Mechanical testing machines can be automated to simplify the analysis of the mechanical performance of materials in a variety of product applications. (Courtesy of MTS Systems Corporation.)
Figure 6-1  Tensile test.
Figure 6-2  Load-versus-elongation curve obtained in a tensile test. The specimen was aluminum 2024-T81.
Figure 6-3  Stress-versus-strain curve obtained by normalizing the data of Figure 6–2 for specimen geometry.
The yield strength is defined relative to the intersection of the stress–strain curve with a “0.2% offset.” This is a convenient indication of the onset of plastic deformation.
Figure 6-5  Elastic recovery occurs when stress is removed from a specimen that has already undergone plastic deformation.
Figure 6-6  The key mechanical properties obtained from a tensile test: 1, modulus of elasticity, $E$; 2, yield strength, Y.S.; 3, tensile strength, T.S.; 4, ductility, $100 \times \epsilon_{\text{failure}}$ (note that elastic recovery occurs after fracture); and 5, toughness $= \int \sigma \, d\epsilon$ (measured under load; hence, the dashed line is vertical).
Figure 6-7  Neck down of a tensile test specimen within its gage length after extension beyond the tensile strength. (Courtesy of R. S. Wortman)
True stress (\(= \text{load divided by actual area in the necked-down region}\)) continues to rise to the point of fracture, in contrast to the behavior of engineering stress. (After R. A. Flinn/P. K. Trojan: Engineering Materials and Their Applications, 2nd Ed., Copyright © 1981, Houghton Mifflin Company, used by permission.)
Stress

Figure 6-9  The toughness of an alloy depends on a combination of strength and ductility.
For a low-carbon steel, the stress-versus-strain curve includes both an upper and lower yield point.
Figure 6-11  The Poisson’s ratio ($v$) characterizes the contraction perpendicular to the extension caused by a tensile stress.
Figure 6-12 Elastic deformation under a shear load.
The brittle nature of fracture in ceramics is illustrated by these stress–strain curves, which show only linear, elastic behavior. In (a), fracture occurs at a tensile stress of 280 MPa. In (b) a compressive strength of 2100 MPa is observed. The sample in both tests is a dense, polycrystalline $\text{Al}_2\text{O}_3$. 

Figure 6-13
Modulus of rupture = MOR
\[ = \frac{3FL}{2bh^2} \]

**Figure 6-14**  The bending test that generates a modulus of rupture. This strength parameter is similar in magnitude to a tensile strength. Fracture occurs along the outermost sample edge, which is under a tensile load.
Figure 6-15 Stress ($\sigma_m$) at the tip of a Griffith crack.
Figure 6-16 Stress-versus-strain curves for a polyester engineering polymer. (From Design Handbook for Du Pont Engineering Plastics, used by permission.)
Figure 6-17 Stress-versus-strain curves for a nylon 66 at 23°C showing the effect of relative humidity. (From Design Handbook for Du Pont Engineering Plastics, used by permission.)
Figure 6-18  Relationship of elastic deformation to the stretching of atomic bonds.
Figure 6-19 Sliding of one plane of atoms past an adjacent one. This high-stress process is necessary to plastically (permanently) deform a perfect crystal.
Figure 6-20  A low-stress alternative for plastically deforming a crystal involves the motion of a dislocation along a slip plane.
Figure 6-21  Schematic illustration of the motion of a dislocation under the influence of a shear stress. The net effect is an increment of plastic (permanent) deformation. (Compare Figure 6–21a with Figure 4–13.)
Figure 6-22  Goldie the caterpillar illustrates (a) how difficult it is to move along the ground without (b) a “dislocation” mechanism. (From W. C. Moss, Ph.D. thesis, University of California, Davis, Calif., 1979.)
Figure 6-23  Dislocation slip is more difficult along (a) a low-atomic-density plane than along (b) a high-atomic-density plane.
Figure 6-24  Slip systems for (a) fcc aluminum and (b) hcp magnesium. (Compare to Figure 1–18.)

(a) Aluminum

{111}\langle 1\bar{1}0 \rangle =
(111)[1\bar{1}0]  (111)[\bar{1}01]  (111)[01\bar{1}]
(1\bar{1}1)[1\bar{1}0]  (1\bar{1}1)[\bar{1}01]  (1\bar{1}1)[01\bar{1}]
(1\bar{1}1)[110]  (1\bar{1}1)[10\bar{1}]  (1\bar{1}1)[011]
(111)[110]  (111)[101]  (111)[011]

(b) Magnesium

(0001)\langle 1\bar{1}20 \rangle =
(0001)[1\bar{1}20]  (0001)[\bar{1}210]  (0001)[\bar{2}110]
Direction of “attempted” dislocation motion

Figure 6-25  How an impurity atom generates a strain field in a crystal lattice, causing an obstacle to dislocation motion.
Figure 6-26 Definition of the resolved shear stress, $\tau$, which directly produces plastic deformation (by a shearing action) as a result of the external application of a simple tensile stress, $\sigma$. 

\[ \tau = \sigma \cos \lambda \cos \phi, \]

where $\sigma = \frac{F}{A}$.
Figure 6-27  Hardness test. The analysis of indentation geometry is summarized in Table 6.10.
Figure 6-28  (a) Plot of data from Table 6.11. A general trend of BHN with T.S. is shown. (b) A more precise correlation of BHN with T.S. (or Y.S.) is obtained for given families of alloys. [Part (b) from Metals Handbook, 9th Ed., Vol. 1, American Society for Metals, Metals Park, Ohio, 1978.]
Figure 6-29  Elastic strain induced in an alloy at room temperature is independent of time.
Figure 6-30  Typical creep test.
Figure 6-31  Creep curve. In contrast to Figure 6–29, plastic strain occurs over time for a material stressed at high temperatures (above about one-half the absolute melting point).
Climb = Vacancy

Figure 6-32  Mechanism of dislocation climb. Obviously, many adjacent atom movements are required to produce climb of an entire dislocation line.
Figure 6-33 Variation of the creep curve with (a) stress or (b) temperature. Note how the steady-state creep rate ($\dot{\varepsilon}$) in the secondary stage rises sharply with temperature (see also Figure 6–34).
High-temperature laboratory data

Service temperature range

Figure 6-34 Arrhenius plot of $\ln \dot{\varepsilon}$ versus $1/T$, where $\dot{\varepsilon}$ is the secondary-stage creep rate and $T$ is the absolute temperature. The slope gives the activation energy for the creep mechanism. Extension of high-temperature, short-term data permits prediction of long-term creep behavior at lower service temperatures.
Figure 6-35  Simple characterization of creep behavior is obtained from the secondary-stage strain rate (\(\dot{\varepsilon}\)) and the time to creep rupture (\(t\)).
Figure 6-36 Creep rupture data for the nickel-based superalloy Inconel 718. (From Metals Handbook, 9th Ed., Vol. 3, American Society for Metals, Metals Park, Ohio, 1980.)
Figure 6-37 Arrhenius-type plot of creep-rate data for several polycrystalline oxides under an applied stress of 50 psi (345 × 10³ Pa). Note that the inverse temperature scale is reversed (i.e., temperature increases to the right). (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, Introduction to Ceramics, 2nd Ed., John Wiley & Sons, Inc., New York, 1976.)
Figure 6-38  Creep data for a nylon 66 at 60°C and 50% relative humidity. (From Design Handbook for Du Pont Engineering Plastics, used by permission.)
Plotting gives $T = 585^\circ\text{C}$.
Figure 6-39  Typical thermal expansion measurement of an inorganic glass or an organic polymer indicates a glass transition temperature, $T_g$, and a softening temperature, $T_s$. 
Upon heating, a crystal undergoes modest thermal expansion up to its melting point ($T_m$), at which a sharp increase in specific volume occurs. Upon further heating, the liquid undergoes a greater thermal expansion. Slow cooling of the liquid would allow crystallization abruptly at $T_m$ and a retracing of the melting plot. Rapid cooling of the liquid can suppress crystallization producing a supercooled liquid. In the vicinity of the glass transition temperature ($T_g$), gradual solidification occurs. A true glass is a rigid solid with thermal expansion similar to the crystal but an atomic-scale structure similar to the liquid (see Figure 4–23).
Figure 6-41  Illustration of terms used to define viscosity, $\eta$, in Equation 6.19.
Figure 6-42  Viscosity of a typical soda–lime–silica glass from room temperature to 1500°C. Above the glass transition temperature (~ 450°C in this case), the viscosity decreases in the Arrhenius fashion (see Equation 6.20)
Figure 6-43 Thermal and stress profiles occurring during the production of tempered glass. The high breaking strength of this product is due to the residual compressive stress at the material surfaces.
Figure 6-44  Modulus of elasticity as a function of temperature for a typical thermoplastic polymer with 50% crystallinity. There are four distinct regions of viscoelastic behavior: (1) rigid, (2) leathery, (3) rubbery, and (4) viscous.
(Courtesy of Tamglass, Ltd.)
Figure 6-45  In comparison to the plot of Figure 6–44, the behavior of the completely amorphous and completely crystalline thermoplastics falls below and above that for the 50% crystalline material. The completely crystalline material is similar to a metal or ceramic in remaining rigid up to its melting point.
Cross-linking produces a network structure by the formation of primary bonds between adjacent linear molecules. The classic example shown here is the vulcanization of rubber. Sulfur atoms form primary bonds with adjacent polyisoprenemers. This is possible because the polyisoprene chain molecule still contains double bonds after polymerization. [It should be noted that sulfur atoms can themselves bond together to form a molecule chain. Sometimes, cross-linking is by an \((S)_n\) chain, where \(n > 1\).]
Figure 6-47  Increased cross-linking of a thermoplastic polymer produces increased rigidity of the material.
The modulus of elasticity versus temperature plot of an elastomer has a pronounced rubbery region.

Figure 6-48  The modulus of elasticity versus temperature plot of an elastomer has a pronounced rubbery region.
Figure 6-49  Schematic illustration of the uncoiling of (a) an initially coiled linear molecule under (b) the effect of an external stress. This indicates the molecular-scale mechanism for the stress versus strain behavior of an elastomer, as shown in Figure 6–50.
High strain modulus (due to covalent bonding)

Low strain modulus (due to secondary bonding)

\[ E_{\text{high}} \]

\[ E_{\text{low}} \]

**Figure 6-50** The stress–strain curve for an elastomer is an example of nonlinear elasticity. The initial low-modulus (i.e., low-slope) region corresponds to the uncoiling of molecules (overcoming weak, secondary bonds), as illustrated by Figure 6–49. The high-modulus region corresponds to elongation of extended molecules (stretching primary, covalent bonds), as shown by Figure 6–49b. Elastomeric deformation exhibits hysteresis; that is, the plots during loading and unloading do not coincide.
Figure 6-51  Modulus of elasticity versus temperature for a variety of common polymers. The dynamic elastic modulus in this case was measured in a torsional pendulum (a shear mode). The DTUL is the deflection temperature under load, the load being 264 psi. This parameter is frequently associated with the glass transition temperature. (From Modern Plastics Encyclopedia, 1981–82, Vol. 58, No. 10A, McGraw-Hill Book Company, New York, October 1981.)