HANSER

The Complete Part Design Handbook

E. Alfredo Campo

For Injection Molding of Thermoplastics

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2 Engineering Product Design

When designing plastic components, success will depend on one prime factor: how well we use the variety of plastic properties and the processing methods for obtaining optimum results.

The designer should select the best resin, realizing that it is essential for the resin's full potential to be exploited to ensure that the molded part will satisfy both functional and cost requirements.

Plastics are governed by the same physical laws and the same rules for good design as other materials. These principles can be applied if the polymer properties are suitable for the operating environment of the product being considered.

It is necessary to know and understand what the end product must do and under what circumstances it will operate, before a design analysis can be done.

2.1 Understanding the Properties of Materials

There is a big difference between the properties, processing methods, and applications of materials manufactured by various industries. There is not a single material that can be used for all applications. Each new outstanding property developed in a material opens the door for new applications, technologies, and innovations that will improve the efficiency and quality of life of the end users.

Product designers should compare the properties of various groups of materials (steels, thermoplastics, aluminum alloys, rubber, etc.), because each material has different properties developed for specific applications and markets and uses different manufacturing processes. All materials have benefits and deficiencies (properties, processes, and quality), making it difficult to compare the cost of finished products made of different materials and processes.

The material properties are directly related to the end use applications whether or not one material is better than another. To illustrate this point, a thermoplastic resin cannot replace a structural steel beam used in building construction; the thermoplastic resins do not have the strength, creep resistance, or melt strength to be extruded into thick walled shapes. Thermoplastic beams would also warp in all directions. However, structural beams can be made of thermoset composites, although this is expensive. In less critical applications, such as the housing industry, wood composite structural beams are replacing steel beams, because of their performance and light weight; they are easy to work with and offer a competitive price.

A thermoplastic resin cannot replace the steel in automotive disc/drum brake housings, because the product requires dimensional stability, low thermal expansion, and high strength and rigidity at elevated temperatures. Thermoplastic resins do not meet the requirements. However, brake pads made of thermoset polyimide have been successfully used in airplanes.

Metals cannot replace automotive rubber tires, bellows, diaphragms, or compression seals, because metals do not have the elasticity, fatigue endurance, wear resistance, and toughness of rubber. Metals are not used for light-weight and compact cellular phone housings, because metals are electrical conductors, heavy, corrosive, and expensive.

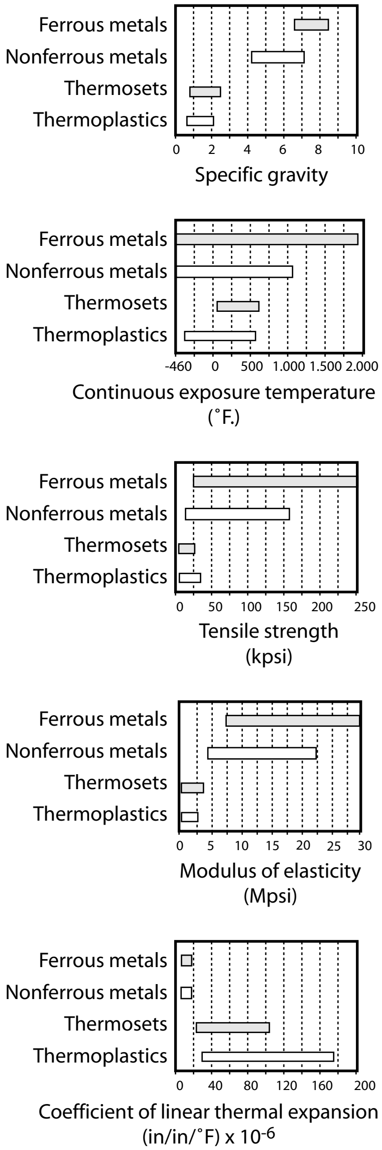

Figure 2-1 Comparison of generic properties of materials

Automotive engine cast iron and aluminum intake manifolds are being replaced by fiber glass reinforced nylon to improve efficiency, lower weight, creating new manufacturing processes, and cost reduction. Automotive steel bumpers, external side panels, and hoods have been replaced with TPE, thermoset composites, and PC alloys to reduce weight, improve styling, and reduce costs.

Portable electrical tools and small kitchen appliance housings are no longer made of die cast steel or aluminum but have been replaced with nylon and ABS, improving toughness, electrical insulation, and styling, lowering weight and cost reduction.

Water faucet valves made of die cast steel, brass, or copper are being replaced by new designs, updated styles, and colors, using acetal, which eliminates corrosion, providing cost reduction and opening new markets.

High performance, large size irrigation valves (from 1.50 to 3.0 in dia.) and small valves (0.75 and 1.00 in dia.) made of die cast steel and brass were successfully replaced with GR nylon 6/12 for the large valves and with GR nylon 6/6 or acetal for the small valves. This improved performance and reliability, eliminated corrosion, and provided cost reduction. Other low performance commercial valves made of rigid PVC (lower cost) are also produced for the irrigation market.

Toilet anti-siphon (ballcock) valves made of several brass and copper components were replaced with a multi-functional design in acetal, improving performance, eliminating corrosion, and providing cost reduction. The acetal valves had excellent performance over a 30 year period.

The comparison of properties is an effective tool when applied to materials in the same family. To illustrate the point that properties between different material families cannot be compared, Figure 2-1 shows several graphs using different generic property values of the different material families.

The ferrous metal bars include cast iron, cold rolled steels, structural steels, alloy steels, stainless steels, and tool steels. The nonferrous metal bars include magnesium, aluminum, copper, nickel and brass alloys, and titanium. The rubber bars include acrylic, butadiene, butyl, chloroprene, nitrile, silicone, urethane, EPDM, EPM, fluorocarbon, and natural rubbers. The thermoset bars include phenolics, silicones, alkyds, DAP, polyimides, aminos, unsaturated polyesters, epoxies, and urethanes. The thermoplastic bars include ABS, acrylics, acetals, nylons, LCP, PBT, PET, PS, PE, PP, PC, PPO, PEI, PEKK, PSU, PPS, PTFE, PVC, and SAN.

The specific gravity graph shows the unit weight of a material compared to water and reveals that metals are two to eight times heavier than plastics. On a strength-to-weight basis, plastics have a more favorable position, as indicated by the specific gravity graph. In general, the cost of metals is much higher than plastics.

The continuous exposure temperature graph shows that metals have wider temperature ranges than plastics; metals can be used at colder and at elevated temperatures. This property is used for the classification and temperature range of plastics.

The tensile strength (kpsi) graph shows that metals are much stronger than plastics; metals resist higher forces when being pulled apart before breaking. The tensile strength of a plastic varies with temperature; it decreases with increasing temperature over a much smaller temperature range.

The modulus of elasticity (Mpsi) graph shows that metals have higher resistance to deflection for short-term, intermittent, or continuous loading than plastics. Metals have better dimensional stability at elevated temperatures than plastics. Since plastics deflect more than metals under the same loading, it is important that metal and plastic parts be loaded using different techniques. Plastics require that the load be distributed in compression mode.

The coefficient of linear thermal expansion graph shows that increasing the temperature causes more dimensional changes for plastics than for metals. When plastics and metals are used together and are exposed to the same temperatures, plastic parts become larger than metals; therefore, design compensations should be provided to compensate dimensional change in plastics.

The thermal conductivity graph shows that metals are good conductors of heat while plastics are excellent insulators. Despite their relatively low effective temperature range, plastics may be superior to metals as high temperature heat shields for short exposures. A plastic part exposed to a radiant heat source soon suffers surface degradation. However, this heat is not transmitted to the opposite surface as rapidly as in metals.

The electrical volume resistivity graph compares only the insulation materials used in electrical applications, (metals are conductors).

The dielectric strength graph shows the voltage gradient at which electrical failure or breakdown occurs as a continuous arc; the higher the value the better the material. Plastics have excellent electrical resistance properties, while metals are conductors.

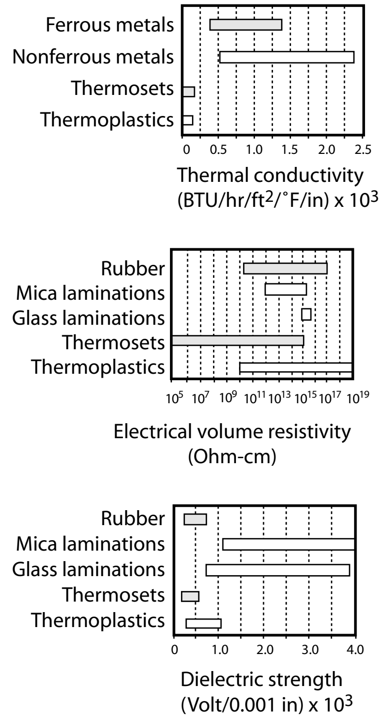

Figure 2-1 (continued)

2.1.1 Plastics Selection Guidelines

More than 20,000 thermoplastic grades and over 5,000 thermoset grades have been developed for the plastics industry. Because of the enormous diversity of plastic materials, the selection of the best plastic material for a given application is relatively difficult and time consuming, especially for inexperienced plastic designers.

Table 2-1 provides a comparison of plastics and their properties. The table includes the most widely used unreinforced, 30% GR thermoplastic, and reinforced thermoset materials; basic mechanical, thermal and electrical properties, and process temperatures, indicating the process characteristics of the resins. Table 2-1 should be used as a preliminary plastic selection guide.

The material properties listed in Table 2-1 were obtained by the resin producers by testing molded bars using ASTM procedures under laboratory conditions. Because most applications are not flat bars, but complex configurations, the actual properties will be different from the published ASTM properties. The values given are only approximate guides used to compare the values between resins for material selection and for preliminary product design calculations. To obtain precise properties for the new product design and configuration, a prototype mold is required, molding the selected materials, and testing the performance under actual service conditions.

This chapter provides detailed information for all important plastics, their chemistry, characteristics, advantages, limitations, and applications. Several plastic organizations, such as ASTM, Modern Plastics, D.A.T.A., Inc., Engineering Plastics, IDES "Prospector" and all the resin suppliers provide data properties sheets.

Table 2-1 Property Comparison for Selected Plastics

Types of Polymers	Specific Gravity	Tensile Modulus @ 73 °F (Mpsi)	Tensile Strength @ Yield (Kpsi)	Notch Izod Impact @ 73 °F (ft-lb/in)	Continue Expose Temperature (°F)	Processing Temperature (°F)	Flammability UL-94	Dielectric Strength (Vol/Mil)	Dissipation Factor @ 1.0×10^6 Hz
ABS Unreinforced	1.05	0.30	5.00	2.50 12.00	167 185	410 518	HB	350 500	0.03 0.04
Acrylic Unreinforced	1.17	0.38	7.50	0.03 0.50	150 190	410 575	HB	450 530	0.09
Acetal Unreinforced	1.42	0.400	10.00	1.30	195 230	375 450	HB	560	0.005
HDPE Polyethylene Unreinforced	0.94	0.20	3.50	No Break	158 176	400 535	HB V2	450 500	0.0005
PP Polypropylene Homo Unfilled	0.90	0.17	4.00	0.50 20.00	212	390 525	HB V2	450 600	0.002
PS Polystyrene Unfilled	1.05	0.45	6.00	0.25 0.60	122 158	390 480	HB V2	300 600	0.004 0.0020
PVC Polyvinyl Chloride Rigid	1.38	0.35	5.90	0.40 20.00	150 185	365 400	HB V1	600 800	0.115
PC – 30% Fiber Glass	1.40	1.25	19.00	1.70 3.00	220 265	430 620	V1 V2	450	0.001
PPO – 30% Fiber Glass	1.25	1.10	14.50	1.70 2.30	200 240	520 600	HB V0	550 630	…
PBT – 30% Fiber Glass	1.53	1.35	17.50	0.90	200 250	470 530	HB V0	750	0.004
PET – 30% Fiber Glass	1.67	1.50	22.0	1.60	392	510 565	V0 5V	430	0.002
LCP – 30% Fiber Glass	1.62	2.25	23.00	1.30	430 465	660 680	V0 5V	640 1,000	0.0019
HTN – 30% Fiber Glass @ 73 °F – 50% RH	1.44	1.50	32.00	1.80	315	580 620	V2 V0	500	0.004
Nylon 6/6 – 33% GR @ 73 °F & 50% RH	1.38	0.90	18.00	2.50	265	530 580	HB V2	400	0.006
PEI – 30% Fiber Glass	1.50	1.30	24.50	1.90	356 390	640 800	V0	495 630	0.0025
PPS - 30% Fiber Glass	1.38	1.70	22.0	1.10	390 450	600 750	V0 5V	450	0.0014
PSU – 30% Fiber Glass	1.46	1.35	14.50	1.10	350 375	600 715	V0 5V	450	0.002
DAP – (TS) Fiber Glass	1.94	1.40	7.50	1.00	390 430	290 350	V1 V0	400 450	0.011 0.017
(EP) Epoxy – (TS) Fiber Glass	1.84	3.00	18.00	0.50	350 4450	300 430	HB V0	380 400	0.02 0.05
(PF) Phenolic – (TS) Fiber Glass	1.74 1.88	1.90 2.28	6.50 10.00	0.75 0.90	350 450	330 390	V1 V0	300	0.03
(UP) Polyester – (TS) Fiber Glass	1.75 1.90	1.90 2.00	10.50 15.00	0.50 18.00	200 250	170 320	V0 5V	450 530	0.01 0.04
(PI) Polyimide – (TS) Graphite Fiber	1.65	0.70	7.50	0.70	600 740	690	V0 5V	500 560	0.010 0.003

Designer Check List

General Considerations
- Performance requirements (structural, loading cycle, aesthetic, etc.)
- Multifunction design
- Product design for assembly
- Structural load (static, dynamic, cyclic, impact, etc.)
- Product tolerance specifications
- Life of product
- Resin selection based on performance of similar applications and end use
- Product design for assembly process
- Quality of product vs. process
- Secondary operations
- Packaging and shipping

Environmental Requirements
- End use temperature
- Time, weather, strain, and stress cracks
- Others (chemical, lubricants, water, humidity, pollution, gasoline, etc.)

Design Factors
- Type, frequency, direction of loads
- Working stress selected (tensile, compression, flexural, combination)
- Strain percentage selected
- Load deformation (tensile, shear, compression, flexural, etc.)
- Tensile, flexural, initial, secant, yield modulus used (temperature, creep)
- Correlating the test results to end use environment conditions
- Safety factor
- Design product for efficient molding

Economic Factors
- Cost estimate of the new product
- Resin cost vs. molding performance
- Number of mold cavities vs. size of machine and automatic fast cycles
- Eliminate secondary operations
- Redesign part to simplify production

Quality Control Tests Required
- Tension
- Compression
- Flexural
- Impact (drop weight, dynatup, etc.)
- Torsion, fatigue
- Creep (tension, flex, temperature)
- Chemical resistance
- Weather (outdoors or accelerated)
- UL electrical classification
- UL continuous service temperature
- UL temperature index
- Final product UL approvals

Resin Processing Characteristics
- Viscosity and crystallization
- Difficulties in molding the resin
- Melt and mold temperature
- Sensitivity to thermal degradation
- Directional layout of reinforcements
- Frozen stresses
- Mold shrinkage control
- Molding problems (flashing, voids, warpage, short shots, brittleness, tolerances, surface finishing, etc.)
- Material handling
- Percentage of reground (runners and rejected molded parts) allowed to mix with the virgin material
- Drying the virgin resin and reground material.
- Prototype molding the product (resin behavior unknown)

Appearance of Product
- Aesthetic product application
- Dimensional control, warpage, etc.
- Color matching, discoloration
- Surface finishing
- Weld lines, sink marks, flow lines
- Parting line flash
- Gate type, size, number, location
- Decoration

If the product information and the quality of data available about a material have not been developed by the resin supplier, the designer should develop a check list by gathering all the facts related to the application. A typical designer's check list has been included here (Table 2-2). It may be used as a guideline to develop a specific check list for any application. All aspects of the part are covered, including the product end use requirements, the structural considerations, the operating environment, the economics, and the appearance factors. This information is provided for making a quick analysis of the part requirements, such as temperature, environment, product life expectancy, and cycle and rate of loading.

Designing with plastics requires maximizing the performance and efficiency of the product and the injection molding process. The following basic principles should be adopted in designing plastic products.

- Design freedom is achieved using multifunctional design concepts.
- When comparing materials that satisfy the requirements, remember that most metals have greater strength than plastics, and that all plastic material properties are time, temperature, and environment dependent.
- Metal design principles are very different from the concepts used in plastic parts design.
- Polymers are not substitutes for metals; in most designs the product geometry must be redesigned using plastic principles to be successful.

We need to remember that there are no bad thermoplastic materials, only bad plastic applications.

2.2 Structural Design of Thermoplastic Components

This section will present principles for structural design of molded plastic parts. The only data provided are what is necessary to illustrate the type of information needed for analysis of plastic design structures. The mechanical properties described are the properties frequently used by designers of plastic components.

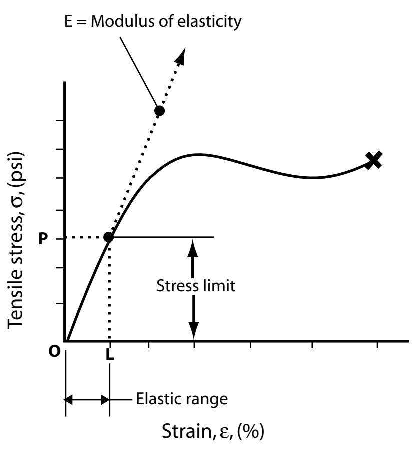

Figure 2-2 Stress-strain curve

Figure 2-2 shows two regions of the stress-strain curve. First, the region of low strain (O – L) will be discussed. This region is known as the elastic range; it is pertinent to applications where minimum deformation of the part under load is of prime concern. The second region of low stress (O – P) is known as the stress limit, which is important when the specimen springs back without deformation. The following discussion of creep and relaxation describes the effect of loading time on strength properties within the stress-strain curve. Specific attention is paid to creep under a constant load and relaxation from a fixed deformation.

The design methods present the recommended methods for using the mechanical properties and concepts for designing with plastics. Illustrations are included to show how the equations, originally developed for metal designs, can be modified. Designing within the viscoelastic modulus utilizes modified elastic design equations. This method is normally used when deformation of the part is of prime concern. Yield design uses design principles that originate from the principles of plasticity. In this section, the yield stress is the controlling material variable. It is emphasized that the major difference between metal and plastic designs is the necessity of allowing for the time dependence of the mechanical properties of polymeric materials over the entire range of temperatures and environmental conditions that the part may encounter in use.

2.2.1 Stress-Strain Behavior

To understand the response of the material, design engineers have been using a set of relationships based on Hooke's law, which states that for an elastic material, the strain (deformation) is proportional to the stress (the force intensity).

Roark and Young, Timoshenko, and others have developed analyses based on elastic behavior of materials that exhibit a good approximation of simple elastic behavior over a wide range of loads and temperatures. For high stress levels and repeated loading and creep, more sophisticated analyses have been developed to deal with these types of applications.

Unfortunately, Hooke's law does not reflect accurately enough the stress-strain behavior of plastic parts and it is a poor guide to successful design, because plastics do not exhibit basic elastic behavior. Plastics require that even the simplest analysis take into account the effects of creep and nonlinear stress-strain relationships. Time is introduced as an important variable and, because polymers are strongly influenced in their physical properties by temperature, that is another important parameter to be considered.

In order to analyze these effects, mathematical models exhibiting the same type of response to applied forces as plastics are used.

The elements that are used in such an analysis are a spring, which represents elastic response because the deflection is proportional to the applied force, and the dashpot, which is an enclosed cylinder and piston combination that allows the fluid filling the cylinder to move from in front of the piston to behind the piston through a controlled orifice.

The retarded elastic response which occurs in plastic materials is best represented as a spring and dashpot acting in parallel. The creep or cold flow, which occurs in plastics, is represented by a dashpot. The combination best representing the plastic structure would be a spring and dashpot in parallel combination, in series with a dashpot. The basic elements and the combinations are shown in Figure 2-3.

One of the results of the viscoelastic response of polymers is to vary the relationship between the stress and strain, depending on the rate of stress application. The standard test used to determine structural properties for many materials is the analysis of the stress-strain curve. Figure 2-4 shows the slope of the curve, which is the elastic constant called Young's modulus; the stress at which the slope of the curve deviates from the straight line is referred to as the tensile strength; and the stress at which the material fails by separation is called the ultimate tensile strength. In the case of viscoelastic behavior, the shape of the curve will depend on the rate of loading or on the rate of straining, depending on the way in which the test is performed. The modulus can vary over a range of three or four to one within the usual testing range and the material can exhibit ductile yielding at the lower straining rates. The value of the tensile strength and the ultimate strength can frequently vary by a 3 : 1 ratio.

It is apparent that, when tensile tests are done on plastics, the loading rates must be specified to make sure the data have any meaning at all. It also becomes clear

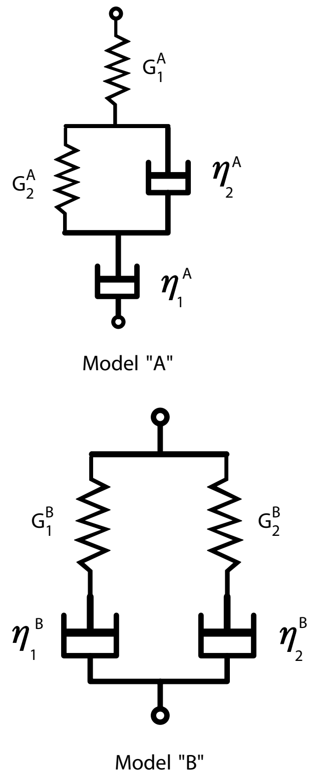

Figure 2-3 Plastic resin structural models, elastic and plastic range

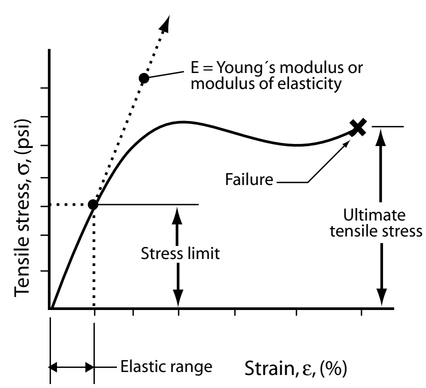

Figure 2-4 Young's modulus

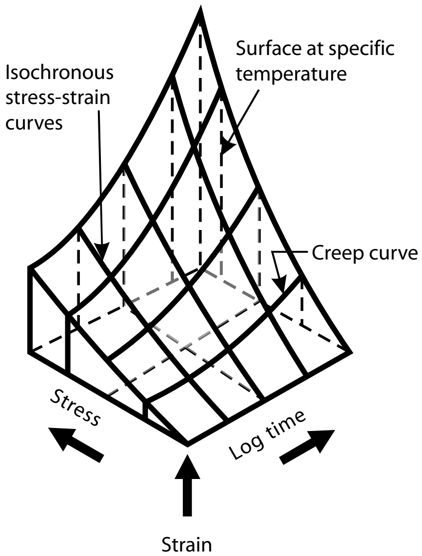

Figure 2-5 Three-dimensional graph, stress-strain-log time

that such conventional data is essentially useless for the design of plastic parts, unless the end use loading rates happen to be the same as those of the test. In order to be useful, the tensile test would have to be run over a wide range of rates and the form in which the data is best presented is a three dimensional plot of stress-strain and time as illustrated in Figure 2-5.

2.2.2 Tensile Testing of Viscoelastic Materials

In this section we will address the internal effects of forces acting on a structure. The thermoplastic components will no longer be considered to be perfectly rigid, such as in the static analysis cases. Structural design is concerned with the analysis of material strength, such as the deformations of various structures under a variety of loads.

The simple tensile test is probably the most popular method for characterizing metals and so it is not surprising that it is also widely used for plastics. However, for plastics, the tensile test needs to be very carefully performed, because plastics, being viscoelastic, exhibit deformations that are very sensitive to such things as cross head speed rate in tension testing, moisture, stress level, temperature, and creep time.

The stress-strain curves as shown in Figures 2-10 and 2-11 illustrate an interesting phenomenon observed in some flexible plastics, such as thermoplastic elastomers. This behavior is known as the plastic range, cold drawing, or continuous elongation of the specimen beyond the yield point without breaking. It occurs because, at low cross head speed rates, the molecular chains in the plastic have time to align themselves under the influence of the applied stress. Therefore, the plastic specimen's molecular chains are able to align at the same rate at which the material it is being strained.

The simplest case to consider is the application of a straight tensile load on a test specimen of constant cross section. The specimen is loaded at both ends with an equal force applied in opposite directions along the longitudinal axis and through the centroid cross section of the tensile test specimen. Under the action of the applied tensile forces, internal resisting forces are set up within the tensile test specimen. The tensile test assumes that the forces are applied through an imaginary plane passing along the middle of its length and oriented perpendicular to the longitudinal axis of the tensile test specimen. The magnitude of these forces must be equal and directed away from the test specimen (tension loading) to maintain an equilibrium of these forces. Typical tensile test equipment, including an extensometer, is shown in Figure 2-6.

Some assumptions are made regarding the variation of these distributed internal resisting forces within the specimen. Because the applied tensile forces act through the centroid, it is assumed that they are uniform across the specimen's cross section. The load distribution depends on the tensile test specimen geometry, dimensions, and manufacturing process. It also depends on the crystalline molecular structure of the polymer, the coupling agent used to reinforce the compound, and the flow orientation of the material reinforcement. However, to determine the mechanical properties of a polymer by performing either test in compression or tension, the cross head speed rate, at which loading is applied, has a significant influence on the physical properties obtained when running the tests at different loading rates. Ductile materials exhibit the greatest sensitivity of physical property variations at different cross head speed loading rates, whereas these effects are reduced and sometimes negligible for brittle materials.

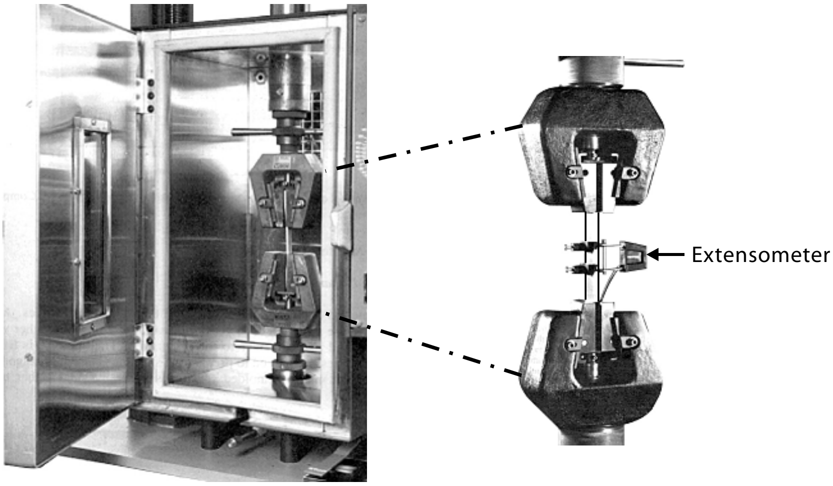

Figure 2-6 Tensile test equipment and temperature chamber

2.2.2.1 Stress or Tensile Strength (σ)

Instead of referring to the internal force acting on some small element of the area, it is easier to use the ratio between the force acting over a unit area of the cross section. The force per unit area is termed as the stress (σ) and is expressed in units of force per unit area, e.g., lb/in^2 (psi). If the forces applied to the ends of the tensile test specimen are such that the bar is in tension, then the term stress or tensile strength (σ) condition can be applied to the specimen. It is essential that the forces are applied through an imaginary plane passing through the centroid cross section area of the tensile test specimen.

2.2.2.2 Tensile Test Specimen

The tensile test specimen is held in the grips of either an electrically driven gear or hydraulic testing equipment. The electrically driven gear testing equipment is commonly used in testing laboratories for applying axial tension or compression loads.

To standardize material testing procedures, the American Society for Testing Materials (ASTM) has issued standard specifications and procedures for testing various metallic, non-metallic, and thermoplastic resins in tension and compression tests. The ASTM test procedures for thermoplastic materials can be found in Chapter 11. Figure 2-7 shows a tensile test specimen specified for plastic materials. The dimensions shown are those specified by ASTM for tensile test specimens to fit the grips of the tensile test equipment.

The elongations of the tensile test specimen are measured by a mechanical extensometer (see Figure 2-6), an internal gauge (micro-processor tester), or by cementing an electric resistance type strain gauge to the surface of the tensile test specimen. This resistance strain gauge consists of a number of very fine wires oriented in the axial direction of the tensile test specimen. As the test specimen elongates, the electrical resistance of the wire changes and this change of resistance is detected on a Wheatstone bridge and interpreted as elongation.

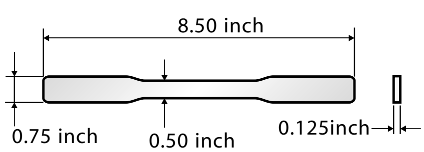

Figure 2-7 Thermoplastic tensile test specimen

Stress-Strain Curves for Various Materials

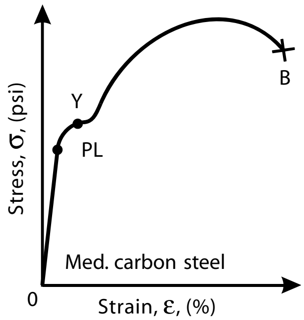

Figure 2-8 Stress/strain curve for medium carbon steel

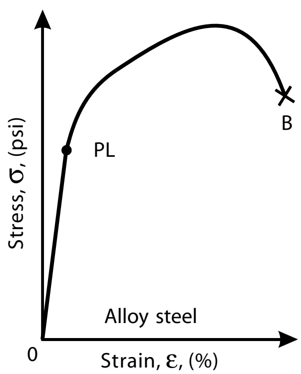

Figure 2-9 Stress/strain curve for alloy steel

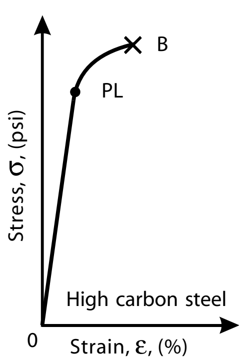

Figure 2-10 Stress/strain curve for high carbon steel

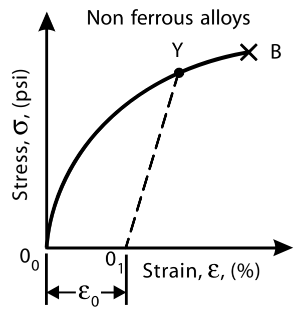

Figure 2-11 Stress/strain curve for nonferrous alloys and cast iron materials

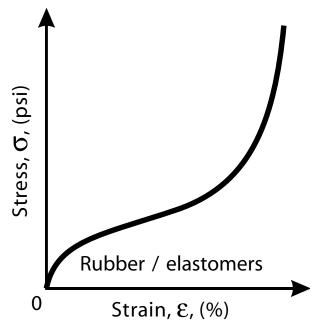

Figure 2-12 Stress/strain curve for rubber or elastomeric materials

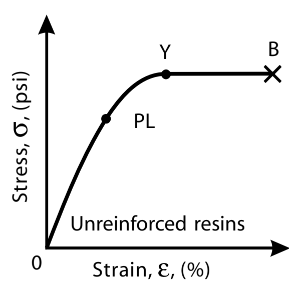

Figure 2-13 Stress/strain curve for unreinforced resins

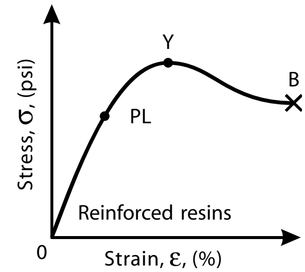

Figure 2-14 Stress/strain curve for reinforced resins

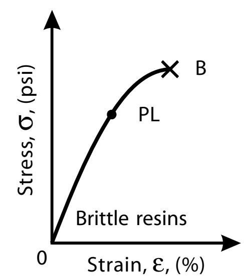

Figure 2-15 Stress/strain curve for brittle resins

2.2.2.3 Strain (ε)

The elongation over the tensile test specimen gauge length is measured for any predetermined increment caused by the tensile load. From these values the elongation per unit length, called strain and denoted by ε, may be found by dividing the total elongation ΔL by the original gauge length L, i.e., $\varepsilon = \Delta L / L$. The strain is usually expressed in units of inch per inch and consequently is dimensionless.

2.2.2.4 Stress-Strain Curve

As the tensile load is gradually increased at a cross head speed rate, the total elongation over the gauge length and the load are measured and recorded continuously at each increment of the load until fracture of the specimen takes place. Knowing the original cross sectional area of the tensile specimen, the stress (σ), may be obtained for any value of the tensile load by applying the following formula:

Tensile Stress = $\sigma = W / A$

where W denotes the tensile load in pounds, and A the original cross sectional area in square inches. Having obtained the numerous values of stress (σ) and strain (ε), the test results are plotted with these quantities considered as ordinate and abscissa, respectively. This is the tensile stress-strain curve or diagram of the material in tension. The stress-strain curve represents the mechanical characteristics or behavior for each type of material, therefore the stress-strain curves assume widely differing geometries for various materials. Figure 2-8 represents the stress-strain curve for a medium carbon steel, Figure 2-9 the curve for an alloy steel, Figure 2-10 the curve for a high carbon steel, Figure 2-11 the curve for nonferrous alloys and cast iron materials, and Figure 2-12 the curve for rubber or elastomeric materials.

Tests conducted at room temperature using ASTM recommended proportional limits showed that polyethylene resin, PP copolymer resin, TPE resins, acetal resin, and unreinforced nylon resin (at 50% relative humidity) are materials that yield gradually until break as shown in Figure 2-13. Reinforced nylon resin (at 50% relative humidity), PC glass reinforced resin, and other compounded polymers that have limited elongation characteristics yield a curve as shown in Figure 2-14. Acrylic resin, PET glass reinforced resin, PBT glass reinforced resin, LCP, PF, PAI, PEI, PEAK, dry as molded nylon glass reinforced resins and most brittle compounded resins usually break before yielding occurs, as shown in Figure 2-15.

2.2.2.5 Hooke's Law

For any material having a stress-strain curve of the form shown in Figure 2-16, the relation between stress and strain is linear for comparatively small values of the strain. This linear relation between elongation and tensile stress was first noticed by Sir Robert Hooke in 1678 and is called Hooke's law. This initial linear range of action of the material is described by the following formula:

Stress (σ) = Modulus of Elasticity (E) $\times$ Strain (ε)

or

Strain (ε) = σ / E

where E (Modulus of Elasticity) denotes the slope or the straight line **0-PL** (origin to the proportional limit) as shown in the stress-strain curve Figure 2-16.

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