 V, 2 Fe, 3 Al	Solution + age	185	174	10	19
Beta Alloys					
13 V, 11 Cr, 3 Al	Solution + age	177	170	8	
	Solution + age	185	175	8	
8 Mo, 8 V, 2 Fe, 3 Al	Solution + age	190	180	8	
3 Al, 8 V, 6 Cr, 4 Mo, 4 Zr	Solution + age	210	200	7	
	Annealed	128	121	15	
11.5 Mo, 6 Zr, 4.5 Sn	Solution + age	201	191	11	

^a Also contains 0.2 Pd.^b Also contains 0.8 Ni and 0.3 Mo.

Source: Titanium Metals Corp. of America and RMI Co.

For strength in MPa, multiply strength in ksi by 6.8947572

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 (14-16°C) 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 (260°C), 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 (120°C).
Polysulfone	Durable thermoplastic, good electrical properties, operates at temperatures in excess of 300°F (150°C).
Polyurethane	Thermoplastic, excellent impact and abrasion resistance, resists sunlight and weathering.
PTFE (polytetrafluoroethylene)	Thermoplastic, low coefficient of friction, withstands up to 500°F (260°C), 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 encompass a wide range of materials that consist of long chains of carbon atoms with attached atoms of other elements, mainly hydrogen, and small, repeating chemical functional groups that influence the plastics' properties. Some other elements found in plastics are oxygen, nitrogen, chlorine, sulfur, and fluorine. A special class, the *silicones*, have chains of alternating silicon and oxygen atoms with small carbon-based side groups. These repeating chain segments are called *mers*, giving the term *polymers* for these materials. The pure (*neat*) materials are also known as *resins*. Commercial plastics are resins containing additives in amounts ranging from trace quantities to 50 percent or more. In any sample of resin, molecular chain lengths will generally vary widely, but the average must exceed several thousand mer units if the resin is to possess good mechanical properties. There are two main classes of resin: *thermoplastics* (which includes *elastomers*) and *thermosets*.

Thermoplastics: Plastics that soften when heated are called thermoplastics. These plastics can be repeatedly melted and then solidified by cooling. This reversible change may actually be repeated several times until a final product is made. For example, freshly polymerized polypropylene is a fine powder that is converted into conveniently processible pellets by extrusion. The extruder compacts and melts the powder and pumps it through a strand die, where the emerging strands are water-chilled and sliced into $\frac{3}{16}$ -inch (10mm) BB-sized pellets. A sheet maker may then reprocess the pellets in an extruder to produce long rolls of thin sheet or short slabs of thicker sheet. These are transported to a thermoformer, which again heat-softens the sheet and pulls it down over a chilled mold to make packages from the thin sheet or wastebaskets from the thicker ones. Some examples of commodity thermoplastic families are polystyrenes (PS), polyethylenes (PE), acrylics (PMMA), cellulotics (e.g., cellulose acetate butyrate, CAB), and polyvinyls—from soft and flexible to hard and stiff. *Engineering Thermoplastics*, such as the nylon family, acetal resins, polycarbonate, and others listed in the preceding table generally have superior strength, toughness and resistance to heat and chemicals. Thermoplasticity makes it easy to recycle these resins. Although the heating/cooling cycle can be repeated, recycling reduces mechanical properties and appearance.

Thermosets: Thermosetting plastics, such as amino, epoxy, phenolic, and unsaturated polyesters, come to the final processor as partially polymerized mixtures of chemically active, long-chain molecules. When they are heated during molding, the mixture components react to form chemical bonds, called *cross-links*, between the original chains, forming huge three-dimensional molecules. Such products generally have good heat resistance. However, if heated above their molding temperatures, they do not melt but instead decompose. They cannot be reprocessed, so opportunities for salvaging scrap for recycling are limited. Many rubbers that are processed by vulcanizing, such as butyl, latex, neoprene, nitrile, polyurethane, and silicone, also are classified as thermosets.

Elastomers and Rubbers: Raw natural or synthetic rubber, initially thermoplastic, is mixed with finely divided carbon and sulfur. During molding these materials undergo cross-linking by sulfur, a process called *vulcanizing*. Elastomers typically have low elastic moduli (stiffness) but high elasticity (stretch). Many if stretched to twice their length (or much more) and then released, will snap back resiliently to their original length and shape. Thermoplastic elastomers are often used in place of rubber, and may also be used as additives for improving impact strength of rigid thermoplastics.

Thermoplastic Structures.—Thermoplastics can be classified by their structures into three categories:

Amorphous: These randomly structured materials are sometimes called *noncrystalline*. Such thermoplastics include acrylates, polycarbonate (PC), polystyrene, acrylonitrile-butadiene-styrene (ABS), styrene acrylonitrile (SAN), and polyvinylchloride (PVC) and its acetate copolymers.

Crystalline: Half or even more of the chains in crystalline thermoplastics are organized into tiny regular regions called *crystallites*. Representative members are nylons, acetals, polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). The crystallites are linked by amorphous zones; the resulting microstructures make these materials stronger and stiffer than similar materials without crystallinity. They are generally higher melting, with more sharply defined melting ranges than amorphous resins.

Liquid-Crystalline Polymers (LCP): These contain crystal-like structures even in the melted resin. They have highly ordered, rod-like microstructures with good mechanical properties and high melting temperatures. They have the lowest shrinkage and warpage of the three types of thermoplastics.

Copolymers, Blends, Additives, and Reinforcements.—Plastics can be manipulated to modify mechanical, chemical, electrical, and cost characteristics.

Copolymers: Combining two or more different polymers can create a new material with properties that are completely different from those of the individual polymers (*homopolymers*) from which they are made. The copolymers are alloyed: mechanically blended from the 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 impact strength and flame resistance. The properties usually are intermediate between those of the constituent homopolymer materials.

Copolymers such as SAN and ABS have long been commercially available. Newer blends and alloys are not always readily available in sheets or in standard industry stock shapes supplied for machining.

Additives and Fillers: Plastics compounds with desired sets of properties are produced from “neat” resins by adding many types of other chemicals and materials. Antioxidants, lubricants, pigments and dyes, fire retardants, and ultraviolet protectants in small percentages usually do not significantly alter mechanical and physical properties. *Larger* quantities of particulate fillers such as wood flour (used with thermosets), silica powder, glass or phenolic microballoons, carbon and metal powders do affect density, thermal and electrical conductivity, mechanical properties, and unit cost. The use of such additives makes available many grades of a given plastic type from each commercial plastics manufacturer.

Plasticizers: Plasticizers soften and toughen the base resins with which they are compounded. While they are used in several resin families to some extent, polyvinyl chloride resins (PVC) and related plastics use plasticizers and many other additives in high percentages. These modified resins produce a myriad of grades of PVC from the familiar rigid pipe material (the dominant consumer of PVC) to wire coatings, flooring, and elastomerics used in footwear.

Fibers: Plastics, which have much lower moduli and strengths than glass and metals, can be made stiffer and stronger by incorporating glass, graphite or other fibers. Short chopped fibers in fractions up to about 40 percent, randomly oriented in molding compounds, provide substantial increases in stiffness and strength. But more dramatic improvements are obtained by incorporating longer fibers in carefully chosen directions, as in fishing rods and golf club shafts, where content of glass or carbon fiber may be more than 50 percent by weight. Historically, sturdy composites have been and still are made by compression molding multilayer canvas, paper, or cotton-felt sheets impregnated with phenolic or other thermosetting resins. (See also *Plastics Gearing* on page 592.) A relatively recent reinforcement material is *oriented aramid* (aromatic polyamide, Kevlar), whose strength and modulus rival those of metals. Its most familiar use has been in “bullet-proof” vests for law-enforcement and military personnel.

Cellular Plastics.—Many rigid and flexible, thermoplastic and thermosetting resins families are available as foamed plastics in the form of sheets, boards, bars, and cylinders as well as molded shapes. The internal structure of plastic foam consists of tiny gas-filled cells bounded by shared membranes of the resin.

In *closed cell* foams, each cell is a tiny polyhedral cavity adjacent to, but not opening into, other cells. Foamed polystyrene hot liquid beverage cups are an example of closed cell foams. In *open cell* foams the cells are not completely closed but instead form continuous connecting tunnels with other cells in all directions throughout the object. Kitchen sponges are open cell foams.

Densities of plastics foams range from 90 percent of the resin's unfoamed density down to just a few percent. Foaming may be accomplished physically by injection of a gas or volatile solvent during extrusion or molding, or by mixing a chemical blowing agent with the resin. When the mix is processed, the unstable blowing agent decomposes in the melt, generating bubbles. Foams have many uses: as low-cost space filling, cushioning, thermal and electrical insulation, and as the interlayer member of sandwich materials. Polystyrene, polyethylene, and polyurethane (rigid and flexible) are important foam families.

Application and Physical Properties.—Selecting a plastic for a specific application requires knowledge of many different kinds of properties of candidate materials. Density and mechanical properties will be important considerations in most cases. The plastics must bear tensile, compressive or bending loads, resist or allow twisting or stretching, survive impacts, withstand thousands or even millions of repeated stress cycles, and resist abrasion. Special service environments—extremely low or high temperatures, humidities, outdoor exposure, and the presence of active solvents and chemicals—will modify the selection criteria. Thermal or electrical properties such as coefficients of thermal expansion, thermal or electrical conductivity, heat capacity (specific heat), dielectric strength, and dielectric-loss factor may sometimes be important.

Over many years Committee D-20 of ASTM (formerly American Society for Testing Materials) has developed thousands of characterization and test methods for plastics and their products. ASTM Standards, Section 8, "Plastics," is updated and reissued annually by ASTM. All leading U.S. resin makers and many compounders can furnish the product designer with the results of batteries of tests made on their materials according to numbered ASTM standards. For example, ASTM Test D638, Tensile Properties, prescribes the preparation and dimensions of specimens to be tested by pulling from both ends. Several useful mechanical-property values are obtained from this test: tensile modulus yield strength, tensile strength at break, and elongation (percent stretching) at break. Most plastics products are made by molding from a molten or pre-polymer condition by processes such as extrusion or injection- or compression-molding. Products so made are apt to have a somewhat different microstructure close to the surfaces than are found in their interiors. In theory, the behavior of a simple test bar in bending should be calculable from the straight tensile-test modulus E , as it is with metals. However, because of the "skin effects" found in molded plastics such predictions are not very reliable. For this reason, ASTM Committee D-20 developed Method D790 for flexural properties. Flexural moduli, theoretically the same as E , actually tend to be somewhat higher in molded thermoplastics, as are their flexural strengths.

Even with homogeneous plastics whose properties are expected to be about the same in all principal directions, certain processing conditions, such as stretching while the heat-softened plastic is cooling, can cause alignment *orientation* of the long polymer chains or crystallites in the stretching direction. This will increase tensile strength in that direction but with some reduction in the perpendicular cross directions. Even more striking anisotropic effects are achieved with long-fiber reinforcements.

Suppliers of unreinforced sheet, bar, and rod stock for machining usually relieve stress by controlled annealing of any residual stresses developed in processing, thereby preventing distortions related to the relief of residual strains during machining.

Some of the more important application properties are defined here.

Density and Specific Gravity: These are closely linked properties. *Density* is the mass (or weight) per unit volume of a material, used mainly to calculate the mass of material

required to make a part whose volume has been calculated from its dimensions. In the plastics industry, commonly used units are lb/in^3 or g/cm^3 . *Specific gravity* is the ratio of a material's density to that of water, both being measured at the same temperature, at 23°C (73.4°F) for plastics. Since the density of water at typical room temperatures is very close to 1.00 gm/cm^3 , specific gravity and density measured in metric units are numerically almost equal. In the U.S. Customary System units, water density equals 0.0361 lb/in^3 . Specific gravities of neat resins range from 0.83 for polymethylpentene to 2.20 for polytetrafluoroethylene (PTFE - Teflon). Because specific gravity is a ratio of densities of like units, it is dimensionless. See also *Specific Gravity* on page 368.

Unlike specific gravity, *specific volume* is not dimensionless, but is defined as the reciprocal of density, in^3/lb or cm^3/g .

Shrinkage: This is the difference in measurement between a linear dimension of a mold and the corresponding dimension of a plastic article made in the mold, divided by the mold dimension, and expressed in/in, mils/in, or percent. The dominant material property here is the *coefficient of linear thermal expansion* since the shrinkage is mainly due to cooling from the high temperature of the melt as it solidifies under pressure in the mold to room temperature after its removal from the mold. Expansion coefficients of plastics are much larger than those of metals and ceramics, ranging from 30 to over $100 \text{ in/in } ^\circ\text{C}$ ($\text{cm/cm } ^\circ\text{C}$). For type-66 nylon, which freezes at 260°C (500°F), shrinkage may be as much as 20 mils/in (0.02 cm/cm), i.e., 2 percent. Shrinkage can also be affected by other molding conditions and by additive content. Amorphous and liquid-crystalline thermoplastics have lower shrinkages than crystalline materials. Glass- or carbon-reinforced and mineral-filled compounds have lower shrinkage than their neat resins. For accurate assessment of shrinkage, test moldings are advised before mold-cavity dimensions are finalized.

Water Absorption: The increase in weight of a test specimen due to absorption of water, expressed as a percentage of the original dry weight. Standard test specimens (ASTM Method D570) are first dried for 24 hours, then weighed before and after immersion in water at 23°C (73.4°F) for a specified time. Absorption of water affects not only the dimensions of plastics parts but also mechanical and electrical properties. Parts made from materials with low water absorption tend to have greater dimensional stability.

Transparency: A measure of the percentage of incident light that is transmitted through a test specimen. It is quantified as *luminous transmittance*, the ratio of transmitted to incident light. *Haze* measures the percentage of light entering a specimen that is scattered more than 2.5 degrees from the incident beam.

Elasticity: An *elastic* material is one that can be deformed to an extent less than its *elastic limit* such that when the deforming stress is removed, it will recover its original shape and dimensions. A more precisely formulated definition of "elastic", which few plastics obey, is "A material that obeys Hooke's law of proportionality of strain to stress up to its proportional limit" (see page 550.) The *modulus of elasticity* is Hooke's law constant E , the quotient of stress divided by strain in the proportional region. In a tensile test, strain is the fractional amount of elongation reached under a given stress. Because plastics generally deviate from strict linearity, even at very low stresses, the moduli reported are usually "one percent moduli," that is the quotient of stress and strain at one percent strain. For most materials the limit of recoverable strain is a few percent or less. For rubbers and a handful of thermoplastic elastomers, maximum recoverable strain may be as high as 100 percent or more. Stress and strain in relation to plastics part design is discussed on page 547.

Plasticity: The deformation behavior exhibited when materials are stressed beyond their elastic limits without breaking, i.e., when stress exceeds the *yield point*. In this mode there can be considerable flow among the microstructural elements of the material, and permanent changes in the dimensions and shape of the deformed article occur. Plastic deformation continues with small increases in stress until finally there is rupture. Plasticity is exhibited to some degree by most unreinforced plastics. While parts are normally designed

to operate in their material's elastic ranges, and plastic deformation may render a part useless for its designed function, plastic deformation *can* sometimes prevent catastrophic failure. A few plastics have such compliant plasticity that they can be cold-formed by metal-working methods—rolled, stretched, or even forged into final products. This property in metals is called *ductility*.

Toughness is a complex property that relates to the ability of a material to absorb mechanical energy without cracking or breaking. Often it depends on the rate at which the specimen is deformed. In a standard tensile test (ASTM D638), the strain rate is fairly low—from 0.15 to 15 (in/in)/min. In a tensile-impact test (ASTM D1822) the specimen is abruptly stretched to failure in milliseconds at a strain rate of about 20,000 (in/in)/min. The tensile tester of D638 generates a graph of stress (psi) vs. strain (in/in). The area under this curve is the energy in ft-lb_f/in³ absorbed by the gage volume as it is stretched and finally broken. The impact tester, on the other hand, directly determines how many foot-pounds of energy are needed to stretch and break the specimen. That value, too, can be converted to energy per unit of specimen volume, but the number will be very different from the other. A widely used test of toughness for plastics is the Izod impact test (ASTM D256), in which a falling pendulum strikes and breaks off the upper half of a cantilever test bar whose leading face has a 0.1-inch (2.54 mm) deep, V-shaped notch across it just above the clamping point. This test (the oldest in ASTM's Plastics list, first published in 1926) involves not only toughness but also the *notch-sensitivity* of the plastic. The test result is expressed in ft-lb_f/in of notch width. Izod-test values for 1/8-inch (3.2 mm) wide specimens of neat thermoplastics range from 0.4 for crystal polystyrene or wood-flour-filled phenolics to 14 for polycarbonate and phenolics with a high content of glass fiber. Particulate fillers may increase or decrease Izod impact strength; fibrous reinforcements usually increase it. Thus, applying tabulated toughness values to plastics part design is not a simple task.

Brittleness: Lack of toughness, characterized in plastics by Izod impact test values below 1.0 ft-lb_f/in (53 J/m) or by abrupt fracture with little or no yield in tensile tests.

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

Hardness: The ability of a material to resist dents and scratches; it is related to *abrasion resistance* and general durability. Several ASTM test methods are in use for plastics, Rockwell (ASTM D785) being a popular one. One of three hardened steel balls is pressed into the test specimen, first with a low force, then a much higher one, while a micrometer indicates the increase in depth of impression. Five scales are available for plastics: R, L, M, E, and K, in order of increasing hardness, requiring progressively smaller balls and stronger forces. The scale *must* be identified in the report of Rockwell hardness numbers. When an article is expected to suffer abrasion in service, the abrasion loss of candidate plastics may be experimentally determined with an abrasion machine (ASTM D1242).

Homogeneous plastics have the same composition throughout a part down to the micro-structural level, but not to the molecular level as in simple chemical compounds. A $\frac{3}{16}$ -inch (5 mm) BB-sized pellet of a neat resin contains many long-chain molecules of various chain lengths. However, even compounds containing several additives, pigments, and powdery fillers behave in molded articles as if they were homogeneous.

Heterogeneous (inhomogeneous) plastics vary in composition and structure. A compound reinforced with centimeter-long, randomly oriented, chopped glass fibers will not look homogeneous under 50× magnification, yet it may be safely treated as such in the design of parts that are larger than the test samples whose properties have been measured.

Isotropy and Anisotropy: These properties are related to homogeneous and heterogeneous plastics properties. In isotropic materials, measured properties are equal in all directions. Cast metals and plastics tend to be isotropic. Processing effects such as flow orientation that do not change homogeneity can create substantial directional differences

in properties. This effect is called anisotropy. In plastic films made by extruding molten resin onto chilled rolls, the films are usually stronger in the “machine” direction, weaker in the lateral or cross direction. Laminates made of laid-up reinforcing fibers or woven cloths can be nearly biaxially isotropic in the laminate plane, but their interlaminar shear is low because no fibers cross through the plane. Extremely anisotropic are unidirectional laminates where all the fibers are parallel, as in golf club shafts reinforced with graphite fibers.

Wood, see page 373, is a natural anisotropic material, strong and stiff in the grain (growth) direction, less so in the perpendicular and tangential directions. Commercially important fibers, both natural and synthetic, are also highly anisotropic with their greatest strength and moduli aligned with length.

As the degree of anisotropy increases, the number of physical constants (moduli) required to define a material's stress-strain behavior also increases, up to a maximum of 21. Absence of such complete information on complex laminates and the inadequacy of simple analysis methods point to the need for extensive end-use testing of plastics parts before approval of a particular application design. Computer modeling using finite element analysis (FEA) techniques can help in the successful implementation of these materials. Detailed properties data are required for reliable and accurate modeling.

In addition to mechanical properties, isotropy and anisotropy can affect molding shrinkage. Anisotropic shrinkage caused by patterns of flow in the mold is important in molding crystalline and fiber-reinforced plastics, for which different shrinkage values are experienced in the flow and cross-flow directions. These values are of most concern to the tool designer and molder; however, the existence and severity of anisotropic shrinkage must be considered when a material is chosen for a part having tight tolerances.

Coefficient of Friction: This property comes into play in plastics gears and bearings and other applications where low dynamic (kinetic) friction is desired between moving surfaces in contact. When a weighted block of a plastic is dragged at a steady velocity along a horizontal slab of the same or different material and the contact surfaces are smooth, the coefficient of friction is defined as the ratio of the horizontal drag force to the total weight of the block, called the normal force. In general, the observed coefficients will be different for different pairs of materials, so a test report must identify both materials. While some coefficients were (long ago) determined in this basic manner, ASTM D3028 now prescribes a sophisticated machine (“frictionometer”) for measuring the property. Coefficients of friction change with temperature. Materials such as 66-nylon, acetal resin, and polytetrafluoroethylene containing molybdenum disulfide, which have low self-coefficients, typically enjoy long operating life in unlubricated gears and bearings.

Significance of Elasticity, Homogeneity, and Isotropy in Plastics: In the section *The Basics of Stress and Strain in Plastics* on page 547, formulas for stress and strain in a wide variety of structural geometries are based on the assumptions that 1) the materials are perfectly isotropic and elastic, obeying Hooke's law in tension, compression, and shear; and 2) the only mechanical properties needed are the elastic modulus E , the shear modulus G , and, occasionally, Poisson's ratio ν . See pages 549 and 550.

The structural material low-carbon steel obeys these assumptions at temperatures below dull red heat. For this metal, $E = 30,000$ kpsi (206.8 GPa), $G = 11,400$ kpsi (78.6 GPa), and Poisson's ratio $\nu = 0.32$. The elastic limit is about 40 kpsi (276 MPa), which indicates that its elongation in tension at that limit is only 0.13 percent. Its stress-strain graph up to the elastic limit is a straight line. If it is loaded up to half its elastic limit and maintained at that load for a couple of decades, when the loading is removed, the 0.065 percent elongation will be instantly and completely recovered. Rate of loading in the normal applications does not affect properties.

Plastics, in contrast, are *viscoelastic* materials. They are complex aggregates of many different elastic and fluid elements and therefore display properties between those of crystalline metals and very viscous fluids. Their stress-strain graphs tend not to be linear; even

at low stresses, they are sensitive to rate of loading and to temperature, as shown generically in Fig. 1. Curves A and B identify brittle materials, whereas curves C through E display increasing ductility.

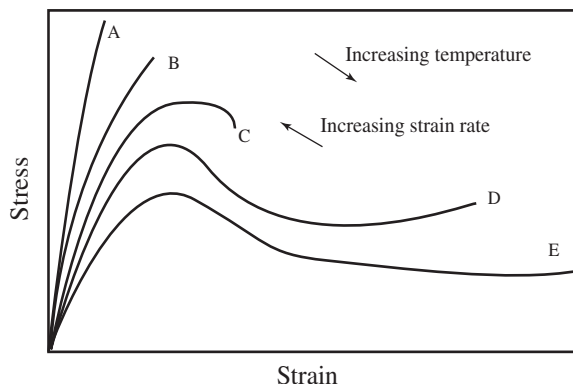


Fig. 1. Generic Tensile-Test Graphs for Plastics, Showing Typical Range of Behavior from Brittle to Highly Ductile

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 this discussion 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.

Creep: When plastics are subjected to sustained high loads, they *creep*. That is, they tend to slowly deform (flow), exhibiting the viscous side of their nature. If the load is removed, the stressed object will usually not return completely to its original shape and dimensions. Creep is more rapid at higher temperatures, even at temperatures expected in normal service. Laboratory stress-strain curves obtained according to ASTM D638 at moderate strain rates and 23°C (73.4°F) or other temperatures will resemble those in Fig. 2. Most plastics have no true proportional limits, instead exhibiting curved dependence of stress-vs-strain at the lowest strains. Tangent moduli from D638 therefore tend to be subjective and inaccurate when used for predicting deformation. The isometric diagram of Fig. 2 shows the dependence of stress in Styron 475, a rigid modified polystyrene, at various strains and times. Note the logarithmic time scale (0.01 h = 36 s, 10,000 h = 1.14 yr). The curve on the left panel, for 0.01 h, is the stress-strain graph one might obtain at one of the slower testing rates of ASTM D638. The stress ordinate at the left edge, front, i.e., 600 psi (4.1 MPa) for a strain of 0.15 percent, corresponds to a short-time modulus for this resin of 400 kpsi (2.8 MPa), in agreement with values reported elsewhere. When this small strain was maintained for 1000 hours (6 weeks), the stress had decayed along the first curve (left rear to right front) to about 400 psi (2.8 MPa), two-thirds of its initial value.

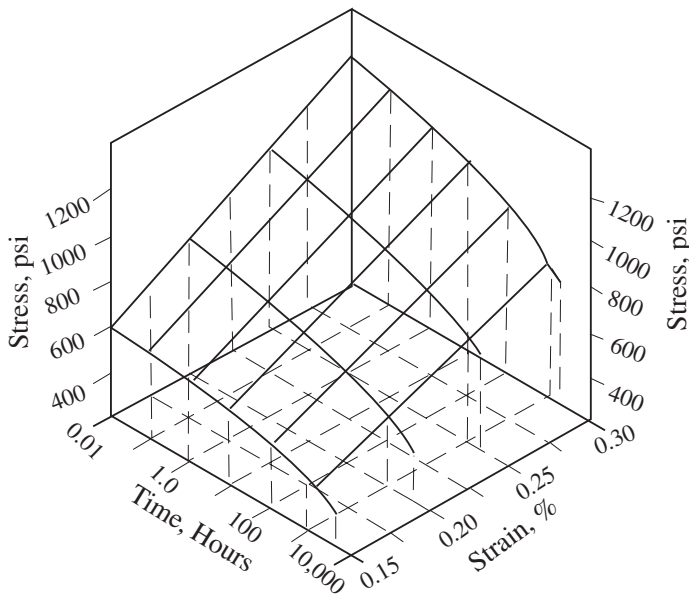


Fig. 2. Isometric Plot for High-impact Polystyrene Showing Stress Response to Imposed Strains Over Three Decades of Time

Some hygroscopic resins can absorb water from the air, with stress-strain behavior ranging from curve B or C of Fig. 1 when very dry to curve D or E at high moisture contents. Polyamides (nylons), classified as engineering resins with superior properties, exemplify this moisture dependence, picking up about 0.3 percent in very dry climates and 2.5 percent or more in very humid ones.

One must not use modulus and strength values reported from ASTM D638 testing in the design of plastics products that must sustain loads over long periods. Still, the values from the standard tests do provide information aiding in the preliminary selection of materials. Fig. 3 compares the short-time tensile moduli and breaking strengths of some common rigid plastics. Properties for these and other plastics are included in the plastics properties table on page 378.

The Basics of Stress and Strain in Plastics.—The mechanical behavior of plastics is similar in many ways to that of metals, but there are important differences that must be kept in mind in the design of plastics products and parts.

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 as shown in Fig. 4. 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. 4, 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.

Stresses must be defined by both magnitude and direction. The stress S acting in the direction shown in Fig. 4 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*.

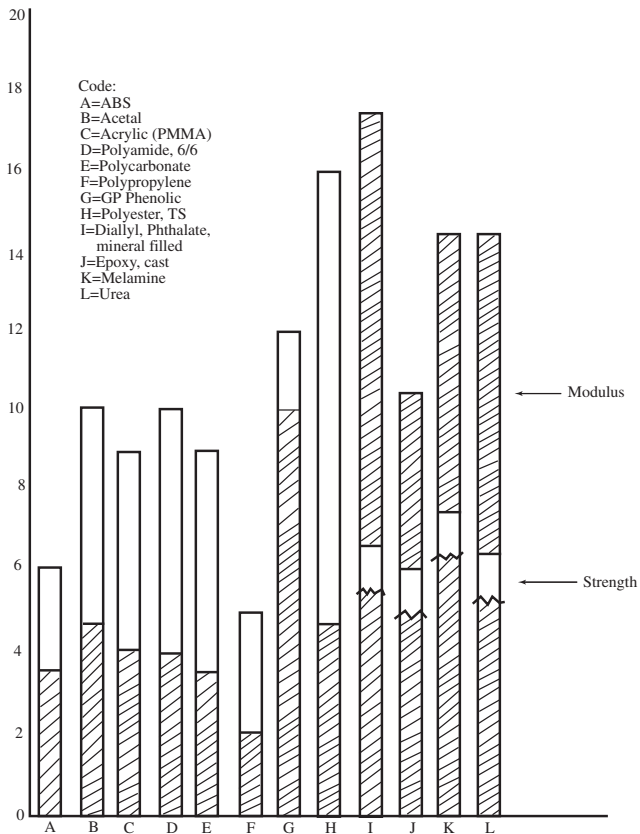


Fig. 3. Comparison of Tensile Moduli and Strengths for Five Thermoplastics and Five Thermosets of Interest to Designers of Plastics Products

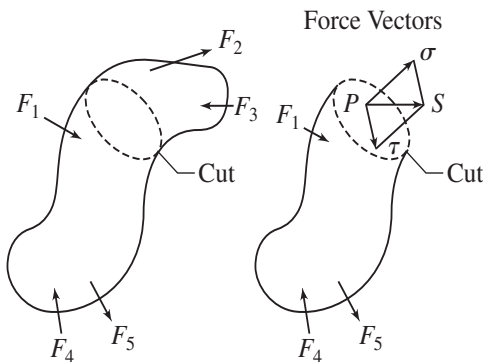


Fig. 4. Internal Forces and Stresses in a Body

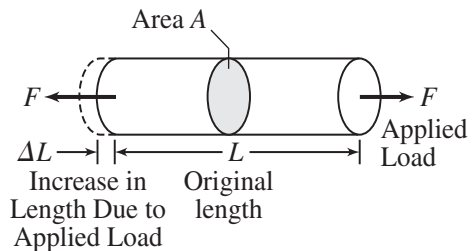


Fig. 5. Simple Tension Load

Normal stress (σ) is illustrated by the simple tension test shown in Fig. 5, 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 page 2749 and Table 39 on page 2781) the stress σ is expressed in newtons/meter² (N/m^2).

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

If the load is applied as shown in Fig. 5, the test piece is in tension, and if reversed, it is in compression.

Normal strain (ϵ) is also illustrated by the diagram in Fig. 5, 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

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

Strain is the ratio between the amount of deformation of the material and its original length. It 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:

$$1000\mu\epsilon = 0.001 = 0.1 \text{ per cent strain}$$

$$10000\mu\epsilon = 0.010 = 1 \text{ per cent strain}$$

Modulus of Elasticity E: 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 by various names: the *modulus of elasticity*, *Young's modulus*, or, in the plastics industry, *tensile modulus*. Referring to Fig. 5, 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 percent secant modulus, which is the ratio of stress to strain at 1 percent strain on the stress-strain curve. In the illustration of typical stress-strain curves in Fig. 6, the secant modulus at the point E is the slope of the line OE .

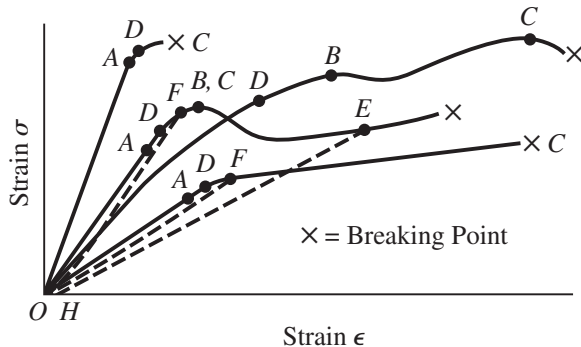


Fig. 6. Typical Stress-Strain Curves

For metals, Young's modulus is expressed in terms of $10^6 \text{ lb}_f/\text{in}^2$, N/m^2 , or Pa , as convenient (see *Units of Pressure and Stress* starting on page 2779.)

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

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. 6. 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. 6. 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. 6. 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. 6 and is the level beyond which a 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 plastics 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. 6 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 percent strain, *F* would be described as the yield strength at a 2 percent strain offset.

Poisson's Ratio ν is the ratio of the lateral contraction to longitudinal elongation. 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, Poisson's ratio of the lateral to the longitudinal strains will be constant. The formula is:

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

When a bar like that in Fig. 5 is stretched in tension, mass must be conserved; so if there is no change in diameter, the average density diminishes inversely as the strain increases. If the area decreases in percentage as much as length increases in percentage, the stretched volume would equal the original volume and density would be preserved. In fact most real materials do contract laterally when stretched, but not enough to preserve constant density; so density does usually diminish with elongation.

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 ther-

most plastics have Poisson's ratios between 0.20 and 0.40, whether filled or unfilled, and elastomers can approach 0.5.

Table 1 lists values of ν determined at 23 °C for some plastics by measuring of lateral contraction and longitudinal elongation in tensile tests.

Table 1. Poisson's Ratio at 23 °C for Resins and Compounds

Plastic	Poisson's Ratio, ν	Plastic	Poisson's Ratio, ν
ABS, unfilled	0.35	PCTFE	0.33
Acetal	0.35	Polyester, thermoplastic, gfr ^a	0.35-0.41
Acrylic (PMMA)	0.35-0.40	Polyester, thermoset, gfr ^a	0.24
Alkyd, mineral filled	0.17	Polyetherimide	0.36
Diallyl phthalate	0.27	Polyethylene, HD	0.45
FEP resin	0.48	Polyphenylene ether	0.35
Phenolic, cellulose-filled	0.24	Polyphenylene oxide	0.27-0.38
Phenolic, gfr ^a	0.20	Polystyrene, cross-linked	0.35
Polyamide 6, dry, gfr ^a	0.36	Polyethersulfone	0.40
Polyamide 6/6, dry, gfr ^a	0.32	PTFE	0.46
Polyamide, min-filled, gfr ^a	0.32	PVF	0.40
Polycarbonate	0.37	PVDF	0.34
PC, gfr ^a	0.38		

^a gfr = glass-fiber reinforced, 30 or 33%

Mineral fillers and glass-fiber reinforcements in plastics reduce Poisson's ratio. In anisotropic structures such as uni- and bi-directional laminates Poisson's ratio may be different in orthogonal (i.e., perpendicular) directions. Usually, the value perpendicular to the reinforcing fibers will be the one most likely to be relevant. Vulcanized gum rubber has exceptional behavior; its Poisson ratio = 0.5, and it conserves density. This must be kept in mind in designing items to be compressed, such as rubber cushions and bumpers. When a rubber specimen is compressed it is shortened and its sides must be free to bulge out; otherwise the incompressibility of the rubber would not allow it to deform at all.

Shear stress is described on page 203. 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. 7, 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.

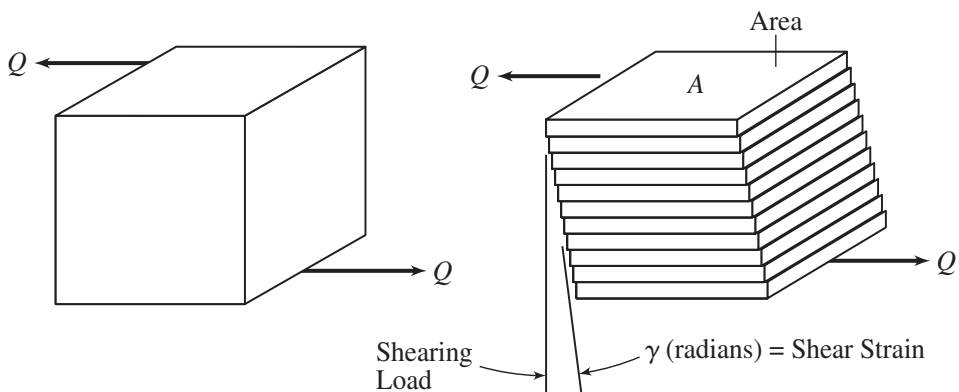


Fig. 7. Shear Stress Is Visualized as a Force Q Causing Infinitely Thin Layers of a Component to Slide Past Each Other, Producing a Shear Form of Failure

Example: In Fig. 8a, shear stress in the overlapped zone equals the tensile force F divided by the contact area of the adhesive. That is, $\tau = F/(WL)$. As F is increased, the joint will finally fail in shear, either in the adhesive layer or in the material of one of the bars, depending on which material has the greater shear strength.

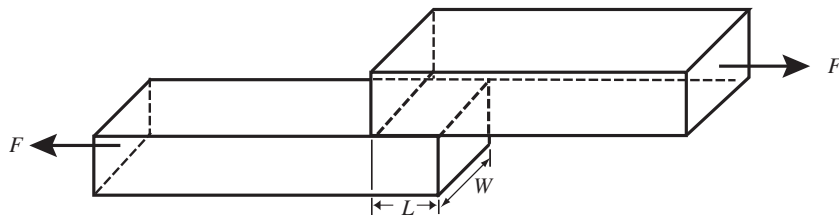


Fig. 8a. Adhesive Lap Joint

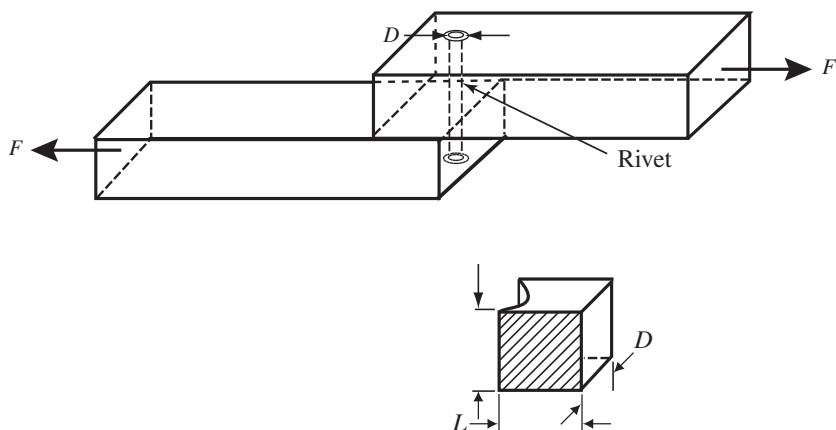


Fig. 8b. Riveted Lap Joint

In Fig. 8b, a similar lap joint is joined with a rivet of diameter D . In this case, the shear area in the rivet is $\pi D^2/4$, a much smaller area. But what if the rivet were aluminum and much stronger than the plastic being joined? A second, very different shear area comes into play, shown as a free body in the lower portion of Fig. 8b, the small bar-end volume adjacent to the rivet. The area shown shaded is equal to $L \times t$ and is $\frac{1}{2}$ of the shear area, so the total shear area equals $2Lt$. Thus, the shear stress τ exerted by the rivet and trying to push that plug out of each bar end is $F/(2Lt)$. As the force F is increased, the mode of failure in the rivet or the bar end will be decided by which of these shear stresses first exceeds the shear strength of the material in which it is acting.

Geometries like those in Figs. 8a and 8b are not useful for determining shear *modulus* because there is very little recordable shear deformation prior to failure at the shear strength. However, the very simple shear geometry shown in Fig. 9 is used in ASTM D732 test to measure the shear strengths of plastics. The washer-shaped test sample has an outer diameter of 2 inches (50.8 mm) and a central hole of about 9/16 inch (14.3 mm) to allow the half-inch (12.7 mm) bolt to pass freely through the specimen. The thickness may be any measured value between 0.05 and 0.5 inch (1.27 and 12.7 mm). In this test the shear area is given by $\pi \times \text{punch diameter} \times \text{disk thickness}$. 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. Shear strengths reported from this test have coefficients of variation of about 4 percent.

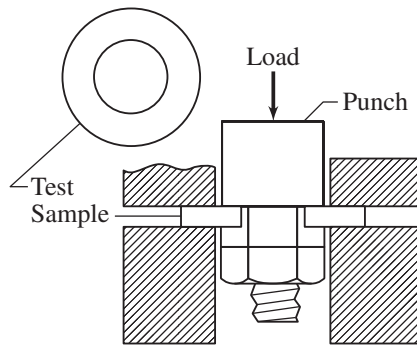


Fig. 9. Setup for Testing Shear Strength of Plastics in ASTM Test D732.
Specimen may be Molded or Cut from Sheet

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.

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

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

For isotropic materials in their Hooke's-law range at low deformations, it may be assumed that the modulus in compression is equal to E . Then a simple theoretical relationship links the tensile and shear moduli with Poisson's ratio:

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

ASTM D1043 provides a method for determining the shear modulus G of plastic specimens at various temperatures by a torsion test. Material suppliers can furnish values of G for their compounds.

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 Equation (10) or rewritten in the following form, based on elasticity principles:

$$\frac{E}{G} = 2(1 + \nu) \quad (11)$$

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

Bulk Modulus B : When a sample of material is subjected to high pressure from all sides, its volume diminishes with a corresponding increase in density. Bulk modulus B is defined as the increase in pressure divided by the fractional decrease in specific volume:

$$B = \frac{\Delta P}{(\Delta V)/V} \rightarrow \frac{dP}{d \ln V} \quad (12)$$

Since $\rho = \frac{1}{V}$, it follows that

$$\frac{1}{B} = \frac{(\Delta\rho)/\rho}{\Delta P} \rightarrow \frac{d\ln\rho}{dP} \quad (13)$$

The dimensions of B are pressure per unit of fractional volume contraction. In English units B is in Mpsi/(in³/in³), or just Mpsi; and the SI units for B are GPa/(cm³/cm³) or just GPa. The last equation indicates that what happens to volume (and specific volume) also happens in the same degree to density, but with the opposite sign, i.e., as the volume increases, the density decreases and vice versa.

For isotropic elastic materials it has been shown that bulk modulus is linked to Young's modulus and Poisson's ratio by the equation

$$B = \frac{E}{3(1 - 2\nu)} \quad (14)$$

Thus, all three moduli, E , G , and B , are linked through Poisson's ratio.

True stress and true strain are terms not in frequent use. In Fig. 5 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 amount of stress in lb/in² (or 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 a beam of rectangular cross-section is bent under a vertical load midway between the beam supports, the bottom surface is stretched in tension while the top surface is compressed. Extending from end to end along the vertical center of the beam is a plane of zero stress called the *neutral axis*. Whatever the shape of the cross-section—constant along the beam—the neutral axis is located at the center of gravity (centroid) of that cross-sectional area. The theory of bending for simple beams makes the following assumptions: 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 cross-sections remain planar during bending.

For a beam of length L with a rectangular section of width b and depth h carrying a central load F , the formula for the maximum bending stress σ at the bottom surface is

$$\sigma = \frac{3FL}{2bh^2} \quad (15)$$

and the formula for the maximum deflection at the center of the beam is

$$y = \frac{FL^3}{4Ebh^3} \quad (16)$$

Note that, if the deflection equation is solved for E , Young's modulus, the modulus can be estimated by measuring the deflection of a beam under a known central force:

$$E = \frac{FL^3}{4ybh^3} \quad (17)$$

This is the basis for ASTM Test D790 for the flexural modulus and strength of plastics. The flexural modulus reported is usually the initial modulus from the load/deflection curve. Most plastics parts undergo bending, so use of flexural values, which tend to be higher than tensile values for many molded plastics, should give more conservative and hence trustworthy results in product design.

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 applications and request the appropriate data. End-use testing must always be considered, 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 at constant stress. The rate of creep for a given material depends on applied stress, temperature, and time.

Creep behavior of a material is an important, even crucial, issue with plastics where parts are to be subjected to loads for extended periods and where the maximum allowable deflection is critical. To determine 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 logarithmically scaled time. In general, crystalline materials have lower creep rates than amorphous plastics. Glass reinforcement substantially improves the creep resistance. **Fig. 10** shows the great differences in creep-rupture behavior that exist among different plastics at several temperatures.

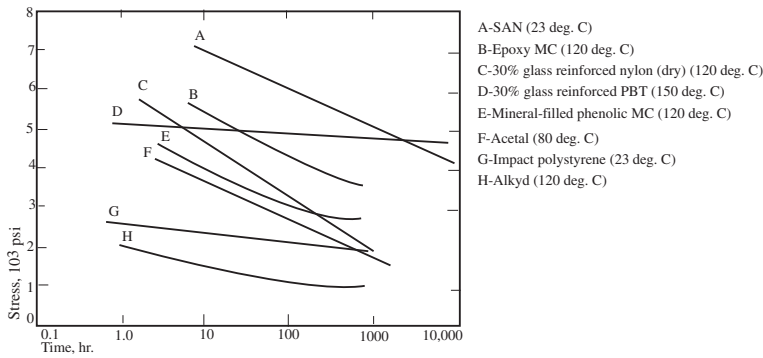


Fig. 10. Plots Showing Diminishing Strengths of Several Plastics as Creep Period Is Extended. (Curves are Steeper at Higher Temperatures, Except Curve D for Glass-fiber-reinforced Polybutylene Terephthalate)

Apparent or Creep Modulus: If the deflection of a part subjected to continuous loading is calculated using the short-test modulus of elasticity E , results are likely to be disappointing or even disastrous 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 beam deflection from the traditional equation given earlier.

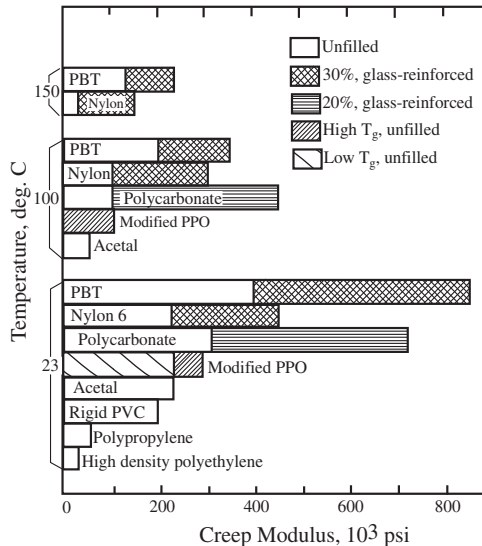


Fig. 11. 1000-hour Creep Moduli of Several Plastics at Room Temperature and Higher

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. The bar graphs of Fig. 11 show 1000-h creep moduli for several engineering resins at 23 and 100 °C. This kind of information may also be provided as tables of values at constant stress and temperature for various time periods.

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 percent of the strain at the yield point or yield strength is suggested for high-elongation plastics. For low-elongation brittle plastics that have no yield point, 20 percent 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 percent of the yield or ultimate strength mentioned above should not be exceeded.

Impact loading describes a situation in which a load is applied extremely rapidly. Any moving body has kinetic energy, and when the motion is stopped by a collision, the energy is dissipated. Ability of a plastic 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, and 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 (ASTM Method D6110) 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_f (J). The value of such tests is that they permit comparison of the relative notch toughness of two or more materials under specific conditions.

The tensile impact test mentioned earlier aids ranking materials because it represents more realistically conditions that are encountered by actual parts in certain applications.

Fatigue tests measure the ability of plastics materials to withstand repeated stresses or other cyclic phenomena. Example applications are a snap-action or snap-fit latch that is frequently opened and closed, a gear tooth, a bearing, and 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. ASTM Test D671 is of this type, with a cycle rate of 30 Hz. The number of cycles to failure is recorded for each stress level. Data are normally presented in plots of stress versus log cycles called S-N curves for specific cycle rates and environmental temperatures.

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 encountered by actual parts in certain applications.

Thermal Properties.—Melting temperatures of highly 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 service temperatures, well beneath the melting range.

Glass transition is a reversible change that occurs in an amorphous polymer or in amorphous regions of a partly crystalline polymer when it is heated from a very low temperature into a certain range, peculiar to each polymer, characterized by a rather sudden change from a hard, glassy, or brittle condition to a flexible or rubbery condition. Physical properties such as coefficient of thermal expansion, specific heat, and density usually undergo distinct changes in their temperature derivatives at the same time. The symbol for the glass-transition temperature is T_g .

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 (ASTM D1525) measures the ability of a thermoplastics material to withstand short-term contact with a heated surface and is most useful for crystalline plastics. Amorphous thermoplastics 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 inch (12.7 mm) thickness, loaded to a specified bending stress, will deflect by 0.010 inch (0.25 mm). This ASTM test (D648) is run at bending stresses of 66 lb_f/in² (0.455 MPa) or 264 lb_f/in² (1.82 MPa) or both. The value obtained was once referred to as the *heat distortion temperature* 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 psi (242.7 MPa) at 66 psi stress, and 140,000 psi (965.3 MPa) at 264 psi stress.

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 (α) is the ratio of the fractional change in a linear dimension for a unit change of temperature and is expressed as in/in-F, or cm/cm-C. Typical average values for common materials and selected plastics are shown in Table 8, page 363. ASTM Method D696 directs that if samples should be prepared so as to give a minimum of anisotropy, but if anisotropy is suspected, specimens shall be cut so as to measure α along the principal axes of anisotropy. The values in Table 8, page 363, may be presumed to have been measured according to those instructions.

Thermal Conductivity is the rate at which a material conducts heat energy along its length or through its thickness. For example, if a tightly covered plastic insulated cooler at 32°F (0°C) is filled with ice and chilled beverage cans and the outside is 80°F (27°C), heat from the surrounding warm air passes slowly through the box wall, melting the ice inside. The low thermal conductivity of the wall resists this heat flow. The property is defined by *Fourier's law of heat conduction* as follows:

$$Q_x = k \frac{\Delta T}{x}$$

where Q_x = flux, i.e., the rate of heat flow per unit area of the wall surface,

k = thermal conductivity of the box-wall material,
 ΔT = temperature difference from the hot side to the cold side, and
 x = wall thickness.

English units for k are Btu/h-in² (°F/in); SI units are J/s-m²(K/m).

In sharp contrast to metals, plastics are poor heat conductors but excellent insulators, and plastic foams even more so. Plastics are also good electrical insulators. These insulating properties are valuable in many applications. Conductivities can be enhanced where needed by loading the plastics with copper or aluminum powder. In anisotropic materials, thermal conductivity may differ along major axes. Thermal conductivities for plastics are listed in the table *Typical Properties of Plastics Materials* on page 378.

Aging at elevated temperatures may affect physical, mechanical, electrical, or thermal properties of plastics materials. Data from tests on specimens stored at specific temperatures 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. The importance of flammability testing for plastics is reflected by ASTM's listing of ten different tests under the index subject "Flammability—Plastics." The high carbon and hydrogen content of plastics means they are usually flammable. Some exceptions are fluorocarbons and chlorofluoroplastics, which are not flammable. Silicones and rigid PVC won't sustain fire by themselves. Compounds can significantly reduce any plastic's flammability by judiciously choosing from among hundreds of available fire-retarding additives.

Effect of Temperature on Mechanical Properties.—The equivalence of high strain rates and low temperatures (and vice versa) 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. That is, 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 and employing time-temperature superposition methods to estimate creep at lower temperatures and longer times. End-use 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 increase is shown by the curves in Fig. 12 for crystalline and amorphous materials, where a gradual drop in modulus is seen as the glass-transition temperature T_g is approached. The deflection temperature marks a flexural modulus of 35,200 psi (242.7 MPa) at a test stress of 66 psi (455 kPa), giving rise to the horizontal dashed line in Fig. 12. Above the glass-transition temperature, amorphous materials suffer rapid diminution of modulus, and, even with glass-fiber reinforcement, modulus drops rapidly above T_g . Some crystalline resins maintain usable moduli at temperatures approaching the crystalline melting point (T_m). Glass-fiber reinforcement can substantially improve the modulus of crystalline materials between the glass-transition and melting temperatures. Generally, strength-versus-temperature curves exhibit shapes like modulus curves, while, as expected, elongations increase with rising temperatures.

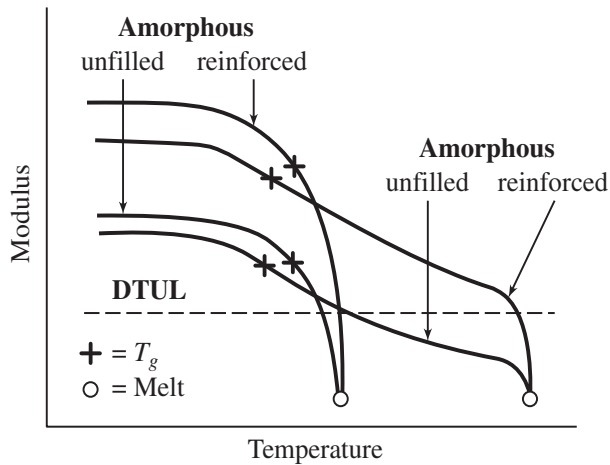


Fig. 12. Schematic of Modulus Behavior of Crystalline and Amorphous Plastics Showing T_g and T_m and the Beneficial Effect of Reinforcement on Deflection Temperature Under Load (DTUL)

As temperatures drop significantly below normal ambient values, most plastics materials become brittle and lose much of their room-temperature impact strength, although a few materials show only a gradual decrease. Concern over failures at low temperatures led to the development of ASTM D746, Brittleness Temperature of Plastics, in 1943. In this test, small, unnotched test bars are set up as cantilever beams in groups of five or more, brought to a preset low temperature, and struck by a weighted, blunt-nosed bar falling at 2 m/s. The experiment is repeated at other temperatures, higher and lower, and the fraction of breaks is plotted vs temperature on normal-probability graph paper. From the plot, the temperature at which half the bars break is estimated and reported as the brittleness temperature. Plastics reinforced with long glass fibers have relatively high impact values, both notched and unnotched, at room temperature. They retain much of these values at lower temperatures.

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 steady electromotive force (emf) difference is applied to a sample of the material that is made part of an electric circuit. Ohm's law governs the flow of direct current:

$$I = \frac{V}{R}$$

where I = current, amperes (A)

V = emf difference across the test element, volts (V)

R = its resistance, ohms (Ω)

R is determined by the element's dimensions and the material's electrical resistivity:

$$R = \rho \frac{L}{A}$$

where L = length of the element, cm

A = its cross-sectional area perpendicular to the current direction, cm^2

ρ = resistivity of the conductor material, ohm-cm

Materials having resistivities above 10^8 ohm-cm are considered insulators, and materials with values between 10^8 and 10^3 ohm-cm are considered partial conductors. Most plastics have volume resistivities in the range of 10^{12} to 10^{18} ohm-cm.

Surface resistivity is a measure of the susceptibility of an electrical insulating material to surface contamination, particularly moisture, which makes it electrically conductive. The tests use parallel electrodes that are placed on the same surface of the material. Measured resistance is multiplied by the width of the electrodes and divided by the distance between them and reported as ohms per square. Methods for determining both volume and surface resistivities of insulating materials are spelled out in ASTM D257.

The results of such measurements are sometimes reported in terms of their reciprocals, *volume conductivity* (siemens/cm) and *surface conductivity* (siemens). The unit siemens is the reciprocal of resistance, $1/R$ (with units $1/\Omega$.) The siemens was formerly known as the mho.

Dielectric strength is a measure of the voltage required to cause an insulator to break down and allow an electric current to pass through the resulting conductive path. It may be measured (ASTM Test D149) at any or several frequencies from 0 Hz (direct current) to 800 Hz; the results are expressed in volts per mil (0.001 inch, or 0.0254 mm) of thickness. High values of this property are desired in capacitor films and wire coverings. Variables that may affect test results include temperature, frequency, sample contamination, internal voids, rate of voltage increase, and duration of test. Although the use of volts/mil units in test results suggests that the same dielectric strength value should apply to different film thicknesses, tests show that thinner films fail at lower V/mil than thicker ones.

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. Polarization occurs because of charge-carrying atoms or functional groups (dipoles) in materials. When the field is applied, these groups try to align their positive and negative ends with the field. Reversal of the direction of the electric field 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 capacitors and high-frequency electrical apparatus. Changes in temperature, humidity, electrical frequency, and part thickness may affect the dielectric constant. Dielectric constants for a dozen various engineering thermoplastics are listed in [Table 2](#), page 562. Many others are included in the main table of plastics properties, *Typical Properties of Plastics Materials* on page 378.

Heat Dissipation Factor: If a polar material is subjected to an alternating electric field, its dipoles reverse their orientation twice per cycle. This movement encounters frictional resistance at the molecular level, and at high frequencies that friction can generate considerable heat, as detected by the electrical phase angle between voltage and current. This effect is called the *heat dissipation factor*. The heat dissipation factor is a measure of heat energy dissipated by rapidly repeated reversals of polarization, as with an alternating current. The dissipation factor can also be thought of as the ratio of electrical energy lost to that transmitted at a representative frequency, such as 1 MHz (10^6 cycles/s). This high-frequency heat generation, undesired in many insulation uses, can be used to preheat thermo-setting materials just before molding. It is also the basis for electronic heat-sealing, widely used in the fabrication of articles from plasticized-PVC films. Some heat dissipation factor values are shown in [Table 2](#).

Table 2. Typical Values of Dielectric Constants and Heat Dissipation Factors for Several 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

Arc Resistance as determined by ASTM D495 is the length of time (seconds) required for an electric arc applied on the surface of an insulating material to develop a conductive path. Materials that resist such a development are preferred for switchgear parts and other high-voltage apparatus. This test is used mostly for thermosetting materials because, unlike thermoplastics which tend to melt in the arc, thermosets decompose and do produce conductive paths.

Comparative Tracking Index (CTI) is a UL test with an ASTM counterpart (D3638) 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, a condition 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 to 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 resistances from some commonly used thermoplastics materials are shown in Table 3, but are only general guidelines and cannot substitute for values derived from 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.

While the preceding tests may provide useful data about chemical compatibility, they do not generate reliable information on performance properties for design purposes. The only tests that provide such information are the creep modulus and rupture tests, conducted at appropriate temperatures in the environment that will be encountered by the product, preferably on prototype parts. Many plastics are slowly degraded to varying degrees by ultraviolet light (UV), which causes fading, chalking, and embrittlement. Acrylics and a few others are not damaged by UV. However, hundreds of additives are available that, when compounded into neat resins, will give compounds that are resistant to heat, burning, UV, staining, etc.

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 they may not be directly transferable to the components produced. Because of the somewhat lower modulus of elasticity of plastics materials (10^5 lb_f/in² for plastics compared with 10^6 lb_f/in² for metals, in metric units 100 MPa compared with 1000 MPa), 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 of 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 need additional design assistance.

Design Analysis

Structural Analysis.—Plastics parts may be subjected to stresses caused by assembly, handling, temperature variations, and other environmental effects. Simple analysis using information in *Moment of Inertia* on page 224 and *Beam Calculations* on page 248 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 during product life. 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

Table 3. Chemical Resistance of Various Materials by Chemical Classes

Polyarylate										Polycarbonate									
Polyphenylene Sulfide*										Polysulfone*									
Liquid Crystal Polymer*										Modified Polyphenylene Oxide									
Polyester Elastomer										Polypropylene									
Thermoplastic Polyester (PET)										ABS									
Thermoplastic Polyester (PBT)										316 Stainless Steel									
Nylon 6/6										Carbon Steel									
Acetal Homopolymer										Aluminum									
Acetal Copolymer																			
ACIDS AND BASES																			
Acids, weak	A	B	C	A	A	A	A	A	A	B	A	A	A	A	A	C	Dilute mineral acids		
Acids, strong	C	C	C	B	—	C	B	A	—	C	C	—	A	A	B	C	Concentrated mineral acids		
Bases, weak	A	C	A	B	B	A	B	A	—	C	A	A	A	A	A	B	Dilute sodium hydroxide		
Bases, strong	A	C	C	—	—	B	C	A	—	C	A	—	A	A	B	B	Concentrated sodium hydroxide		
Acids, organic, weak	A	B	C	A	A	A	A	A	A	B	A	A	A	A	A	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	C	A	C	C	A	A	A			
Automotive, lubricants	A	A	A	A	A	A	A	A	C	C	A	A	A	A	A	B	A		
Automotive, hydraulic	A	A	—	A	A	—	A	A	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, halo-genated	A	B	C	B	B	A	A	A	C	C	C	—	—	—	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	B	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	C	A	A	Toluene, xylene, naphtha		
Aromatic hydrocarbons, halo-genated	—	—	—	—	—	C	—	A	C	C	C	—	—	—	A	A	Chlorobenzene		
Aromatic, hydroxy	C	C	C	C	—	C	A	A	—	C	C	—	A	—	B	C	Phenol		
Esters	B	B	A	B	B	B	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, bro-mine (wet)		
Oxidizing agents, weak	C	C	C	A	—	A	A	A	—	A	—	A	A	A	B	C	Sodium hypochlorite solution		
Water, ambient	A	A	B	A	A	A	A	A	A	A	A	A	A	—	A	C			
Water, hot	B	C	B	C	C	B	A	A	—	C	—	A	C	—	A	C			
Water, steam	C	C	C	C	C	C	B	A	—	C	—	—	C	—	A	C			

A—minimal effect; B—some effect; C—generally not recommended.

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.

Room temperature except for hot water, steam, and materials marked with a * $\approx$ 200°F (93.3°C). Generally, data covering extended exposure (more than a week) were used.

with the structural analysis information indicated above and the equations presented here, for preliminary design analysis and for 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 plastic pressure vessel is a cylindrical tube with internal pressure. In selecting a wall thickness for the tube it is convenient to use the thin-wall hoop stress equation:

$$\text{hoop stress } \sigma = \frac{P d_i}{2t} \quad (18)$$

where P = uniform internal pressure in the tube, d_i = inside diameter of the tube, and t = tube-wall thickness. This equation is reasonably accurate for tubes where the wall thickness is less than $0.1 \times d$. Also, it is easy to solve for the wall thickness t required to support an internal pressure P with an allowable hoop stress σ . For wall thicknesses greater than $0.1d$, the maximum hoop stress on the wall surface inside the tube can be calculated from

$$\text{hoop stress} \quad \sigma = P \frac{d_o^2 + d_i^2}{d_o^2 - d_i^2} \quad \text{or} \quad \sigma = P \frac{1 + R}{1 - R} \quad (19)$$

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

By substituting $d_o = d_i + t$ into the left equation one can solve it for the required wall thickness t to provide a working equation for design. The result is

$$t = \frac{d_i}{2} \left(\sqrt{\frac{\sigma + P}{\sigma - P}} - 1 \right) \quad (20)$$

In the above equations all units must be consistent.

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 a) fail immediately by developing a crack parallel to the hub axis to relieve the stress, a typical hoop stress failure; b) survive assembly but fail prematurely due to creep rupture caused by the high induced-stress levels; and c) 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 :

$$\gamma = \frac{1 + (d_s/d_o)^2}{1 - (d_s/d_o)^2} \quad (21)$$

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

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + 1} \quad (22)$$

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

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + 1}{\gamma} \quad (23)$$

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

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{(\gamma + \nu_p)} \quad (24)$$

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

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + \nu_p}{\gamma} \quad (25)$$

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, fluoroplastics tape should be used on female plastics pipe threads. If torque cannot be controlled, an external hoop ring, either pressed on or molded in, should be considered. Flats should not be designed into plastics parts for assembly purposes because they will encourage overtightening. If some provision for improved gripping must be made, wings or a textured surface may be used. An approximate formula for the hoop stress σ produced in a plastics boss with internal pipe threads is

$$\sigma = \frac{3T}{tdL} \quad (26)$$

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

Equation (26) 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 which usually have much lower coefficients of thermal expansion than plastics. The basic relationship for thermal expansion is

$$\Delta L = \alpha L \Delta T \quad (27)$$

where ΔL = change in length, α = coefficient of thermal expansion (see Table 8, page 363), 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

$$\epsilon_T = \frac{\Delta L}{L} = \alpha \Delta T \quad (28)$$

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

$$\sigma_T = (\alpha_m - \alpha_p) E_p \Delta T \quad (29)$$

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. 13.

Most plastics expand more than metals with temperature increase, 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. 13:

$$\Delta L_{rel} = (\alpha_p - \alpha_m) L \Delta T \quad (30)$$

Designing for Stiffness.— The designer must take full advantage of the ability of plastics to be easily formed into a desired shape, in contrast to woods where every shape must be machined or assembled from planks or blocks. To a lesser degree, the same is often true of metals, although die-castable metals have a considerable shape versatility. Though the modulus of elasticity is much less in plastics than in metals, *stiffness* is a property not of the material but of the *structure* that can be made from it. When the product must support bending loads, as in a bookshelf, a simple beam of rectangular cross section would be the logical approach if the shelf material were pine or mahogany. If the material is plastic, other cross sections of higher stiffness per unit weight can be considered. Fig. 14 shows some alternatives to the traditional rectangular cross section that achieve greater stiffness with less material.

Manufacture of Plastics Products

The main processes for manufacturing large quantities of plastics products are extrusion, injection molding, blow molding, and sheet thermoforming for thermoplastic materials; compression molding, transfer molding, prepreg molding, and pultrusion for thermosetting materials.

More tonnage of thermoplastics pass through extrusion machines than any type of plastics forming machines. The dominant type of extruder is the single-screw extruder. A feed

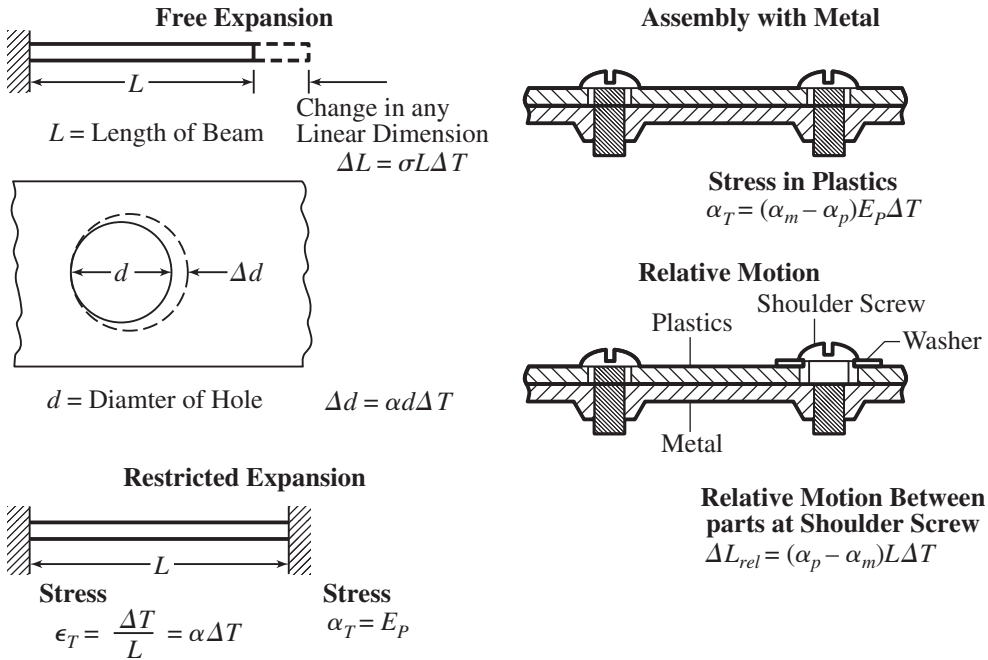


Fig. 13. Thermal Expansion Equations for Various Combinations of Materials and Situations

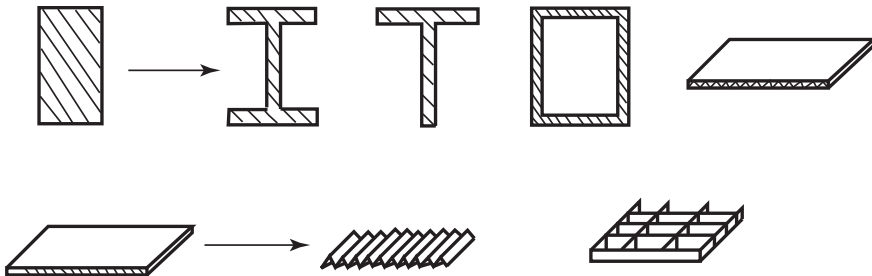


Fig. 14. Placing Most of the Material Far From the Centroid Achieves Far Higher Bending Stiffness per Unit Weight of Plastics

hopper supplies small plastic granules to a thick-barreled, heated cylinder, inside which turns a sturdy, precisely contoured screw. A powerful variable-speed motor drive turns the screw at 50 to 500 rpm. At the delivery end is attached a die, a block of metal with a specially shaped orifice. The screw has two main jobs: one, to melt by friction and thoroughly mix the feed, transforming it from cold, solid particles into a homogeneous hot, viscous melt; two, to develop the very high pressure (2,000-8,000 psi, or 14-55 MPa) needed to pump the melt through the die. This produces a continuous length of product whose cross-section resembles but is not identical to that of the die opening. Extruders are widely employed in intermediate processing of material in the plastics industry. Some final consumer products made by this process are pipes, sheets and films, garden hoses, electrical wires, netting, fishing lines and leaders, and house sidings. Many extruded products are parts of other industrial or consumer products. For example, huge quantities of ABS sheet and flexible vinyl gasketing go into refrigerators and freezers each year. Mop handles are extruded tubing cut to the length needed. Produce bags are made from extruded tubular blown polyethylene film that is laid flat, printed, heat-sealed across and perforated for tear-

off at intervals, then wound on roll cores for delivery to supermarkets. An important class of extruded products includes rods, bars, and tubes from which machinists fabricate smaller quantities of objects, such as prototypes for testing prior to mass production.

The extrusion process can determine a product's cross-sectional shape and size but not its third dimension (length).

Sheet Thermoforming.— Also known as vacuum forming, this widely used molding process operates at pressures of 100 psi (689.5 kPa) or less, usually at 14.7 psia (atmospheric pressure) i.e., 101.35 kPa. The process begins with a sheet of plastic from which a single product or sometimes up to several dozen small products are to be made per operating cycle. Mounted in a frame, the sheet to be formed is preheated in an oven or slid between paired radiant heaters at the thermoforming press until it begins to sag. The temperature is still well below that at which the same resin would be injection molded. The sheet is then positioned over the mold, which, in the original and simplest variant of the process, is a female mold made porous by drilling many small holes through it. The mold is enclosed in a chamber (vacuum box) so that a vacuum can be drawn from below. The softened sheet is clamped to the mold around its edges, vacuum is applied, and atmospheric pressure presses the sheet against the mold surface. Cooling and solidification of the part is done with fans, water mist, or cooling channels in the mold. The unclamped molding is then indexed to a die-cutting table where the edges are trimmed and multiple parts cut out. Trim scrap, which may be as much as 20 percent of the sheet area, is recycled to the sheet extruder.

Because the vacuum-drawn sheet contacts the upper areas of the mold early in the mold cycle and the bottom last, the wall thickness of the finished part is thinner at the bottom than the upper areas. Often, at least average thickness is needed in the bottom areas to satisfy the design service and service life requirements. Over the years, techniques have been developed that permit draw depths of more than twice the clamping width with much more uniform wall thickness. Polystyrene cups for cold drinks are now made in this way. [Fig. 15](#) shows the steps in a more sophisticated variant vacuum air-cushion forming, in which a male mold component provides plug assistance without actually touching the softened plastic membrane. Clearly, though, thermoforming cannot match the tight tolerances of injection molding. Nor can it produce intricate shapes nor parts that require substantial or abrupt variations in wall thickness. Because of the low pressure, molds do not require the elaborate design planning and massive construction of injection molds. They can be made much more cheaply of aluminum – even plaster for short runs – and usually do not need the extensive polishing and hard-chrome plating typical with injection molds. Also, thermoforming machines are much less massive for equal part sizes than injection machines. Production efficiency is higher in multi-station machines but requires a higher financial investment.

Blow Molding.— In its most common form, blow molding couples an extruder with a chilled aluminum mold to make a hollow object such as a two-liter soda bottle. A cross-head die attached to the extruder extrudes a tube of hot melt (*parison*) downward between the mold halves, as in [Fig. 16](#). The parison-inflating air injection at stage 4 is done through a needle that penetrates the pinched-off melt at the inverted top of the bottle. Bottles with capacities from 2 ml to 10 gallons (38 liters) and myriad other hollow objects are produced by this process. Close tolerances are maintained on the threaded closures where the mold halves meet; elsewhere they are looser, comparable to those of sheet thermoforming. As in thermoforming, when a particular product, e.g., a half-gallon or 2-liter bottle, warrants a very high production rate, highly automated, multi-station machines are economical.

Processing of Thermosets.— While some thermosetting materials have been adapted to injection molding processes, most are still processed by compression molding, transfer molding, prepreg molding, sprayup, and hand layup. Commonly used *compression molding* is a process in which precompounded and catalyzed resins, still thermoplastically formable, are preformed into buns or bricks of known weight. One or more bricks are pre-

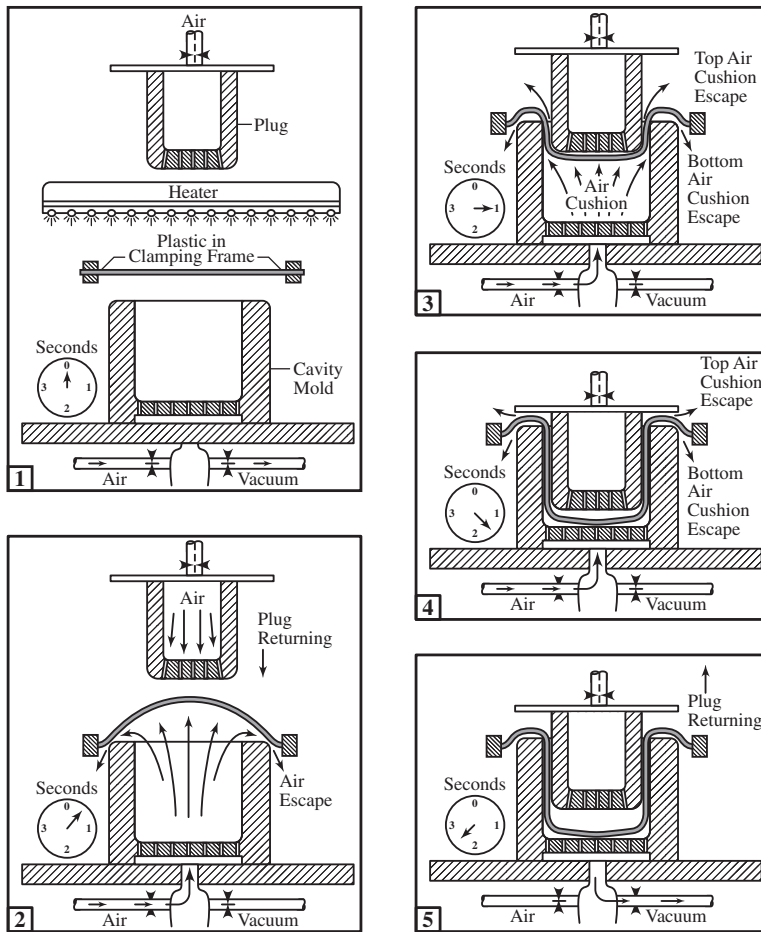


Fig. 15. Five Stages in the Cycle of Air-cushion Vacuum Forming. Balancing the Air Pressures at Stages 3 and 4 Can Be Tricky. Removal and Trimming Follows Stage 5.

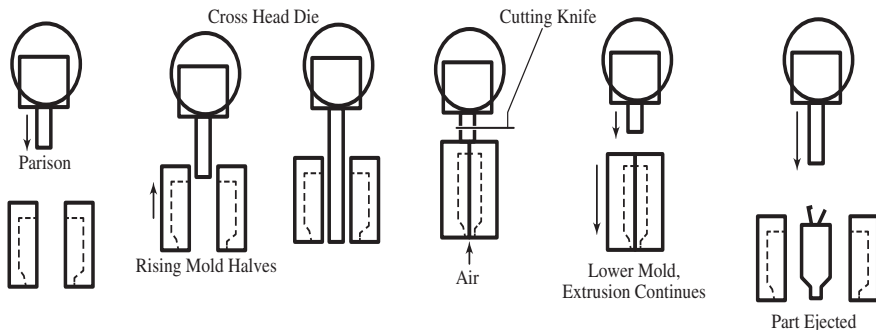


Fig. 16. Six Stages of Extrusion/Blow Molding are Shown in this Schematic of Process

heated in convection or electronic ovens and quickly positioned in the female half of a horizontal mold. It and the hovering male half are at the molding temperature. The mold is closed and brought to high pressure, squeezing the softened bricks, which, ideally, flow into all parts of the mold cavity. Pressure is maintained for the time required to complete the chemical cross-linking reaction and to solidify the molding, after which it is ejected

from the mold, any slight leakage at the parting line (*flash*) is trimmed, and it is set aside to cool. With the correct choice and dose of catalyst, time in the mold need not be long. As with injection molding, the high pressures dictate massive molds and presses.

Compression molding is also an efficient way to process unsaturated polyesters, perhaps the most versatile and user-friendly resins available for reinforced plastics processing. When reinforced with chopped glass and mixed to a dough-like consistency, these compounds, known as premix or “gunk,” have been widely used in the automotive and boat industries. Compression molding is also used with sheet-molding compounds. Glass-fiber cloths are preimpregnated with resin and need only heat and pressure to cure them into finished products.

If a mold is provided with both heating and cooling, thermoplastics, too, may be compression molded, an obviously slow process, but sometimes convenient for making prototypes and test pieces.

In *transfer molding*, also called *plunger molding*, the thermosetting compound is preheated in a separate cylinder (the pot) until it is fully fluid, then forced by a plunger through a runner into the final mold. This process is capable of molding complex parts that cannot be made by compression molding, and also offers closer dimensional tolerances and glossier surfaces than the latter. Multi-cavity molds are feasible. Transfer molding has been used widely in the electronics industry.

Another popular method of processing thermosets into unidirectionally reinforced products is *pultrusion*, in which continuous glass roving or mat is pulled through a resin bath or impregnator and then into a preforming fixture where the cross-section is partly shaped. The preliminary profile continues through dies where curing mechanisms are applied, and finally to a cut-off saw to produce shapes such as channels, rods, and tubes. Ladder rails, fishing rods, tool handles, tent poles, and numerous other parts are made by this process.

Polyurethanes.— Polyurethanes (PUR) are among the most versatile of polymers, both as thermoplastic and thermosetting, as well as being the most ubiquitous in everyday products. For example, the flexible thermoplastic members of the family are mainly elastomers that are favorites for athletic shoes, while the rigid, transparent thermoplastics are vying with polycarbonate for the high-value market in eyeglass lenses.

The thermosets are formed by linking two reactive components, an isocyanate and a polyol. Toluene diisocyanate and diphenylmethane diisocyanate are the most used isocyanates, while a variety of polyols are commonly used. Short-chain, low-molecular-weight types result in rigid plastics, and longer-chain types form flexible materials. About 70 percent of all PURs worldwide go into automotive, building and construction, mattresses, and furniture including frame members produced by reaction injection molding. Densities of rigid PUR foams range from 1 to 8 lb/ft³ (16–128 kg/m³) and much higher in furniture members. Flexible PUR foams range from near that of the parent plastic down to 1 lb/ft³ (16 kg/m³). Since the reactive components must be mixed instantly and thoroughly at the moment of application, a special industry of PUR processing machinery has developed to deal with that requirement.

Cast rigid PUR is available in rod, tube, and bar stock form.

Reinforced Plastics.— Mentioned previously were compression molding of premixes and pultrusion for unidirectionally reinforced structures. For superior strength and modulus, many items are reinforced with cloths of various fibers and weaves. Felted mats are often cross-layered and then impregnated with liquid resin (e.g., polyester or epoxy) prior to being cured to make final products. Some of these products, if not too large, can be compression molded. But with judicious catalysis, the resin can be cured at room temperature, facilitating manufacture at low pressure, with or without heat, of large structures such as boats and storage tanks for liquids. With layup one can handily distribute the reinforcing web in accordance with the stress distribution expected when the product is placed in service. Fig. 17 shows four increasingly positive (and more costly) ways of curing hand

layups. Also, many laminates are produced in sheets, typically 4 ft by 8 ft (122 by 244 cm), for subsequent fabrication into final products. The familiar decorative laminates (Formica), for example, are produced in large presses with multiple steam-heated platens interleaved between laminates, permitting production of dozens of sheets in one pressing. Properties of some reinforced plastics available in sheet form are given in **Table 5**.

Table 5. General Properties of Reinforced Plastics (ASTM Test Procedures)

Material	Specific Gravity	Tensile		Compressive Strength 10 ³ psi	Flexural Strength 10 ³ psi	Izod Impact Strength ft-lb/in notch	Heat Resistance Continuous °F	Arc Resistance seconds
		Strength 10 ³ psi	Modulus 10 ⁶ psi					
Polyester								
Glass cloth	1.5-2.1	30-70	1-3	25-50	40-90	5-30	300-350	60-120
Glass mat	1.3-2.3	20-25	0.5-2	15-50	25-40	2-10	300-350	120-180
Asbestos	1.6-1.9	30-60	1-3	30-50	50-70	2-8	300-450	100-140
Paper	1.2-1.5	6-14	0.5-1.5	20-25	13-28	1-2	220-250	28-75
Cotton cloth	1.2-1.4	7-9	0.5-1.5	23-24	13-18	1-4	230-250	70-85
Epoxy								
Glass cloth	1.9-2.0	20-60	2-4	50-70	70-100	11-26	330-500	100-110
Glass mat	1.8-2.0	14-30	1-3	30-38	20-26	8-15	330-500	110-125
Paper	1.4-1.5	10-19	0.5-1	20-28	19-24	0.5-1	260-300	30-100
Phenolic								
Glass cloth	1.8-2.0	40-60	1-3	35-40	65-95	10-35	350-500	20-130
Glass mat	1.7-1.9	5-20		17-26	10-60	8-16	350-500	40-150
Asbestos	1.7-1.9	40-65	2-5	45-55	50-90	1-6	350-600	120-200
Paper	1.3-1.4	8-20	1-2	20-40	10-30	0.3-1	225-250	Tracks
Cotton cloth	1.3-1.4	7-16	0.5-1.5	30-44	14-30	0.5-3	225-250	Tracks
Nylon cloth	1.1-1.2	5-10	0.3-0.5	28-36	9-22	2-4	150-165	Tracks
Silicone								
Glass cloth	1.6-1.9	10-35	1-2	25-46	10-38	5-13	400-700	150-250
Asbestos cloth	1.7-1.8	10-25	1-2	40-50	12-20	6-9	450-730	150-300

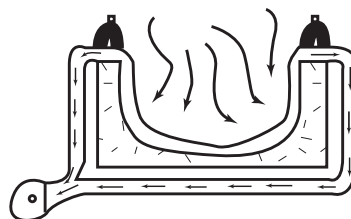
Injection Molding.— This process produces the majority of plastics consumer and industrial products. The modern injection molding machine consists of an extruder, much like the one described previously, but with the added feature that the screw can be slid forward to quickly inject the stored-up hot melt into the second main part, the mold. A nozzle at the end of the extruder presses tightly into a recess (*sprue*) in the stationary half of the mold. The two halves of the mold, with a vertical parting surface, are made from heavy steel and mounted on thick steel tie-bars. Within the mold is a network of *runners* distributing melt from the sprue to the mold cavities that determine the dimensions of the molded product. The mold halves are clamped together with high pressure by hydraulic piston. Coolant channels passing near the cavities keep the mold cold, well below the freezing range of the plastic. The screw moves forward, forcing the melt through the runners and into the cavities, and maintains melt pressure (5,000-15,000 psi, 34-103 MPa) while the moldings cool and freeze. Then the far half of the mold is withdrawn, activating ejection pins that push the moldings and runners out of the mold. Meanwhile the extruder has retracted and generates more hot melt. Typically the process is highly automated with computer controls. Injection machines are rated by their melting capacity, shot size, and clamping force. They range from machines shooting two ounces of melt into a family mold that makes the parts for a hobbyist's model airplane to machines that mold 40-gallon (151 liter) trash cans in molds with two cavities—one for the can, the other for its lid.

Injection molding is capable of making identical items with very close tolerances on dimensions, so it is ideal for the production of interchangeable industrial parts destined for complex assemblies. Undercut shapes can be molded with the aid of side-draw mold sections. For example, millions of bottle caps are molded in automatic unscrewing molds. Producing mold cavities and their male halves in fine tool steels is costly, so one should be quite certain that the part design is accurate before finishing the mold cavities. Successful



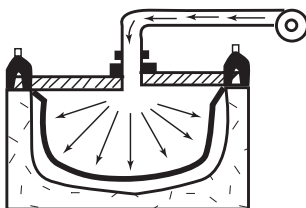
Contact Molding

Resin in contact with air. Layup normally cures at room temperature; heat may accelerate cure. A smoother exposed side may be achieved by wiping on cellophane.



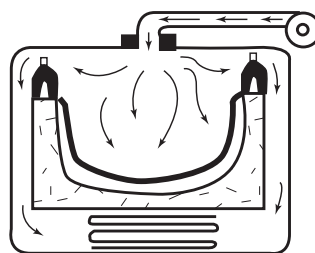
Vacuum Bag

Cellophane or polyvinyl acetate is placed over the layup. Joints are sealed with plastic; vacuum is drawn. Resultant atmospheric pressure eliminates voids and forces out entrapped air and excess resin.



Pressure Bag

Tailored bag – normally rubber sheeting – is placed against layup. Air or steam pressure up to 50 psi (345 kPa) is applied between pressure plate and bag.



Autoclave

Modification of the pressure bag method; after layup, the entire assembly is placed in steam autoclave at 50–100 psi (345–690 kPa). Additional pressure achieves higher glass loadings and improved removal of air.

Fig. 17. Variants of Hand-layup Method of Reinforced Plastics Molding with Cloth or Mat Provide Improved Control of Final Product Qualities

production requires the inputs of all persons connected with the project: the product designer, the mold designer, the mold maker, the molder and the customer. Because of the high investment in the mold, injection molding is seldom considered for short runs. However, inexpensive molds that may serve to make a few hundred parts have been made from metal-filled epoxy casting compounds.

Historically, injection molding was limited to thermoplastics. Now, however, special temperature-control techniques in molds have opened the process to thermosets too.

Design for Injection Molding.— Product analysis is a good starting point in the design process for plastics molding. Make a detailed checklist of the functions the new part will have to perform and the operating conditions it will encounter. If the part will replace an older design that required fabrication from other materials and, perhaps, subassembly with fasteners or adhesives, the new design may be able to take advantage of injection molding's versatility to meld the several functions into a single new part design.

Properties Checklist: Identify potential candidate materials that can fulfill required functions. Preliminary analysis using relevant properties should reduce the list to a few materials that can do the job and the required volume (in^3 or cm^3) of each.

Considerations and questions to ask in this phase of the project are:

- 1) What are the strength, structural stiffness, impact loading, exposure to chemicals, operating temperature range (and possible overheating and cooling), electrical factors, and other relevant material factors?
- 2) Will building codes or other government regulations be involved?
- 3) Must the design be approved by clients or in-house managers?
- 4) Has the marketing group determined the anticipated production run?
- 5) Input from the prospective mold builder and molder (often not the same) should be sought before the design is made final.
- 6) The cost for each part produced of the plastics to be used.

Relative Plastics Costs: The list of some comparative unit costs in **Table 6** should serve to narrow materials choices, but current quantity quotations from various suppliers must be obtained. For injection molding of a large production run, a crude estimate of part cost is double the material cost.

Table 6. Volumetric Costs of Plastics, Dollars per Cubic Inch and per Cubic Meter

Material	Price		Material	Price	
	\$/in ³	\$/m ³		\$/in ³	\$/m ³
ABS	0.032	1953	Polyester (PET)	0.055	3356
Acetal	0.074	4516	Polyester, thermosetting	0.043	2624
Acrylic	0.034	2075	Polyetherether ketone	1.72	104961
Alkyd	0.068	4150	Polyetherimide	0.25	15256
Cellulosics	0.075	4577	Polyethylene, low-density	0.014	854
Diallyl phthalate	0.154	9398	Polyethylene, high-density	0.01	610
Epoxy	0.081	4943	Polyphenylene ether	0.05	3051
Fluoropolymers	0.48	29291	Polyphenylene oxide	0.05	3051
Liquid-crystal polymer	0.43	26240	Polyphenylene sulfide	0.119	7262
Melamine	0.049	2990	Polypropylene	0.01	610
Phenolic, GP	0.038	2319	Polystyrene	0.015	915
Polyamide (6 or 6/6)	0.058	3539	Polysulfone	0.20	12205
Polyamideimide	0.95	57973	Polyurethane, thermoplastic	0.074	4516
Polycarbonate	0.073	4455	Polyurethane, thermosetting	0.062	3783
Polycarbonate-ABS alloy	0.078	4760	Urea	0.053	3234

Use the formula $\$/\text{in}^3 = 0.0361 \times \text{specific gravity} \times \$/\text{lb}$ to convert supplier dollars-per-pound prices to dollars per in³.

Based on 1999 market prices.

Wall Thicknesses: Wall thicknesses throughout the part are often of great importance. Nominal dimensions and tolerances should be calculated and decided before the mold is made, since modifications are costly. In general, wall thicknesses should be kept as thin as needed to meet the part's design requirements and as uniform as possible. Ideally, the flow of molten plastic should be arranged to flow through thicker sections into thinner ones rather than the reverse. This is accomplished—in consultation with the mold builder—by gating cavities at the edges of thick sections. The mold builder will help, too, with the decisions on how many cavities are needed, how to arrange them in the mold for optimal temperature control, the best runner layout and sizing, and what size mold and injection machine will be economical for the production desired. Most injection-molded plastics parts have wall thicknesses in the range from 0.03 to 0.25 inch (0.8 to 6 mm). For compounds containing half-inch (12.7 mm) and longer glass fibers, and for thermoplastic polyurethanes, the range shifts upward by about a factor of 3.

When the plastics selection for the part has been finalized, the suppliers of that plastic type can provide recommendations of grades and wall thicknesses appropriate to those grades. **Table 7** shows typical nominal wall thicknesses for various thermoplastics.

Table 7. Typical Nominal Wall Thicknesses for Various Classes of Thermoplastics

Thermoplastics Group	Typical Working Range		Thermoplastics Group	Typical Working Range	
	inch	mm		inch	mm
Acrylonitrile-butadiene-styrene (ABS)	0.045–0.140	1.14–3.56	Polyester elastomer	0.025–0.125	0.64–3.18
Acetal	0.030–0.120	0.76–3.05	Polyethylene	0.030–0.200	0.76–5.08
Acrylic	0.025–0.150	0.64–3.81	Polyphenylene sulfide	0.020–0.180	0.51–4.57
Liquid-crystal polymer	0.008–0.120	0.20–3.05	Polypropylene	0.025–0.150	0.64–3.81
Long-fiber-reinforced plastics	0.075–1.000	1.91–25.4	Polystyrene	0.035–0.150	0.89–3.81
Modified polyphenylene ether	0.045–0.140	1.14–3.56	Polysulfone	0.050–0.150	1.27–3.81
Nylon	0.010–0.115	0.25–2.92	Polyurethane	0.080–0.750	2.03–19.05
Polyarylate	0.045–0.150	1.14–3.81	Polyvinyl chloride (PVC)	0.040–0.150	1.02–3.81
Polycarbonate	0.040–0.150	1.02–3.81	Styrene-acrylonitrile (SAN)	0.035–0.150	0.89–3.81
Polyester	0.025–0.125	0.64–3.18	...	...	...

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 (15), (16), and (17) on page 555 can be related to formulas using the section modulus and moment of inertia on page 249, where for Case 2, stress at the beam center is given by $\sigma = -Wl/4Z$.

On page 248, 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 227 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 $\sigma = -Wl/4Z$, 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 the maximum deflection y at load, equate Equation (16) from page 555 and $Y = Wl^3/48EI$ from page 249, where $W = F$, $l = L$, $E = E$, and $I = bh^3/12$. Therefore,

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

Example: Assume that a beam (see Figs. 19a and 19b) as described in connection with Equations (15), (16), and (17) on page 555 is 0.75 inch wide with a constant wall thickness of 0.080 inch, so that the cross-sectional area is 0.060 in², and there is a central load W of 5 lb. Based on a bending or flexural modulus of 300,000 lb/in², the maximum stress is calculated at 6250 lb/in² and the maximum deflection at 0.694 inch. Both the stress and the deflection are too high, so a decision is made to add a rib measuring 0.040 inch thick by 0.400 inch deep, with a small draft of $\frac{1}{2}$ degree per side to reinforce the structure.

The equations on page 249, the drawing on page 233 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 in², the calculated stress is reduced to 2270 lb/in², and the deflection goes down to 0.026 inch, 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 inch, tripling the weight of the beam and increasing molding difficulties. The rib adds only 24.3 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 they are best avoided when 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 materials are used that have low shrinkage, ribs can be made 75 or 100 percent 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 inch (0.127 mm) 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.

When determining wall thickness, design engineers must also have some knowledge of mold design and should consider the ability of plastics to flow into the narrow mold channels. The degree and rate of flow depend on temperature and pressure to some extent but vary for different materials, as shown in Fig. 18.

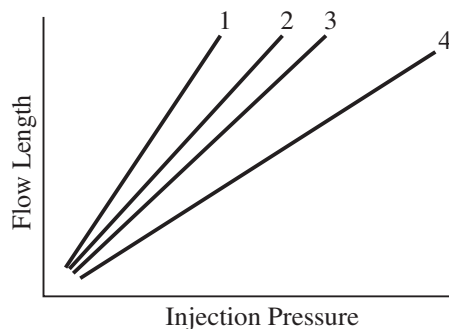


Fig. 18. Typical Spiral-Flow Curves for (1) Nylon 6/6, (2) Polyester Thermoplastics PBT, Liquid-Crystal-Glass-Reinforced, and Polyphenylene-Sulfide-Glass-Reinforced, (3) Acetal Copolymer, and (4) PBT-Glass-Reinforced Plastics Materials

Stresses and Deflections in Load-Bearing Parts.—If the plastic part is to carry loads, load-bearing areas should be analyzed for stress and deflection according to the principles presented earlier. If stress or deflection is found to be too high, solutions are to use ribs or contours to increase section modulus; to use a higher-strength or higher-modulus (i.e.,

fiber-reinforced) material; or to increase the wall thickness if it is not already excessive. Where space allows, adding or thickening ribs can increase structural integrity without making walls thicker.

Formulas given in *Beam Calculations* starting on page 248, which presume elastic behavior, can be used if care is taken to use moduli and strengths related to anticipated service times and temperatures.

Example: Consider a simple case of a beam with rectangular cross section b wide and h deep, of length l centrally loaded and freely supported at its ends. This is an example of case 2 on page 249 with a beam cross-section depicted generically in the first diagram of *Moments of Inertia, Section Moduli, and Radii of Gyration* on page 227. Applicable formulas for the moment of inertia I of the beam cross-section, the section modulus Z , and the maximum tensile stress s beneath the central load are

$$I = \frac{bh^3}{12} \quad Z = \frac{I}{(h/2)} = \frac{bh^2}{6} \quad \sigma = \frac{Wl}{4Z} = \frac{6Wl}{4bh^2}$$

From the last box for Case 2, the maximum deflection at the beam center is given by

$$y = \frac{Wl^3}{48EI} = \frac{Wl^3}{4Ebh^3}$$

We can now exercise these equations in an example of a small beam whose width = 19 mm, depth (wall thickness) = 2.0 mm, and length between supports = 102 mm. The beam is to support a central load of 22.24 N (5 lb). This beam's cross-section is depicted in Fig. 19a. As it has very little depth, hence a low sectional modulus, it may not handle the job. The plastic's flex modulus is 2068.5 MPa (300,000 psi). Using the formulas above, the four quantities to be calculated are

$$\begin{aligned} I &= \frac{19(2^3)}{12} = 12.666667 \text{ mm}^4 \\ Z &= \frac{(12.666667)2}{2} = 12.666667 \text{ mm}^3 \\ \sigma &= \frac{6(22.24)102}{4(19)2^2} = 44.77 \text{ MPa} \\ y &= \frac{(22.24)(102^3)}{(4)(2068.5)(19)(2^3)} = 18.77 \text{ mm} \end{aligned}$$

Both the stress and the deflection are too high. The wall thickness could be increased, but instead a rib will be added that will run along the underside and center of the beam, changing its cross section to that shown in Fig. 19b. The rib will be 10 mm deep but only 1.0 mm thick, with a slight draft of 0.5 degree per side. Following the formulas given in the table *Moments of Inertia, Section Moduli, and Radii of Gyration* starting on page 226, see the third row of the T-sections for the one with the tapered rib; the new cross-sectional area is 47.125 mm², and the location of the neutral axis is 9.84 mm above the most extreme fiber at the bottom of the rib. The new cross-sectional moment of inertia I is 353.60 mm⁴, 28 times greater than the original I . The section modulus $Z = 353.60/9.84 = 35.94$ mm³. The recomputed extreme stress is 15.8 MPa, and the maximum deflection is 0.67 mm, acceptable for both the material and the application. To achieve the same result from a heavier rectangular-section beam would require a thickness (depth) of 6.1 mm, tripling the beam's weight and increasing molding difficulties. The new rib adds only 24 percent to the total section weight.

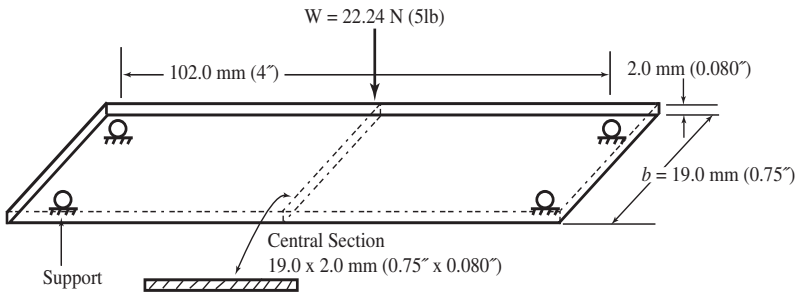


Fig. 19a. Original Beam (Dimensions in parenthesis are for Example on page 575)

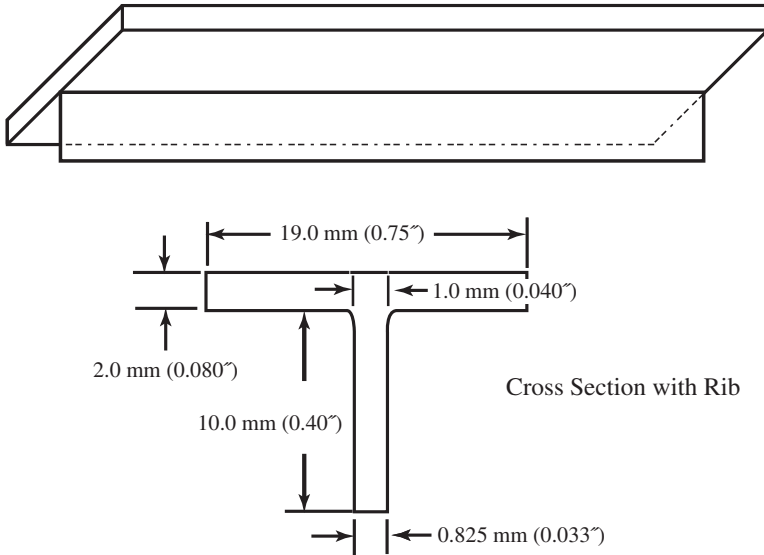


Fig. 19b. Beam with Small Rib (Dimensions in parentheses are for Example on page 575)

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. The drawing of Fig. 20 defines draft and the dimensions associated with it. 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 the minimum, although up to 3 degrees per side is often used.

The exact relationship between the draft angle α and the dimensional difference from the top to the bottom of the draw depth D is given by

$$d = D \tan \alpha \quad (31)$$

where $\tan$ is the tangent of the draft angle. An excellent approximation is

$$d = 0.0175 \alpha D \quad (32)$$

This is accurate to the nearest 0.001 inch (0.025 mm) for draft angles up to 5 degrees and draw depths up to 10 inches (254 mm).

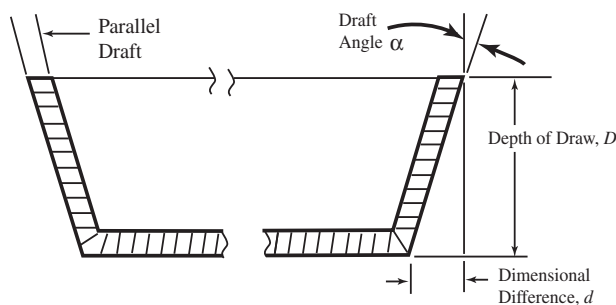


Fig. 20. Defining Dimensions Related to Draft and Draft Angle

Where minimal variation in wall thickness is needed to produce sidewalls that are perpendicular to the direction of draw, the mold sometimes can be designed to produce parallel draft, as indicated at the left in Fig. 20. The amount of draft also depends on the surface finish of the mold walls. Any texturing of the surface will increase the draft requirement by at least 1 degree per side for every 0.001 inch (0.025 mm) of texture depth.

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.

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 equal to half the nominal wall thickness with a minimum of 0.020 inch (0.51 mm) for parts subject to stress, and 0.005 inch (0.127 mm) radius for stress-free parts. Outside corner radius should equal 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 196. A suitable value for q in Equation (8) on page 197 for plastics materials, is 1. That is, the actual stress-concentration factor equals the theoretical value.

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 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.

Melt Flow in the Mold.—The designer of plastics products needs a basic appreciation of what goes on during injection molding and the special properties of plastics that affect molding. Some of these, such as thermal properties, have been previously described. It is the flow properties of molten plastics that dominate mold filling. Foremost are the very high viscosities of thermoplastic melts—thousands to hundreds of thousands times that of room-temperature water—requiring pressures (P) of 5,000–15,000 psi (35–103 MPa) to move the melt quickly through the short distance from the injection cylinder through the mold runners and into the cavities. Second is the strong dependence of viscosity on temperature, so the transfer to the chilled mold must be nearly instantaneous to obtain fully filled cavities and accurately dimensioned products. Because of the high viscosities and rapid flow, frictional heat is dissipated within the melt, helping to keep it warm during its travel.

Another property, also helpful, is more subtle: plastic melts have non-Newtonian physical properties. That is, viscosity depends not only on temperature, as with ordinary liquids, but also on the flow rate (or pressure drop ΔP). Doubling ΔP may triple or quadruple the flow rate through the mold passages, but the pressure itself squeezes molecules closer together and tends to increase viscosity and freezing point. In an injection machine one can only raise ΔP by raising P . Unpredictable results can be obtained if the melt temperature is near the freezing range.

If the product designer is calling for thin wall sections, *Flow Rate (FR)*, formerly known as *Melt Flow Index (MFI)*, can be used as a selection property characteristic among grades of candidate plastics. The higher the flow rate, the easier it will likely be to fill thin sections during molding. Flow rate values are obtained by testing (ASTM Test D 1238) in a simple extrusion plastometer. In this device, a small sample of resin is loaded into a 9.55-mm diameter well in a heated cylinder and brought to a test temperature above the plastic's melting range. At the bottom of the well is a die 2.1 mm in bore diameter and 8 mm long.

A weighted piston drives the melt through the die while a timer runs. Extrudate is collected and weighed, and the flow rate is reported in grams per 10-minute interval. To accommodate the wide range of plastics flow behaviors, 36 standard conditions specifying both the melt temperature in °C and the total piston weight in kg have been adopted. *FR* values are meaningless without the condition numbers. Most polypropylenes (PP), for example, are tested at condition 230/2.16, meaning a PP resin reported to have an *FR* of 8 (230/2.16 assumed) would be one that at 230°C under a piston weighing 2.16 kg_f, produced a flow rate of 8 g/10 min. Resin and compound suppliers can supply the *FR* values for their grades. Product designers should obtain all three numbers.

A somewhat more practical way of judging resin flows under actual molding conditions uses a spiral-flow mold. This injection mold and variants were in common use by the early 1950s. A similar mold is the basis for testing the flow of transfer-molding compounds (ASTM D 3123). A half-round or shallow-trapezoidal groove, 1/8 inch (3.2 mm) wide and beginning at the center, circles outward with the spiral radius increasing about 3/8 inch (9.5 mm) per turn, to a total channel length of 70 to 100 inches (178 to 254 cm). Inch numerals and 0.1-inch marks are engraved in the flat upper half of the mold. The injection nozzle fills the mold from its center and, under specified melt and mold temperatures and injection pressure, holds pressure until flow stops. The mold is opened, and the flow distance is read off the molded spiral and recorded. With careful control of molding conditions, flow distances of 40 inches (102 cm) and more can be closely reproduced in repeated shots. Many resin suppliers have spiral-flow data available for product designers and processors.

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

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. The design must have sufficient holding power without exceeding the elastic or fatigue limits of the material. With the typical snap-fit designs in Fig. 21, 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.

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 the strain instead of stress.

Dynamic strain ϵ for the straight beam, is calculated from $\epsilon = \frac{3Yh_o}{2L^2}$ and for the tapered beam, from $\epsilon = \frac{3Yh_o}{2L^2K}$.

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. 22a. Sometimes the snap finger can simply be popped off when the mold is opened. An alternative to the sliding core is shown in Fig. 22b, 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. 23.

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 threads per inch (0.9 mm pitch) is generally not practical.

Chemical Bonding. Chemical bonding is suited to applications that must be leak-tight or where stresses due to assembly must be minimized. However, adhesives and solvents can be hazardous, and their preparation and cure times can be prolonged. Properly applied cyanoacrylate adhesives achieve moderate strength in seconds or minutes and work well with assemblies that can be brought together very quickly after applying the bonding agent.

Chemical bonding may use solvents, solvents bodied with resin, or so-called "100% solids" adhesives, such as epoxies and cyanoacrylates. Use of solvents is limited to compatible materials that can be dissolved by the same solvent. Because most of the solvent must gradually diffuse out of the joint, solvent cementing is used mostly where a very thin film of the solvent can be applied to the accurately mating surface(s) to be joined, followed by rapid assembly, usually with clamping. Bodied solvent cements permit more flexibility in such operations. Safety precautions must be observed in handling the solvents to protect workers and in solvent recovery.

Adhesives that set up or cure with little or no loss of volatiles include epoxies, acrylics, polyurethanes, phenolics, rubbers, polyesters, and vinyls. Cyanoacrylates are often used because of their rapid setting with many materials, both similar and dissimilar, and because they are naturally catalyzed by atmospheric humidity. Their downside is the very short working time they allow for assembly.

Recommendations of both plastics suppliers and adhesives suppliers should be sought because many adhesives contain active components that can partly dissolve the plastics' surfaces, giving improved adhesion. However, some adhesives attack certain plastics, causing crazing and even joint failure. The main disadvantages of adhesives are that their bonds require time to reach full strength, may need long clamp times, may require fixtures and may involve special ovens or curing conditions. Also, surface preparation may be difficult because of the presence of grease or mold-release compounds; even a fingerprint can

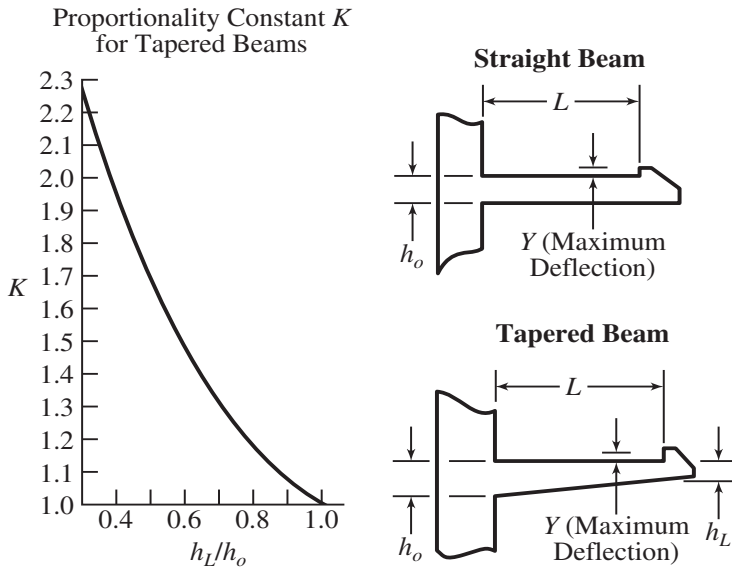


Fig. 21. Snap-fit Designs for Cantilever Beams with Rectangular Cross Sections

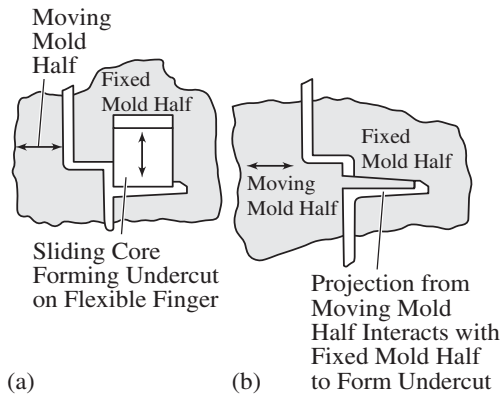


Fig. 22. (a) Arrangement for Molding an Undercut on the End of a Flexible Finger Using a Sliding Core; (b) With the Undercut Formed by a Mold Projection, the Sliding Core is Eliminated

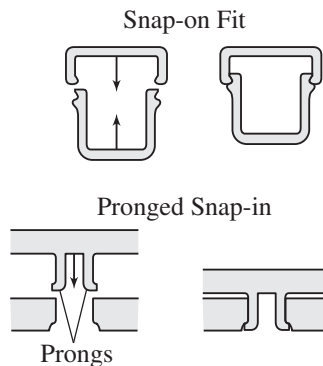


Fig. 23. Examples of Snap-In and Snap-On Arrangements

spoil a bond. Some adhesion-resistant materials such as polyolefins, nylons, and fluorocarbons usually need pretreatment with surface-activating primers prior to applying an adhesive. Some materials may need mechanical roughening to improve joint strength.

Welding Plastics: Plastics welding techniques include ultrasonic, hot-plate, spin, induction, and microwave energy, melt-bead sealing, and hot-gas welding. Thermal methods are also used for staking, swaging, and other post-thermoforming procedures. Materials must be melt-compatible and have similar melting temperatures.

Plastics welding encompasses a variety of processes in which a film melt is created at the surfaces to be joined. *Ultrasonic welding* is frequently used for joining small- and medium-sized parts of a single material or melt-compatible materials that share the same melting-temperature range. High-frequency (20- to 40-kHz) acoustic vibrational energy is briefly applied to the surfaces to be joined, creating localized molecular excitation that causes a thin layer to melt. The surfaces are pressed and held together while the melt freezes. With proper joint designs, welds can be made in only two seconds and on cooling are as strong as the base resins. 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 the freedom to couple acoustically when it is in contact with the horn through which the ultrasonic energy is transmitted. Fig. 24 shows a two typical joint designs for this process. The example on the left shows a simple butt-type, energy-director design that works well with amorphous materials. The inverted-cone projection, known as an *energy director*, concentrates the energy in a small area on both faces of the joint. This area melts quickly and the material flows as the parts are pressed together. Shown at the right in Fig. 24 is a shear-interference joint. Melting of both components starts in 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 can exceed that of the parts joined.

With hygroscopic plastics, welding should be done as soon as possible after molding because even small amounts of moisture can weaken bonds. Drying immediately before welding may be advisable. Drawbacks of ultrasonic welding are the following: 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 compatible plastics. Filled and fiber-reinforced materials are more difficult to weld.

Although horn frequencies in ultrasonic welding are not audible to the ear, sounds that cause discomfort may be generated when plastics parts vibrate at lower frequencies, necessitating sound-proofing.

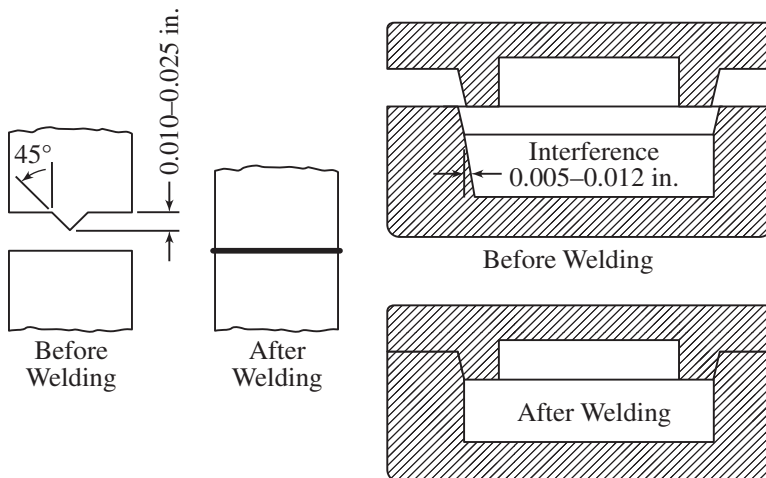


Fig. 24. (left) Energy-director Type of Ultrasonic Weld Joint for Molded-part Assembly and (right) Typical Shear-interference Joint

Vibration Welding: Vibration welding resembles ultrasonic welding except that the parts to be joined are rubbed together to produce frictional heat that melts the faces. The energy is transferred in the form of high-amplitude, low-frequency, reciprocating motion. After a short period of vibration, the weld area cools and solidifies while the parts are held in the alignment provided by the welding fixture. Typical frequencies used are 120 to 240 Hz, and amplitudes range between 0.10 and 0.20 inch (2.54–5.08 mm). 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 appears to affect joint strength less.

Spin Welding: Like vibration welding, spin welding uses frictional heat to melt the faces of circular joint surfaces. It is a rapid and economical method of joining melt-compatible parts. The process is completed in about three seconds and is easily automated. Frictional heat is generated by rotating one part against its mate (usually fixed) with a controlled pressure. When rotation is stopped, pressure is maintained during cooling and solidification of the joint. Simple equipment such as a drill press can serve for this process.

Hot-Gas Welding: Hot-gas welding is a process resembling acetylene brazing and welding of metals. Used mostly with polyolefins, which do not accept adhesives, the hot-gas welding equipment consists of an electric hot-gas “gun” that provides, through any of several interchangeable nozzles, a stream of hot air or preferably hot nitrogen at a temperature above the melting range of the plastic to be worked. A welding rod of the same material provides the melt that forms the joint to be made between two parts. The parts to be joined are set up in their final orientation in a jig. A groove will usually be machined in one or both to accept the molten plastic. The operator directs the hot gas stream along the joint surfaces while feeding and melting the welding rod into the joint. The welded structure is then allowed to cool several hours. Some huge tanks have been fabricated from thick polyethylene sheets by this technique. It is also useful for repairing broken polyolefin parts. Hot-gas welding can produce joints with 85 percent of the strength of the parent material. Hot-gas welding is not recommended for use with substrates less than $\frac{1}{16}$ inch (1.6 mm) thick.

Dielectric Welding: Dielectric welding is also known as *radio-frequency welding*. This process utilizes the dielectric loss that occurs in many plastics when they are placed in a rapidly reversing electric field. It is widely used with flexible thermoplastics films and sheets of materials—typically plasticized PVC and polyurethane—and for joining some injection-molded parts. The parts to be joined are brought together between two electrodes that also supply joining pressure. The field passes through the material, generating heat throughout the volume between the electrodes until it reaches melting range. The field is then turned off and pressure is maintained until the joined parts freeze. Polyolefins and some other plastics are so nonpolar that their dielectric loss is too small to permit welding them by this method.

Electromagnetic or Induction Welding: This form of welding uses inductive heating to generate fusion temperatures in thermoplastics as shown at the top in [Fig. 25](#). Fine iron particles embedded in a gasket, preform, filament, ribbon, adhesive, or molded part are excited by the rapidly alternating magnetic field, generating eddy currents that, through resistive loss, cause distributed local heating. 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 internal pressure by the surrounding component surfaces. Proper joint design is essential to successful induction welding.

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, toler-

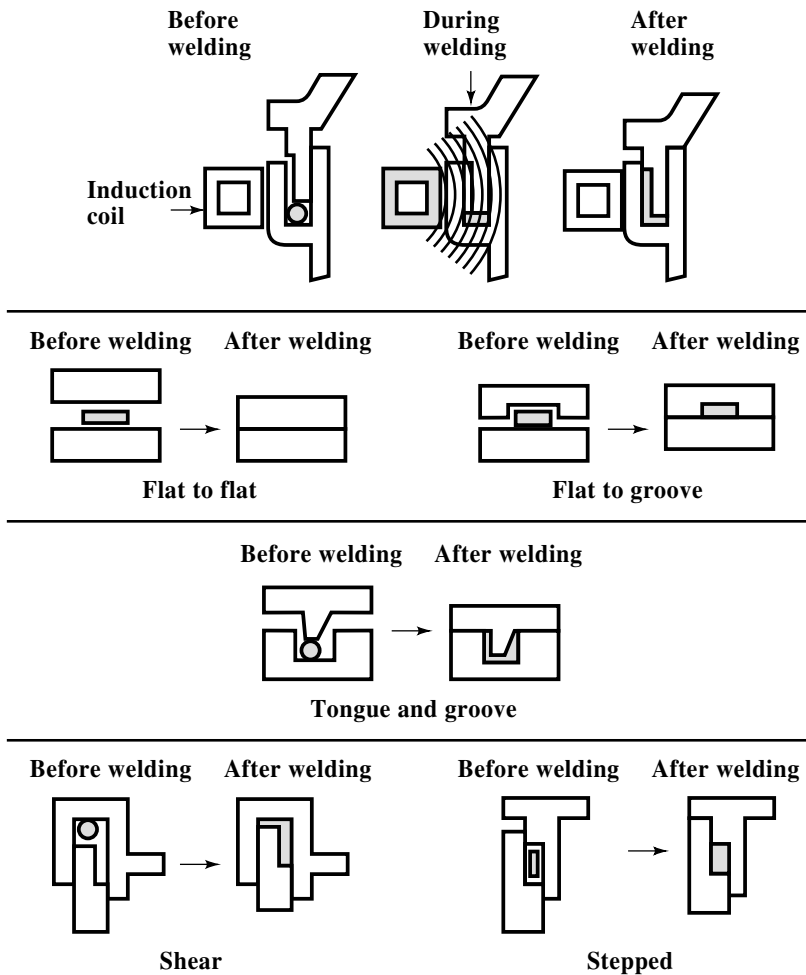


Fig. 25. Typical Joint Designs Used in Induction-welding Plastics Assembly

ance requirements, and ability to bond some dissimilar materials. A limitation is that no ferrous metal can be near the joint line during the energizing of the inductor coil. All components of an assembly (except the weld medium) to be induction-welded must therefore be nonferrous, or ferrous components must be placed where they will not be subjected to the high-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. 26. The shoulder of the metal screw shown in the lower right portion of Fig. 26 meets the metal component when it is tightened, sparing the plastic part from over-compression. Where force cannot be satisfactorily controlled, even with a shoulder screw, various types of washers can be used to spread the compression force over wider areas.

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 knurled or otherwise provided with projections of various configurations that penetrate the plastics and prevent movement under normal torques

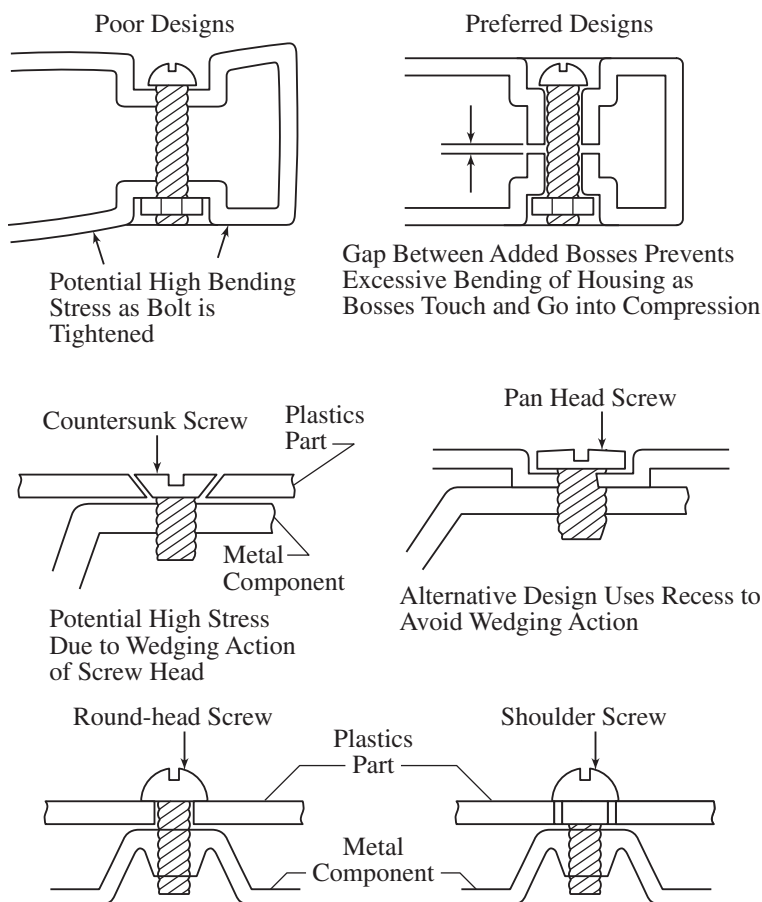


Fig. 26. Examples of Bad and Good Designs in Assembling Plastics with Metal Fasteners

exerted during assembly. “Helicoil” inserts have large standard threads on the outside and receive a smaller standard screw inside, thus lowering the assembly torque on the plastic by diluting it to the larger outside contact area. 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 1751. Thread-forming screws must be used carefully with high-modulus, low-creep plastics, 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. As a general rule of thumb, 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 are also frequently used.

Machining Plastics.—Plastics can be molded into complex shapes and 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. Special methods for development of prototypes are discussed on page 590. 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. Some commercially available bar and rod stock are sold already annealed. If annealing is necessary, instructions can be obtained from plastics suppliers. Plastics moduli are small fractions—2 to 10 percent—of those of metals, and this lower stiffness 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 minimize normal forces.

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 or smaller 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 reliable results in machining.

Plastics have thermal expansion coefficients some 10 times higher than those of metals so that even though actual heat generation during machining may be less than with metals there can easily be more expansion. Adequate tool clearances must be provided to minimize heating. Compared with most structural 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 that have low melting points than with plastics that have higher melting points, such as nylons, 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 should be polished to reduce frictional drag and resulting temperature increases. Proper rake angles depend on depth of cut, cutting speed, and the type of plastic 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.

Turning and Cutting Off: High speed steel and carbide tools are commonly used with cutting speeds of 200-500 and 500-800 ft/min (61-152 and 152-244 m/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: This is the most common machining operation because small-diameter holes are more easily drilled than molded. However, plastics are rather difficult to drill without some damage. Many difficulties not encountered in drilling metals, such as gumming, burning in the drilled hole, cracks around the edges or growth of cracks after drilling, can occur. Two reasons for these difficulties are that swarf flow (chip removal) in drilling is poor and cutting speeds vary from the center to the periphery of the drill, so that drilling imposes severe loading on the workpiece. Some drill types used with plastics are shown in Fig. 27.

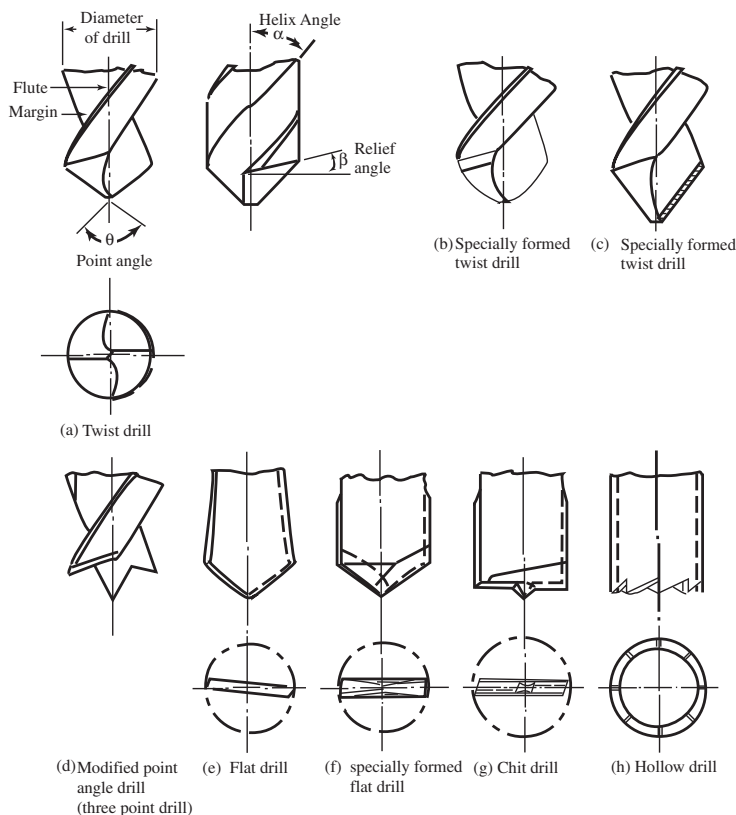


Fig. 27. Drill Designs Used for Drilling Plastics

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 degrees, and wide, highly polished flutes to ease chip exit. Normal feed rates are in the range of 0.001–0.012 in/rev (0.025–0.3 mm/rev) for holes of 1/16 to 2 inch (1.6–51 mm) diameter, and speeds of 100–250 ft/min (30.5–76.2 m/min), with lower speeds used for deep and blind holes. Point angles of 60 to 90 degrees (included) are used for many plastics, but an angle of 120 degrees should be used for rigid polyvinyl chloride and acrylic (polymethyl methacrylate).

Clearance angles of 9 to 15 degrees are usually sufficient to prevent the drill flanks from rubbing in the bottom of the hole, but acrylic materials require angles of 12–20 degrees. Tests may be needed to determine the drill diameter for accurately sized holes, allowing for thermal expansion and elastic recovery. Reaming may be used to size holes accurately, but even those 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 swarf to plug up the drill flutes. For positioning accuracy, removable templates may be used to spot the hole position, then set aside for the drilling to be completed. Pilot holes are not necessary, except when the hole is to be reamed or counterbored. Frequent pull-out (peck drilling) to remove chips and compressed air cooling may be needed, especially for deep holes.

Drilling and reaming speed and feed suggestions for various materials are shown in Table 8. 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 (Fig. 27), usually having large helix angles, narrow lands, and highly polished or chromium-plated flutes to expel swarf rapidly and minimize frictional heating. Circle cutters are often preferred for holes in thin materials. Drills must be kept sharp and cool, and carbide tools may be needed in high production, especially with glass-reinforced

materials. They must be cooled with clean compressed air to avoid contamination. Aqueous solutions are used for deep drilling because metal cutting fluids and oils may degrade or attack the plastics and may cause a cleaning problem. Plastics parts must be held firmly during drilling to counter the tendency for the tooling to grab and spin the work.

Table 8. Speeds and Feeds for Drilling Holes of 0.25 to 0.375 inch (6.3–9.5 mm) 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 (15.2 m/min) is appropriate. Tapping of filled materials is done at 25 ft/min (7.6 m/min). These speeds should be reduced for deep or blind holes and when the percentage of thread is greater than 65–75 percent. 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 inch (3.2 mm) 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, because band saws run cooler they 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 inch (25.4 mm), and saws with buttress teeth are recommended for thicknesses above 1 inch (25.4 mm). 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 [Table 9](#).

Milling of Plastics: Peripheral cutting with end mills is used for edge preparation, slotting and similar milling operations; end cutting can also be used for facing operations. Speeds for milling range from 800 to 1400 ft/min (244–427 m/min) for peripheral end milling of many thermoplastics and from 400 to 800 ft/min (122–244 m/min) for many thermosets. However, slower speeds are generally used for other milling operations, with some thermoplastics being machined at 300–500 ft/min (91–152 m/min), and some thermosets at 150–300 ft/min (46–91 m/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 pro-

Table 9. Speeds and Numbers of Teeth for Sawing Plastics Materials with High-Carbon Steel Saw Blades

Material Thickness		Number of Teeth on Blade	Peripheral Speed			
			Thermoset Cast or Molded Plastics		Thermoplastics (and Epoxy, Melamine, Phenolic and Allyl Thermosets)	
(inch)	(mm)		(ft/min)	(m/min)	(ft/min)	(m/min)
0–0.5	0–13	8–14	2000–3000	607–914	4000–5000	1219–1524
0.5–1	13–25	6–8	1800–2200	549–671	3500–4300	1067–1311
1–3	25–76	3	1500–2200	475–671	3000–3500	914–1067
>3	>76	>3	1200–1800	366–549	2500–3000	762–914

duce 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.

Other Machining 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-inch (0.0762 mm) diameter; tight tolerances, 0.0005 inch (0.0127 mm); and very smooth finishes, 0.15 μ inch (0.381 μ m) with No. 600 boron carbide abrasive powder. Water-jet cutting using pressures up to 60,000 lb/inch² (414 N/mm²) is widely used for plastics and does not introduce stresses into the material. Tolerances of $\pm$ 0.004 inch ($\pm$ 0.102 mm) 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.

Machining Hard Rubber: Hard rubber, or ebonite, is the oldest rigid manmade plastic, and has been used since the 1840s. The base material is a highly vulcanized natural or, today, synthetic rubber, empirical formula C5H8S, containing 32 percent sulfur. A range of compositions containing various amounts of fillers is available. Unfilled ebonite has a specific gravity = 1.18, tensile strength = 9,000 psi (62 N/mm²), elongation = 3 percent, and Izod impact strength = 0.5 ft-lb_f/in (26.7 J/m) of notch. Its continued use is due to its good insulating characteristics, good chemical resistance, and ease of machining. Tools suitable for steel, high-speed steel, or tungsten carbide may be used with hard rubber with no top or side rake angles and 10 to 20 degrees clearance angles.

Without coolant, surface speeds of 200 ft/min (60 m/min) are recommended for turning, boring and facing; they may be increased to 300 surface ft/min (90 m/min) with coolant.

Drilling of hard rubber requires high-speed steel drills of 35 to 40 degrees helix angle to obtain maximum cutting speeds and drill life. Feed rates for drilling range up to 0.015 in/rev (0.38 mm/rev). Deep-fluted taps are best for threading hard rubber and should be 0.002 to 0.005 inch (0.05–0.13 mm) oversize if close tolerances are to be held. Machine oil is used as the lubricant. Hard rubber may be sawed with band saws having 5 to 10 teeth per inch, running at about 3000 ft/min (915 m/min), or it may be cut with abrasive wheels. Use of coolant in grinding ebonite gives a smoother finish.

Piercing and blanking of hard-rubber sheet is best performed with the rubber and dies warmed. Straightening of the often-distorted blanks may be accomplished by dropping them into a pan of hot water.

Development of Plastics Prototypes.— Model prototypes are made for testing of properties, such as stress and fatigue resistance, to find ways to improve quality and reliability, to improve tooling design, 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, insert pull-out resistance electrical properties, and problems of mating with other parts.

Prototypes of moldings are made in five major steps: 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 metal. Some 90 percent of prototypes are made by CAD/CAM methods that allow holding of dimensional tolerances to 2-3 percent of drawing specifications.

Prototypes can also be made by a process called *stereolithography* which uses a tank of photosensitive liquid polymer; an *x-y* scanning, ultraviolet laser with a beam diameter of 0.010 inch (0.254 mm); 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 inch (0.13-0.51 mm) 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 must be carried out at temperatures well below the deflection temperatures of the plastics in order to avoid distortion of parts. See *Deflection Temperature Under Load (DTUL)* on page 558.

Vacuum Metallizing and Sputter Coating require application of a special base lacquer and protective clear top coat before and after treatment. Resistance heating or an electron beam can be used to melt the coating metals such as aluminum, silver, copper, and gold, which usually are pure elements. Wires of the coating metal are hung from tungsten heating elements in an array that gives them direct views of the surfaces to be coated. Sputter plating uses a plasma to produce the metallic vapor, requires line-of-sight setup, and can use brass as well as the other metals mentioned. The appearance of gold or brass is often simulated with vacuum-metallized aluminum by tinting the overcoating lacquer. Chromium plating requires etched surfaces to ensure good adhesion.

Polishing: 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°F (150-205°C) 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, 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 (1525-1830 m/min) are recommended.

For low-melting point plastics, soft cotton buffs are best, with surface speeds of 4,000 to 5,000 feet per minute (1220-1525 m/min) using a wet or greasy tripoli or silica compound.

For satisfactory finishing, rouge alone may be sufficient. 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 are 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 material characteristics. Plastics materials also may be preferred for gears because of superior sliding properties with reduced noise and less 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 2261.

Most plastics gears are made from nylons and acetals, although acrylonitrile-butadiene-styrenes (ABS), polycarbonates, polysulfones, phenylene oxides, polyurethanes, and thermoplastic polyesters have also been used. Additives used in plastics for gears include glass and carbon fiber for added strength and stiffness, and fibers, beads, and powders for reduced thermal expansion and better dimensional stability. Other materials, such as molybdenum disulfide, polytetrafluoroethylene powder (PTFE), and silicones may be incorporated as integral lubricants to reduce friction and wear.

Choice of plastics gear material depends on requirements for size and nature of loads to be transmitted, designated speeds, required life, working environment, type of cooling, lubrication, and operating precision. Because of cost, plastics gears are sometimes not enclosed in sealed housings and 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 10, 11, and 12:**

	US Customary Units		Metric Units
Internal and External Spur Gears	$HP = \frac{S_s F Y V}{55(600 + V) P C_s} \quad (33a)$	$KW = \frac{F Y m S_s V}{327(3.05 + V) C_s} \quad (33b)$	
Internal and External Helical Gears	$HP = \frac{S_s F Y V}{423(78 + \sqrt{V}) P_n C_s} \quad (34a)$	$KW = \frac{F Y m S_s V}{179(5.56 + \sqrt{V}) C_s} \quad (34b)$	
Straight Bevel Gears	$HP = \frac{S_s F Y V (C - F)}{55(600 + V) P C C_s} \quad (35a)$	$KW = \frac{F Y m S_s V (C - F)}{327(3.05 + V) C_s C} \quad (35b)$	

S_s = safe stress in bending (from **Table 11**); F = face width in inches (mm); Y = tooth form factor (from **Table 10**); m = module, mm; C = pitch cone distance in inches (mm); C_s = service factor (from **Table 12**); P = diametral pitch; P_n = normal diametral pitch; and V = velocity at pitch circle diameter in ft/min (m/s).

Table 10. 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 = $40 \div 0.529919 \approx 75$, and $Y = 0.434$.

Table 11. Safe Bending Stress Values for Plastics Gears

Plastics Type	Safe Stress			
	Unfilled		Glass-filled	
	(lb/in ²)	(MPa)	(lb/in ²)	(MPa)
ABS	3,000	20.68	6,000	41.37
Acetal	5,000	34.47	7,000	48.26
Nylon	6,000	41.37	12,000	82.74
Polycarbonate	6,000	41.37	9,000	62.05
Polyester	3,500	24.13	8,000	55.16
Polyurethane	2,500	17.24	...	...

Table 12. 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

Example: 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-inch face width, and a pitch diameter of 2.3438 inches. Using [Equation \(33a\)](#),

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

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

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

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 11](#) 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 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 and 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 tooth thickness limits for a molded gear are to be held to +0.000 inch, -0.001 inch (-0.025 mm), the outside diameter must be permitted to vary up to 0.0027 inch (0.069 mm) for 20-deg and 0.0039 inch (0.099 mm) 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.

Bakelite.—Phenolic resinoid plastics (commonly designated by the trade name “Bakelite”) were invented in 1907 by Dr. L. H. Baekeland. Like most products of creative chemistry, phenol resinoid bears no resemblance to the raw materials from which it is made. Principal among these raw materials are phenol or “carbolic acid,” a white crystalline solid, and formaldehyde, a gas, which when dissolved in water is commonly known as formalin. Both are highly reactive substances. Under certain definite, controlled conditions they may be caused to combine chemically, forming a distinctly new and highly useful product that is resin-like but superior in its properties to any natural resin. In its raw, or primary state, phenol resinoid is quickly softened by moderate heat and is soluble in certain solvents, notably alcohol. Further heating, however, causes it to harden, after which it cannot again be softened at any temperature. Furthermore, the solvents which served to dissolve it in its primary state now have little or no effect on it. This property of being first fusible and soluble, and then, under the influence of heat, becoming infusible and insoluble—of becoming, in fact, a material of pronounced hardness, strength, and resistance to deteriorating agents generally—has made phenol resinoid outstanding among organic plastic materials. It is called a resinoid to distinguish it from natural resinous substances. Bakelite plastics may be classified generally in the following groups: molding materials, coating materials, impregnating materials, cements, bonding resins, cast resinoids, and resinoid varnishes for the production of laminated materials.

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DRAFTING PRACTICES

While there are many national standards-based drafting practices throughout the world, three sets of standards practices predominate internationally. These sets of practices include: the American National Standards Institute (ANSI); those modeled on standards developed by the International Organization for Standardization (ISO); and to a lesser extent, those based on Japanese Industry Standards (JIS). However since JIS has committed to adopting ISO practices, coverage will be limited to ANSI practice and select ISO practices where appropriate. In general, there are several ANSI Standards for use in preparing engineering drawings and related documents.

ANSI and ISO Drafting Practices

Sizes of Drawing Sheets.— Recommended trimmed sheet sizes are shown in [Table 1](#). Customary inch sizes are documented in American National Standard ASME Y14.1-2005, are based on commercial letterhead paper ($8\frac{1}{2} \times 11$ in.) and are in general use throughout the United States. Each successive size beginning with $8\frac{1}{2} \times 11$ in. (A) is double the size of the previous (except size F). Using sizes based on commercial letterhead paper size, and its multiples, permits filing small prints and folded larger prints in the same commercial standard letter files. For drawings requiring trimmed metric sheets, sizes are based on ASME Y14.1M-2005 in the United States and ISO 5457 outside the U.S. Metric sizes are harmonized across the U.S. and the ISO standards. As with the customary inch sheet sizes, each successive metric size sheet beginning with commercial letterhead paper size A4 is double the previous size also for ease of folding and filing.

Metric sizes are based on the width-to-length ratio of 1 to $\sqrt{2}$. Note that the metric size designators increase as the paper decreases in area. Virtually all CAD systems include both inch and metric size paper templates. Most countries outside the United States use metric paper sizes, so for foreign correspondence it is recommended that the metric sheet sizes be used. For additional sizes and details, see the respective standards.

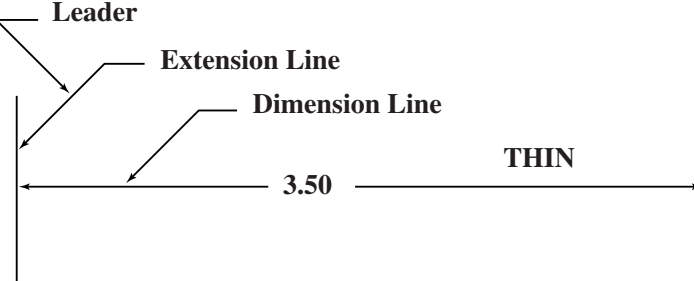
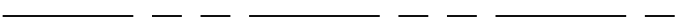
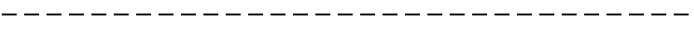
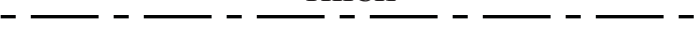
Table 1. Drawing Sheet Sizes

U.S. Customary Size, inches (ASME Y14.1-2005)				Metric Size, millimeters (ASME Y14.1M-2005)			
A	$8\frac{1}{2} \times 11$	D	22×34	A4	210×297	A1	594×841
B	11×17	E	34×44	A3	297×420	A0	841×1189
C	17×22	F	28×40	A2	420×594		

Line Conventions and Drawings.— American National Standard ASME Y14.2M establishes line and lettering practices for engineering drawings. The line conventions and the symbols for section lining are as shown in [Table 2](#) and [Table 3](#).

Approximate width of THICK lines for metric drawings is 0.6 mm, and for inch drawings, 0.032 inch. Approximate width of THIN lines for metric drawings is 0.3 mm, and for inch drawings, 0.016 inch. These approximate line widths are intended to differentiate between THICK and THIN lines and are not values influencing acceptance or rejection of drawings. Basic line conventions in ISO are established in ISO 128-20: 1996. Lines intended to comply with ISO standards use widths of 0.13 mm, 0.18 mm, 0.25 mm, 0.35 mm, 0.5 mm, 0.7 mm, 1 mm, 1.4 mm and 2 mm, but again may deviate as long as lines are consistent in width and it is possible to differentiate “unambiguously” between two adjacent lines with different widths.

Table 2. American National Standard for Engineering Drawings
ASME Y14.2M-1992 (R2008)

Visible Line	 THICK
Hidden Line	 THIN
Section Line	 THIN
Center Line	 THIN
Symmetry Line	 THIN
Dimension Line Extension Line and Leader	 THIN
Cutting-Plane Line or Viewing-Plane Line	 THICK
	 THICK
Break Line	 THICK Short Breaks  THIN Long Breaks
Phantom Line	 THIN
Stitch Line	 THIN  THIN
Chain Line	 THICK