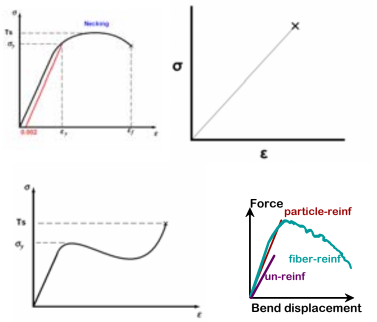
Class 3: Stress Strain Behavior in Materials



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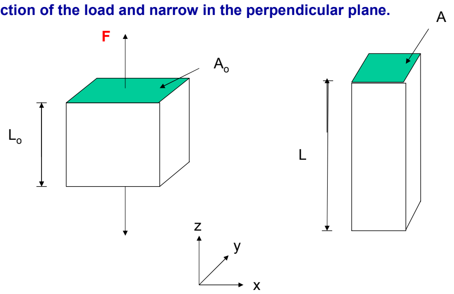
Stress-strain behavior of a material describe how the sample shape changes when a load is applied.

When a tensile load is applied, most materials stretch in the direction of the load and narrow in the perpendicular plane.



Definition of stress, strain, Young's modulus, and Poisson's ratio are independent of the material type

Engineering Tensile Stress

$$\sigma = \frac{F}{A_o}\left[Pa = \frac{N}{m^2}\right]$$

Engineering Tensile Strain

$$\varepsilon = \frac{L - L_o}{L_o}[\text{unitless}]$$

Hooke's Law

$\sigma_Z = \varepsilon_Z E$ [Pa]
E = modulus of elasticity or Young's Modulus

Poisson's Ratio: A measure of volume change

$$\upsilon = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}[\text{unitless}]$$

metals: ν ~ 0.33
ceramics: ~0.25
polymers: ~0.40

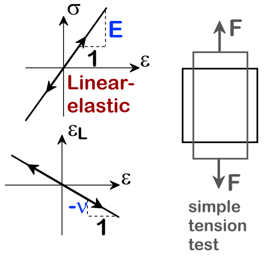


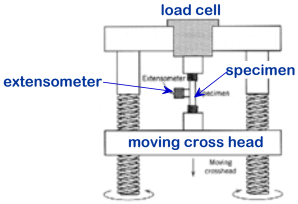
Figure adapted from Callister

Stress strain tests are set by ASTM standards

American Society for Testing and Materials (ASTM) sets standards for testing of materials which includes

- **sample size and shape**
- **pull rates**
- **instructions on loading samples**

Typical tensile test machine



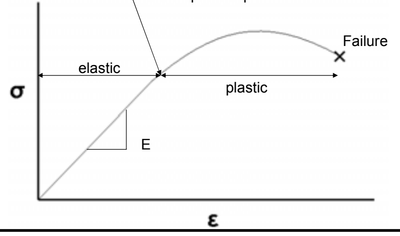
Adapted from Fig. 6.3, *Callister 6e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

In general, stress strain curves give information on elastic and plastic deformation regimes

In the elastic regime, deformation to an applied stress is temporary

In the plastic regime, an applied stress causes permanent deformation

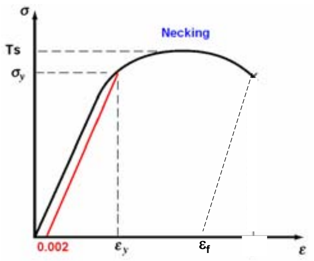
P = Proportional Limit
= The point of permanent deformation



From a stress strain curve for a typical metal, tensile strength, 0.2% yield strength, and fracture strain can be defined

The main points on a stress strain curve for metals are

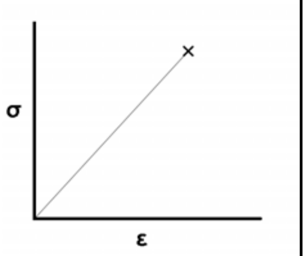
σ_y = yield stress
= 0.2% offset yield
ε_y = yield strain
TS = Tensile Strength
ε_f = fracture strain or ductility
% elongation (ductility) = ε_f * 100
Toughness = energy to fracture= area under curve



A typical stress strain curve for a ceramic has only elastic deformation

Ceramics typically fail in a brittle manner (that is without plastic deformation).

This is because the ionic nature of the bonds prevent slip (dislocation motion).



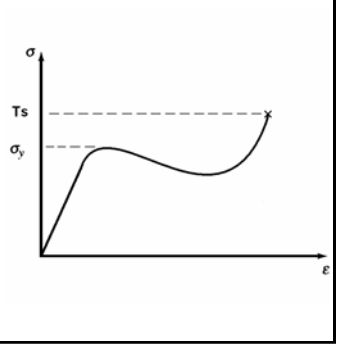
Yield stress and tensile strength in polymers is defined differently than metals

In polymers, plastic deformation takes place from chains untangling. There are no dislocations in polymers!

The yield stress is the maximum on the curve which occurs just beyond the linear-elastic region.

The TS is the stress at which fracture occurs.

The tensile modulus (modulus of elasticity) and ductility are defined the same as in metals.



Composites have the combined properties of the matrix and reinforcement

The mechanical properties of the composite depend on the properties of the matrix and reinforcement.

The effect also depends critically on the reinforcement shape and how it is aligned relative to the load

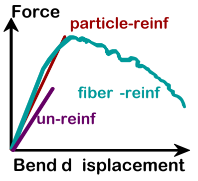
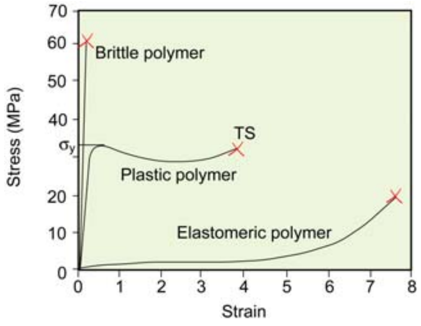


Figure from Callister overheads

Degree of plastic deformation varies with polymer type

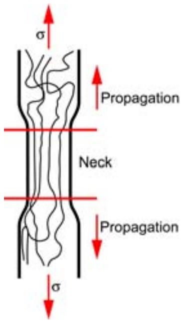


Some highly elastomeric polymers may experience elongations of as much as 1000%.

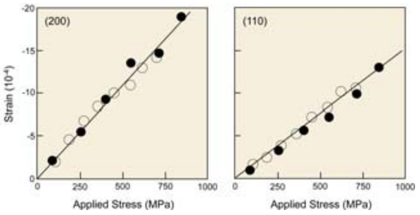
Elastic deformation in polymers takes place by bonds stretching and chains aligning.

Elongation of the chain molecules from their stable conformations in the direction of the applied stress, by the bending and stretching of the strong chain covalent bonds.

Extensive alignment takes place in the neck and this intrinsically strong region propagates up and down the gage length and converts the less deformed and aligned material into the neck morphology.



Elastic deformation in Kevlar®



Relationship between strain of the (200) and (110) planes and the longitudinal applied stress for Kevlar® 49 (open circles) and Kevlar® 29 (closed circles) at 20°C.

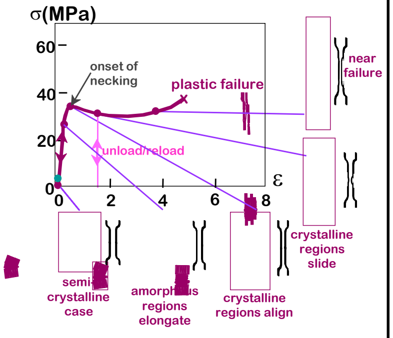
When the stress is applied along the chain direction, the crystal lattice contracts in the direction perpendicular to the chain axis, and is always reversible.

K. Nakamae, T. Nishino, and X. Airu, “Poisson’s ratio of the crystal lattice of poly (p-phenylene terephthalamide) by x-ray diffraction,” *Polymer*, **33** [23] 4898-4900 (1992).

Plastic deformation occurs as crystal regions slide past each other.

Plastic deformation occurs in crystalline polymers with the sliding of lamellar and intervening amorphous regions.

Crystal regions require a greater force to deform them than amorphous regions



Stress-strain curves adapted from Fig. 15.1, *Callister 6e.* Inset figures along plastic response curve

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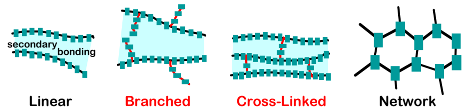
The tensile strength increases as it gets harder to untangle the chains

Higher tensile strength (lower ductility) is achieved by making the chains harder to untangle

- **Bulky side groups**
- **Longer chains**
- **Linear > branched (more secondary bonding between chains)**
- **Networked > Cross Linked > Linear**

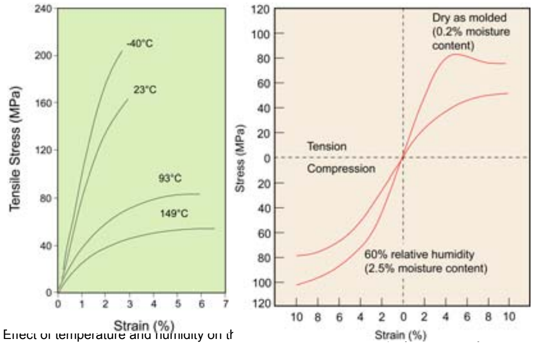


Degree of crystallinity in a polymer has a very large effect on the mechanical behavior of the material.

Percentage crystallinity	Density (10^3 kg/m^3)	Tensile Strength (MPa)
65	0.920	13.8
75	0.935	17.2
85	0.950	27.6
87	0.960	31.0
95	0.965	37.9

T.H. Courtney, Mechanical Behavior of Materials, (McGraw Hill, New York, 1990).

Temperature and humidity have a large effect on the mechanical properties of polymers.



Effect of temperature and humidity on th

J.F. Shackelford, Introduction to Materials Science for Engineers 5/e, (Prentice Hall, New Jersey, 2000).

The glass transition temperature is the limit between a rubbery material and a rigid solid.

At lower temperatures, molecules in polymer chains can not rotate around, giving a rigid solid. The glass transition temperature marks this point.

Below the glass transition temperature, Hooke's law applies to these materials.

Above the glass transition temperature, but below the melting temperature, the material behaves like a rubbery solid. This is termed viscoelasticity.

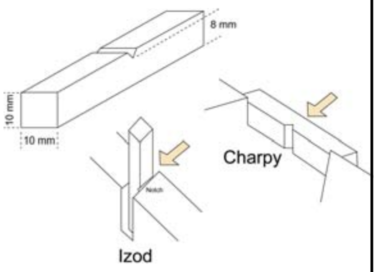
Material	T_g	T_m
LDPE	-110	115
HDPE	-90	137
Nylon 6,6	57	265
PET	69	265
PVC	87	212
Polystyrene	100	240

W.D. Callister, Materials Science and Engineering An Introduction 5/e, (John Wiley and Sons, New York, 2000).

Impact tests are also used to measure mechanical properties.

The diagram shows specimens used for Charpy and Izod impact tests.

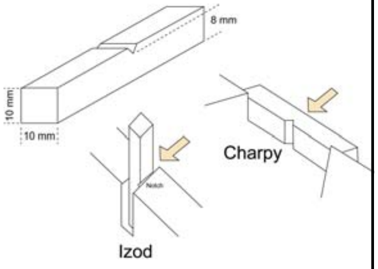
The Izod test is the one used for polymers.



Inpact tests measure the energy to break a sample.

During an impact test, a hammer is released from a fixed height *h* and strikes the specimen.

The energy expended in fracture is reflected in the difference between *h* and the swing height *h'* on the other side of the specimen location.



Izod Test Data for Various Polymers

Polymer	Impact Energy (J)
Polyethylene (High-density)	1.4 - 16
Polyvinylchloride	1.4
Polypropylene	1.4 - 1.5
Acrylics (Lucite)	0.7
Polyamides (nylon 66)	1.4
Polyesters	0.5
Epoxies	1.1
ABS	1.4 - 14
Polycarbonates	19
Acetals	3
Teflon	5

J.F. Shackelford, Introduction to Materials Science for Engineers 5/e, (Prentice Hall, New Jersey, 2000).

In summary, the stress strain properties depend on the material type

ASTM standards exist to properly test metals, ceramics, polymers, and composites

Polymers do not deform by slip. The yield stress and TS are defined differently than in metals.

Tensile strength in polymers can be increased by increasing the difficulty chains can slide past one another or the degree of crystallinity.

Temperature and humidity have a large effect on the mechanical properties of polymers.

An Izod test is the impact test used to measure the energy to break a polymer sample.