ME 4563

Introduction to Manufacturing Processes

College of Engineering
Arkansas State University

Materials in Manufacturing

Materials in Manufacturing

- Materials are one of the key elements of a manufacturing system

Let us look at a typical product …

Representative Materials in a typical Automobile

Steel – 60%

Aluminum – 5%

Composites – 5%

Rubber – 3%

Zinc – 2%

Lead – 1%

% by weight

Iron – 17%

Plastic – 3%

Glass – 2%

Copper – 1%

Others – 1%

(wood, Nickel, etc.)

From: Manufacturing Processes & Systems – Ostwald and Munoz, 9th Ed., 1997, Wiley

Representative Materials in a typical Automobile

- Cast Iron or Al Engine Block
- Ceramic Spark plug
- Copper Wiring
- Plastic wind-shield washer fluid tank
- Steel or Al Wheels
- Lead Battery parts
- Steel Frame

- Rubber tires
- Tungsten filament for lamps
- Plastic tail light lenses
- Glass Windows
- Plastic Bumpers, dashboard
- Cloth/Leather seat covers

From: Manufacturing Engineering & Technology – Kalpakjian & Schmid, 4th Ed., 2001, Prentice-Hall

Materials in Manufacturing

The Automobile is an example of a common product that contains several different types of materials

These materials were selected because, of all the materials that possess the desired properties and characteristics for the intended functions of the specific parts or components, these were the ones that could be manufactured at the LOWEST cost !

Materials in Manufacturing

Reasons for the choice …

- Steel – strong, easy to form, inexpensive
- Plastics – characteristics, wide choice of colors, light weight, ease of manufacturing into various shapes, low cost
- Glass – transparent, hard, easy to clean, resistant to scratching, etc.

Similar observations can be made for other materials as well…

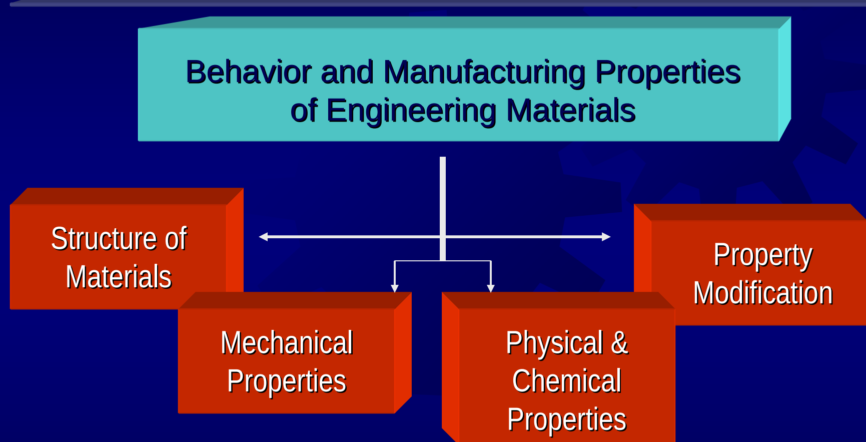
Materials in Manufacturing

- Selection of Materials for a product requires an Understanding their properties and manufacturability is critical for their effective and efficient application
- By saving just 1% on the average cost of per component (such as selecting a different material or manufacturing technique), the manufacturer could reduce the cost of the automobile by $150 !!

Materials in Manufacturing

- Considering all the different types of materials available today, the task of manufacturing engineers becomes a challenging one in terms of evaluating and selecting appropriate materials for use in manufacture

Materials in Manufacturing



Materials in Manufacturing

Behavior and Manufacturing Properties of Engineering Materials

Structure of Materials

- Atomic Bonds
- Crystalline
- Amorphous
- Polymer Chains

Etc.

Materials in Manufacturing

Behavior and Manufacturing Properties of Engineering Materials

Mechanical Properties

- Strength
- Ductility
- Elasticity
- Hardness
- Fatigue
- Creep

Etc.

Materials in Manufacturing

Behavior and Manufacturing Properties of Engineering Materials

- Density
- Melting Point
- Specific Heat
- Thermal Conductivity
- Thermal Expansion
- Oxidation, Corrosion

Etc.

Physical & Chemical Properties

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Materials in Manufacturing

Behavior and Manufacturing Properties of Engineering Materials

- Heat Treatment
- Annealing
- Tempering
- Alloying
- Reinforcements
- Lamination

Etc.

Property Modification

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Relative Mechanical Properties of Materials at Room Temperature

TABLE 2.1

Strength	Hardness	Toughness	Stiffness	Strength/Density
Glass fibers	Diamond	Ductile metals	Diamond	Reinforced plastics
Graphite fibers	Cubic boron nitride	Reinforced plastics	Carbides	Titanium
Kevlar fibers	Carbides	Thermoplastics	Tungsten	Steel
Carbides	Hardened steels	Wood	Steel	Aluminum
Molybdenum	Titanium	Thermosets	Copper	Magnesium
Steels	Cast irons	Ceramics	Titanium	Beryllium
Tantalum	Copper	Glass	Aluminum	Copper
Titanium	Thermosets	Ceramics	Tantalum	
Copper	Magnesium	Reinforced	plastics	
Reinforced	thermosets	Thermoplastics	Wood	
Reinforced	thermoplastics	Tin	Thermosets	
Thermoplastics	Lead	Thermoplastics		
Lead	Rubbers			

From: Kalpakjian & Schmidt, Manuf. Engg. & Technology, 4th Ed. – Tables 2.1 & 2.2

Mechanical Properties of Various Materials at Room Temperature

TABLE 2.2 Mechanical Properties of Various Materials at Room Temperature

Metals (Wrought)	*E* (GPa)	*Y* (MPa)	UTS (MPa)	Elongation in 50 mm (%)
Aluminum and its alloys	69–79	35–550	90–600	45–4
Copper and its alloys	105–150	76–1100	140–1310	65–3
Lead and its alloys	14	14	20–55	50–9
Magnesium and its alloys	41–45	130–305	240–380	21–5
Molybdenum and its alloys	330–360	80–2070	90–2340	40–30
Nickel and its alloys	180–214	105–1200	345–1450	60–5
Steels	190–200	205–1725	415–1750	65–2
Titanium and its alloys	80–130	344–1380	415–1450	25–7
Tungsten and its alloys	350–400	550–690	620–760	0
Nonmetallic materials				
Ceramics	70–1000	—	140–2600	0
Diamond	820–1050	—	—	—
Glass and porcelain	70-80	—	140	—
Rubbers	0.01–0.1	—	—	—
Thermoplastics	1.4–3.4	—	7–80	1000–5
Thermoplastics, reinforced	2–50	—	20–120	10–1
Thermosets	3.5–17	—	35–170	0
Boron fibers	380	—	3500	0
Carbon fibers	275–415	—	2000–3000	0
Glass fibers	73–85	—	3500–4600	0
Kevlar fibers	62–117	—	2800	0

Note: In the upper table the lowest values for E, Y, and UTS and the highest values for elongation are for pure metals. Multiply gigapascals (GPa) by 145,000 to obtain pounds per square in. (psi), megapascals (MPa) by 145 to obtain psi.

Material Properties

Material Testing – Why ?

- Most parts are *formed* into various shapes by applying external forces to the work-piece by means of tools, dies, etc.
  - Example – Forging a turbine disk; extruding a tube; drawing a wire; etc.
- Deformation is through mechanical means – understanding of the material behavior to different types of loads is essential

Material Properties

Material Testing – Repercussions

- Optimum processes are different for different materials and the choice of manufacturing process is affected
- Processes can be directed to change the properties of materials, often by influencing the structure or state in the material
- Sequence of manufacturing processes must be chosen for any given material so that the desired properties will be reached at minimum cost

Material Testing – Repercussions

- Acceptability of the finished product – based on standardized tests for conformance to specifications
- Same tests must be employed during manufacturing to assure that the properties of the final product meet the specifications
- Mechanical tests are often supplemented by other "technological tests" to simulate conditions imposed on the materials during operation

Tests

- A most obvious property of manufactured products is that they have to support loads
- Accordingly, many tests are designed with this in mind and the specific aim of reproducing loading in service
- Standards are followed in each test for uniform conformance to specifications and test results

Material Properties

Tests

Application of Loads during tests

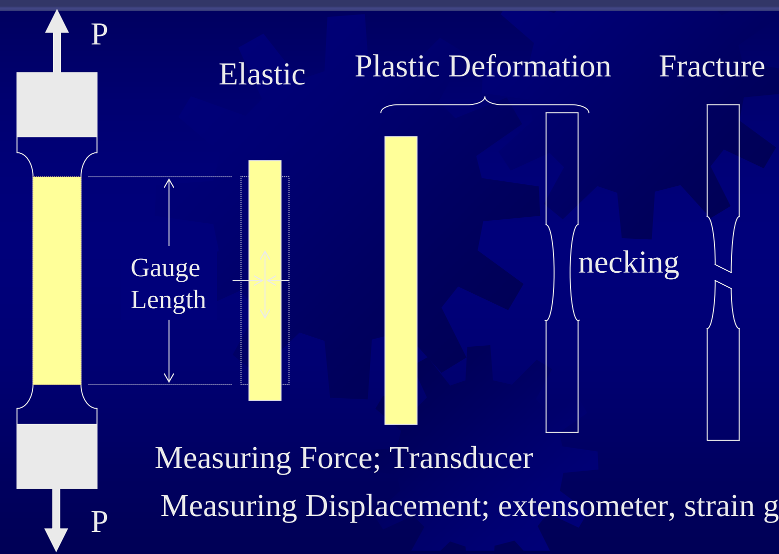
- May be static – constant or stationary
- May be dynamic – changing slowly or rapidly
  - including cyclic
- May be at different temperatures
- May be at controlled speeds of application
- May be under different pressures (vacuum)

Material Properties

Tension Test

- Most common for determining properties such as: Strength, Ductility, Toughness, Elastic Modulus and Strain Hardening
- Test requires preparation of a specimen as per the ASTM standards
- Typical: Gage Length: 50mm (2in) with a diameter of 12.5mm (0.5in)

Tensile Test



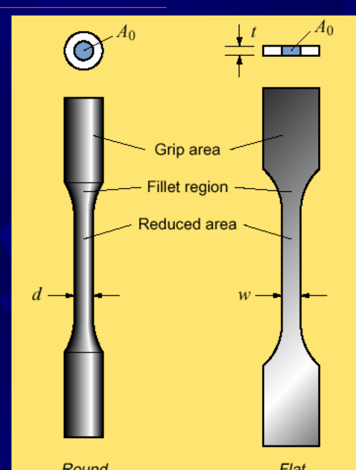
Measuring Force; Transducer

Measuring Displacement; extensometer, strain gauge

Material Properties

Stress

The uniaxial nominal or engineering stress ‘σ’ is defined as follows: $\sigma = F/A_0$

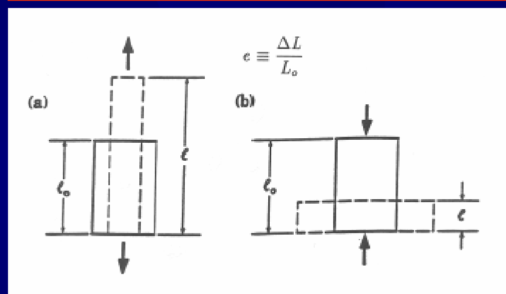


From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Material Properties

Strain

Tensile



Compressive

ΔL = Change in Length

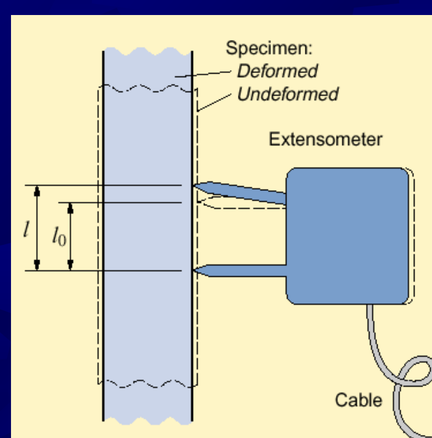
The uniaxial strain 'ε' is defined as follows:

$$\varepsilon = \Delta L / L_0$$

Material Properties

Strain

An *extensometer* is a displacement-measuring device that is attached directly to the specimen in its gage length, and is used to determine the axial strain



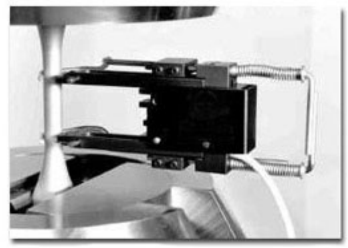
From Mechanical Behavior of Metals, James W. Phillips, University of Illinois at Urbana-Champaign, 1998

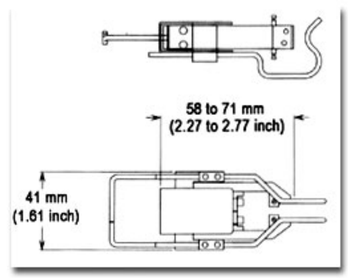
Material Properties

Strain

A general purpose n *extensometer* from Enduratec, Inc.

- full bridge strain gage design
- tension/compression
- DC excitation

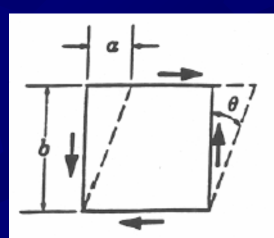




From www.enduratec.com

Material Properties

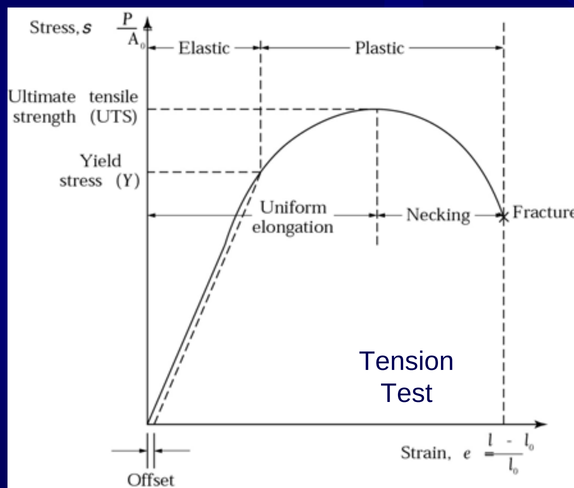
Shear Strain



For small change of angle shown, the shear strain ‘γ’ is defined as follows:

$$\gamma = a / b$$

Stress-Strain Curve

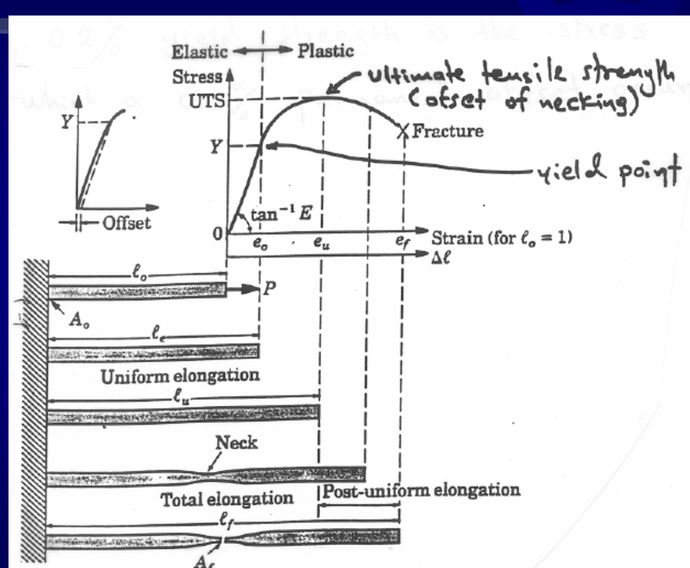


A typical stress-strain curve obtained from a tension test, showing various features

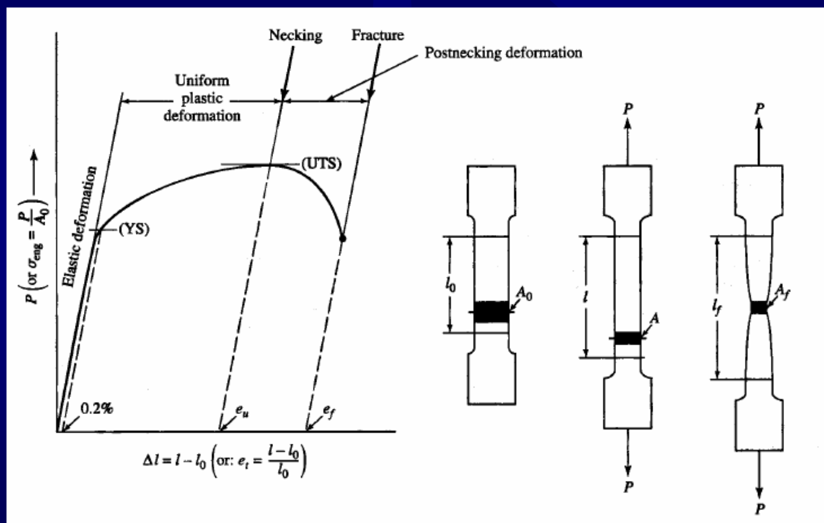
Sequence:

- Elastic Deformation
- Deforms Plastically
- Necking
- Failure

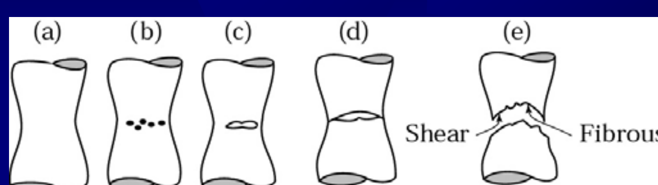
Stress-Strain Curve



Stress-Strain – Test Specimen



Fracture of a Tensile-Test Specimen



Sequence of events in necking and fracture of a tensile-test specimen: (a) early stage of necking; (b) small voids begin to form within the necked region; (c) voids coalesce, producing an internal crack; (d) the rest of the cross-section begins to fail at the periphery, by shearing; (e) the final fracture surfaces, known as cup- (top fracture surface) and cone- (bottom surface) fracture.

Ductile vs. Brittle Behavior

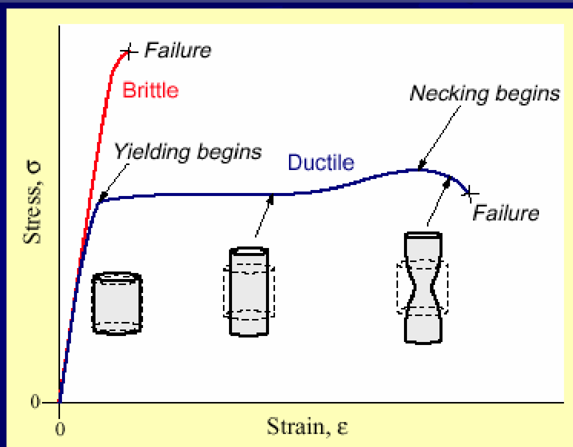
- For a *brittle* material, the stress–strain curve is “sort of” linear almost to failure

Glass, high-strength steels, and many polymers exhibit brittle behavior

- For a *ductile* material, there is an easily discernible *yield point* beyond which the stress grows very slowly (if at all) with strain

From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Ductile vs. Brittle Behavior



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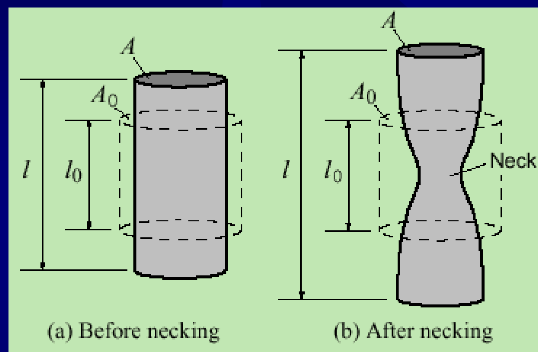
Ductile vs. Brittle Behavior

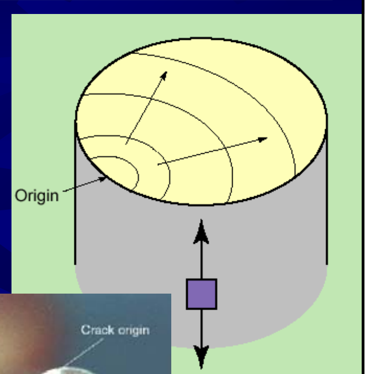


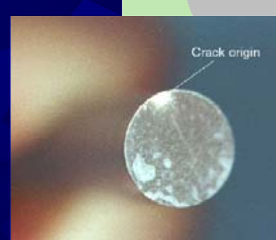
Ductile materials will often *neck* prior to failure. The necking begins when the *ultimate strength* has been reached, at which point the stress begins to decrease with increasing strain

From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Brittle Fracture

- Brittle fractures are characterized by a flat fracture surface perpendicular to the maximum principal normal stress direction
- The fracture originates at the surface, due to the presence of a suitable flaw, such as a scratch, machining mark, or crack

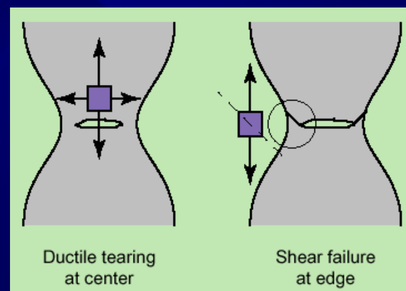




From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Ductile Fracture

- Ductile failures are often of the cup-and-cone type. Necking produces a triaxial state of stress that results in ductile tearing, starting at the *center* of the specimen.
- The fracture propagates outward.
- As it approaches the surface, the outside ring of unbroken material becomes loaded and may fail in shear along 45º surfaces.
- If this shear surface forms continuously around the specimen, then a cup forms on one side, and a cone on the other.



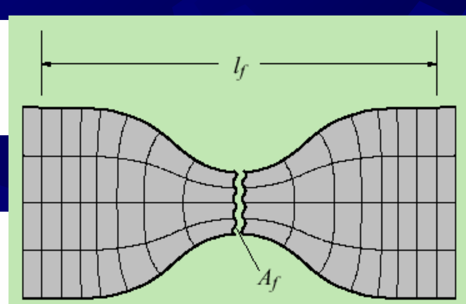
From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Measures of Ductility

Two measures of ductility are used: percent elongation and percent reduction of area

$$\%EL = \frac{l_f - l_0}{l_0} \times 100\% .$$

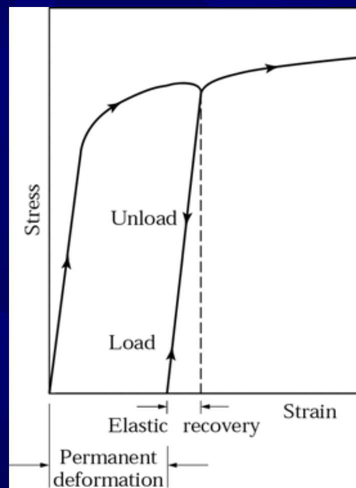
$$\%RA = \frac{A_0 - A_f}{A_0} \times 100\% .$$



From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Loading and Unloading of Tensile-Test Specimen

Schematic illustration of the loading and the unloading of a tensile- test specimen. Note that, during unloading, the curve follows a path parallel to the original elastic slope.

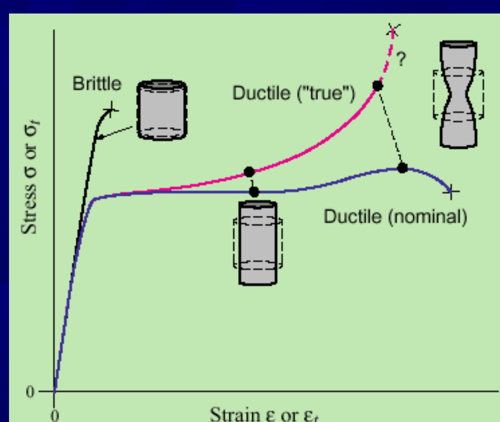


True Stress vs. Nominal Stress

True stress is defined as the load divided by the current area

$$\sigma_t = \frac{P}{A} = \frac{P}{A_0}\frac{A_0}{A} = \sigma(1+\varepsilon)$$

During tension test, when area is reduced during test, true stress is greater than nominal or engineering stress



From Mechanical Behavior of Metals, James W. Phillips, University of Illinois at Urbana-Champaign, 1998

True Strain

An expression for the so-called "true strain," which is based on the summation of incremental strains based on *current* length l, can also be found if the deformation is homogeneous and the axial strain is known

$$\varepsilon_t = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} = \ln(1+\varepsilon)$$

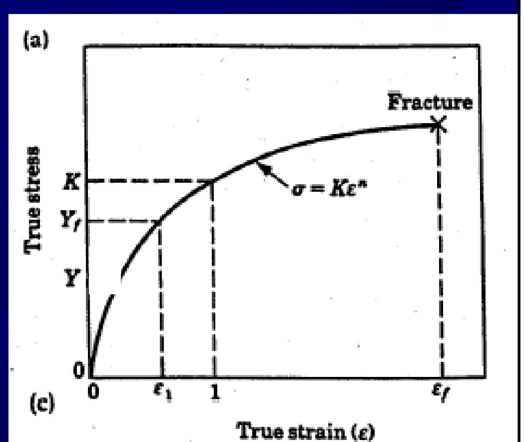
Remember that the formulas for "true stress" and "true strain" written in terms of the nominal strain are valid only when the deformation is homogeneous, that is, they are valid only up to the point at which necking begins. Thereafter, these formulas no longer apply.

From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

True Stress – True Strain Curve

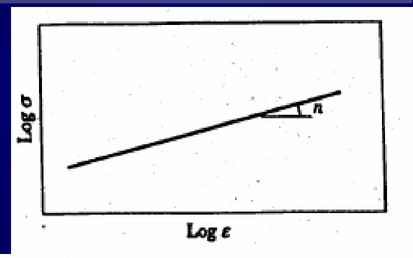
a) True stress-true strain curve in tension. Note that, unlike in an engineering stress-strain curve, the slope is always positive and that the slope decreases with increasing strain. The total curve can be approximated by the power law shown

Here 'Y' is the initial yield stress and 'Y_f' the flow stress of the material

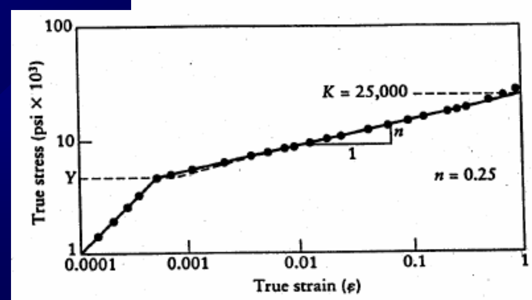


True Stress – True Strain Curve

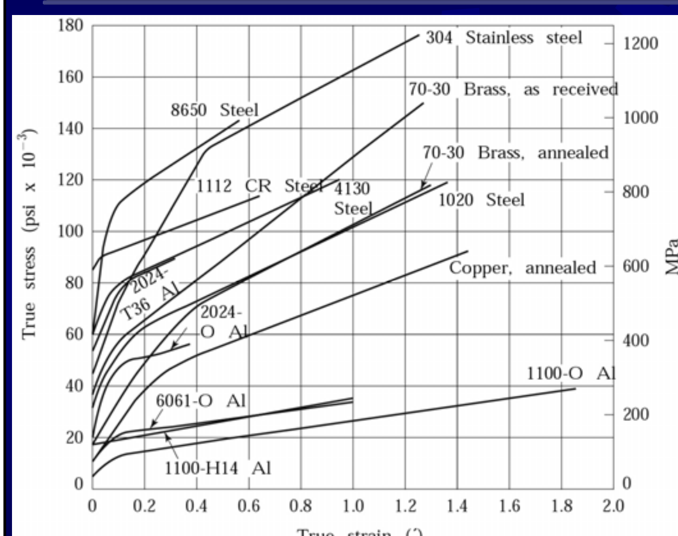
b) True stress-true strain on a log-log scale.



c) True stress-true strain curve in tension for 1100-0 aluminum plotted on a log-log scale (from S. Kalpakjian, Manufacturing Processes for Engr. Materials).



True Stress-True Strain Curves



True stress-true strain curves in tension at room temperature for various metals.

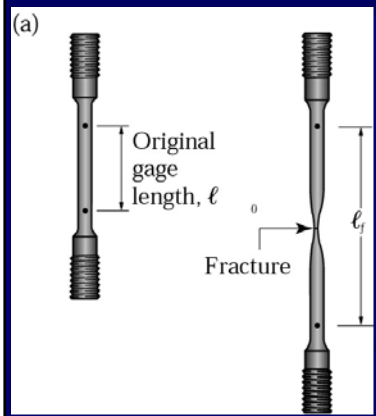
The curves start at a finite level of stress: The elastic regions have too steep a slope to be shown in this figure, and so each curve starts at the yield stress, *Y*, of the material.

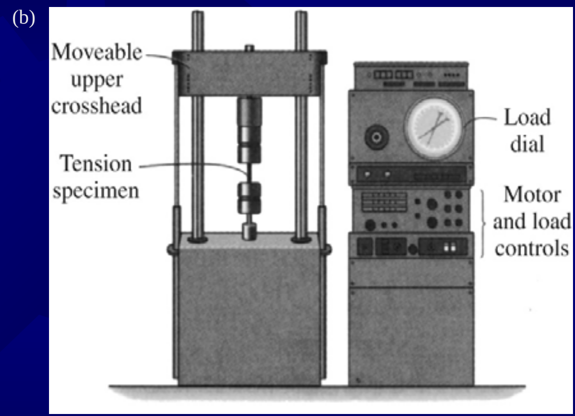
Material Properties

Tension Test

- Specimen is mounted between the jaws of the test machine
- Load is applied and measurement is taken in the elastic region – i.e., when load is removed, specimen comes back to its original length
- Load is then applied till it fails
- Stress, Strain is determined, based on which the Young's modulus is computed

Tensile-Test Specimen and Machine





(a) A standard tensile-test specimen before and after pulling, showing original and final gage lengths
(b) A typical tensile-testing machine

Materials in Manufacturing

Tension Test

Attaching an extensometer to the test specimen

Materials in Manufacturing

Tension Test

- Yield Strength – Force at which materials begin to yield and plastic deformation sets in
- Tensile Strength – Highest force that can be taken by the materials sample during the test (maximum stress)
- Modulus of Elasticity (E) – Also called Young's Modulus, gives a measure of the stiffness of the material. It is also the slope of the stress-strain curve
- Ductility – Measure of the amount of plastic deformation a material undergoes before fracture

Materials in Manufacturing

Tension Test

- Stress - Load / Area
- Strain - Change in Length / Original Length

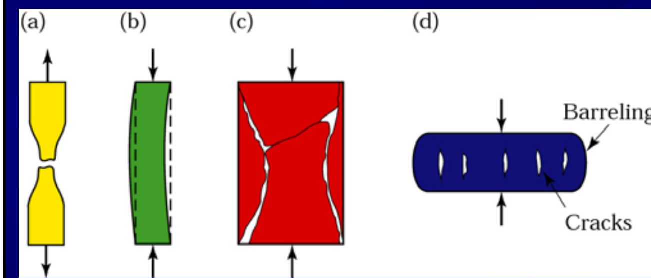
  normally given as a percentage in practice (x 100)
- Stress is proportional to Strain in the elastic region
- Constant of proportionality is the Modulus of Elasticity (E) or Young's Modulus
- In the elastic region, if load is removed, the specimen will return to its original length

Materials in Manufacturing

Tension Test

- Ductile Materials have the elastic and plastic range
- Almost all known metals are ductile in behavior
- Brittle Materials deform only elastically. Further increase in load causes failure
- Brittle behavior exhibits little or no elongation
- Some metals, ceramics, thermosetting polymers; deformation is minimal with some alloys as well

Failures of Materials and Fractures in Tension

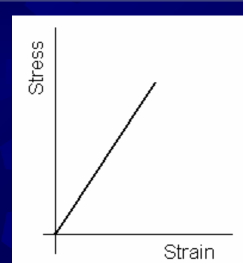


Schematic illustration of types of failures in materials:

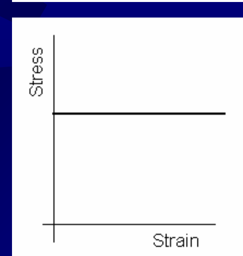
(a) necking and fracture of ductile materials;
(b) Buckling of ductile materials under a compressive load;
(c) fracture of brittle materials in compression;
(d) cracking on the barreled surface of ductile materials in compression.

Types of Stress-Strain Curves

- Perfectly Elastic – behaves like a spring with stiffness 'E.' Behavior of brittle materials like glass, ceramics, some cast irons, etc.

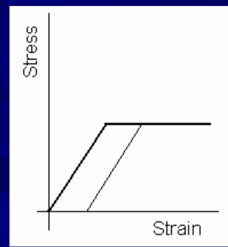


- Rigid, Perfectly Plastic – has by definition an infinite value of 'E.' After yield stress, it continues to undergo deformation at the same stress level. No elastic recovery after load is removed

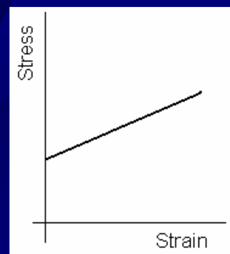


Types of Stress-Strain Curves

- Elastic, Perfectly Plastic – combination of the first two materials: finite modulus and elastic recovery when load is released

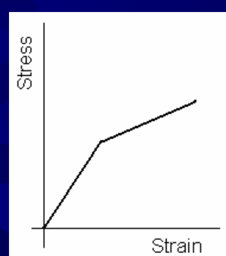


- Rigid, Linearly Strain-Hardening – requires an increasing stress level to undergo further strain; its "flow-stress" increases with increasing strain. No elastic recovery upon unloading

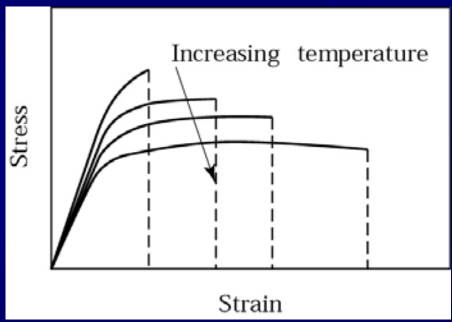


Types of Stress-Strain Curves

- Elastic, Linearly Strain-Hardening – an approximation of the behavior of most engineering materials



Temperature Effects on Stress-Strain Curves



Typical effects of temperature on stress-strain curves.

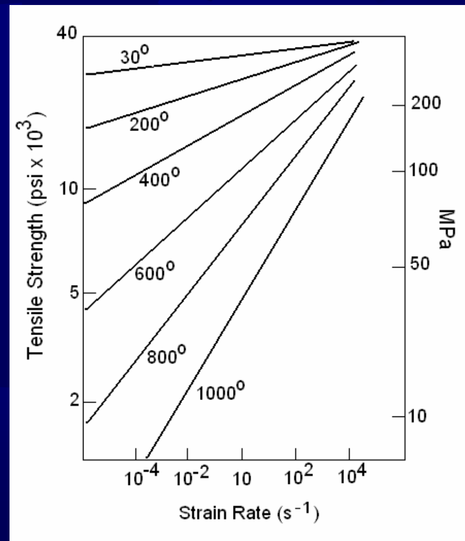
Note that temperature affects the modulus of elasticity, the yield stress, the ultimate tensile strength, and the toughness (area under the curve) of materials.

Effect of Strain Rate

- Depending upon the manufacturing operation and equipment, a piece of material may be formed at low speed or high speed
- Thus in a tension test, the specimen may be deformed at different rates
- Deformation Rate – speed at which the test is carried out
- Strain Rate, *e* – depends upon the geometry of the specimen and is defined as: v/l_0 ,
  - v – speed or rate of deformation
  - l_0 – initial length

Effect of Strain Rate

- Effect of Strain rate on Ultimate strength of Al
- As Temperature increases, the slope increases
- Tensile strength becomes more sensitive to strain rate as temperature increases



Materials in Manufacturing

Tension Test

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Materials in Manufacturing


Instron Tensile Testing Machine


Alwetron Tensile Testing Machine

Material Properties

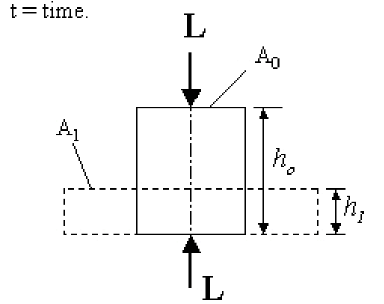
Compression Test

- Materials such as cast iron and concrete are weak in tension, but strong in compression
- Such materials are used for compressive loads
- Many operations in manufacturing processes (such as forging, rolling and extrusion) subject the work piece to compressive forces
- The Compression test, in which the specimen is subjected to compression loading gives useful information for these processes as well as for design

Material Properties

Compression Test

L = Load (Force) causing plastic deformation.
A_0, h_o = initial cross section and length
A_1, h_l = final cross section and length
A, h = instantaneous cross section and length
V = Die (Ram) velocity.
t = time.



Material Properties

Compression Test

- Can be performed on any suitable product to determine compression related parameters

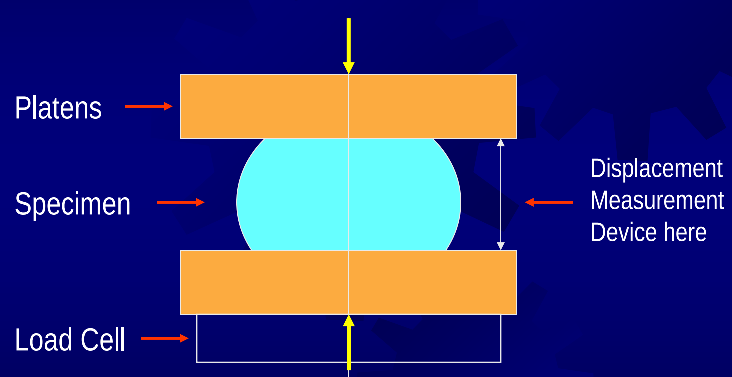
Material Properties

Compression Test

- In a typical test, a solid cylindrical specimen is pressed between two flat dies (platens)
- The cylindrical surface bulges (called barreling) because the friction between the platen and specimen prevents any expansion
- Barreling is caused by friction at die-specimen interfaces, which retards free flow of material
- Test is important in manufacturing applications such as metallic sheets, tubes, metal containers, rods and wires, etc.

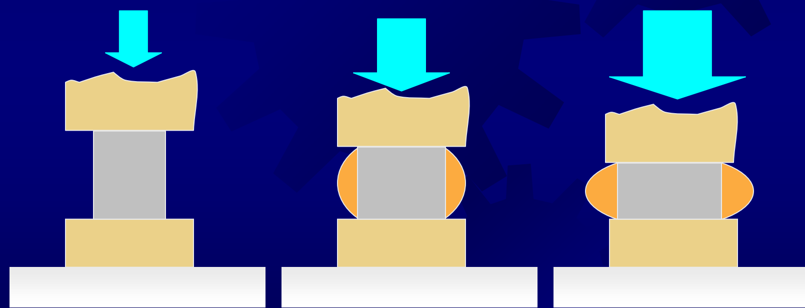
Material Properties

Compression Test - Schematic



Materials in Manufacturing

Compression Test – Barreling Effect



Materials in Manufacturing

Compression Test - Fracture

- Barreling in the presence of friction generates tensile stresses on the surface and cracks develop if ductility is limited
- Sooner or later, ductility is exhausted and fracture sets in
- Brittle materials fail suddenly on reaching a critical stress value

Materials in Manufacturing

Compression Test

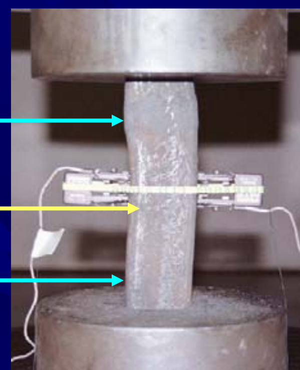
Test of a square mild steel bar

- Both barreling and buckling can be seen
- Engineering strain rate, $\dot{e}$, is given by

$$\dot{e} = v / h_o ,$$

v – speed of the die

h_o – original height of specimen



From Mechanical Behavior of Metals, James W. Phillips, University of Illinois at Urbana-Champaign, 1998

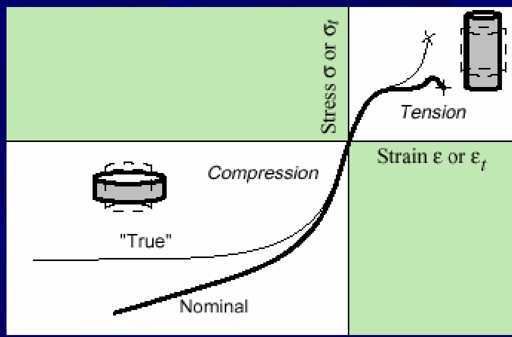
Material Properties

Compression Test

Materials in Manufacturing

Compression Test

Typically how the stress-strain curve varies in tension and compression

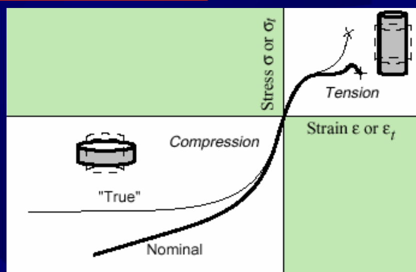


From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Materials in Manufacturing

Compression Test

- The behavior of a material in compression often differs from that of the same material in tension
- For ductile metals, it is often observed that failure will not occur in compression
- A striking example is cast iron, which is extremely brittle in tension but is very malleable in compression



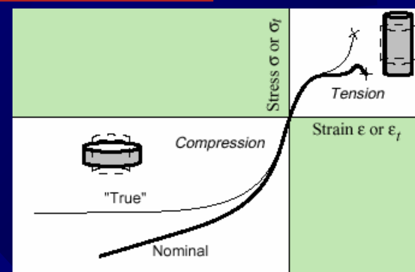
From Mechanical Behavior of Metals, James W. Phillips,University of Illinois at Urbana-Champaign, 1998

Materials in Manufacturing

Compression Test

Notice that in compression, the axial stress and strain are *negative* and therefore the stress–strain curve is correctly plotted in the third quadrant

For most materials that yield, the yield stress in compression is approximately equal to the yield stress in tension



From Mechanical Behavior of Metals, James W. Phillips, University of Illinois at Urbana-Champaign, 1998

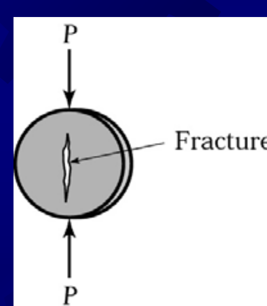
Materials in Manufacturing

Compression – Disk Test – Brittle Materials

- A disk is subjected to compression by placing between two flat platens
- Fractures in the middle of the disk and breaks in to two
- Stress can be computed using the formula:

$$\sigma = 2P/\pi.d.t$$

P – load at fracture; d – diameter; t - thickness



Material Properties

Torsion Test

- In addition to tension and compression, materials undergo shear strains as well
- Example – punching holes in sheet metal, metal cutting, etc.
- Test method generally used for determination of properties in shear is the Torsion test

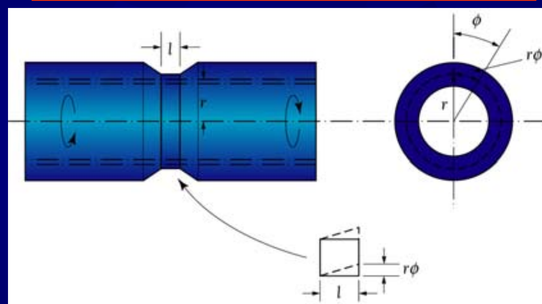
Material Properties

Torsion Test

- Specimen used has a reduced cross section in order to confine the failure to a narrow zone
- Tubular test specimens are normally used
- Shear stress and shear strains are calculated based on the load and the area of deformation and the thickness of the tube

Material Properties

Torsion Test



Stress: $\tau = T / 2\pi r^2 t$

Strain: $\gamma = r\phi / l$

Material Properties

Torsion Test

- In a typical test, the specimen is mounted between two heads of a testing machine and twisted
- The shear deformation is then calculated from the shear strain (which is based on the angle of twist, the radius and length of the test portion)
- Shear Modulus (or Modulus of Rigidity) G – is the ratio of the shear stress to the shear strain

$$G = \tau / \gamma$$

$$G = E / 2(1 + \nu)$$

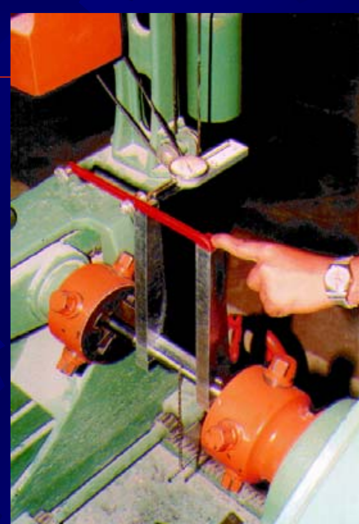
Material Properties

Usefulness of Torsion Test

- Torsion tests on solid round bars at high tempera-tures provide an estimate of forgeability of the metal
  - greater the number of twists before failure, better the forgeability
- Effect of compressive stresses on shear strain – benefits of a compressive environment on the ductility of materials (useful in cutting)

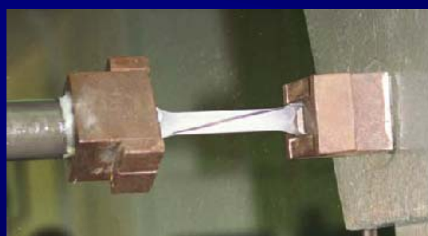
Material Properties

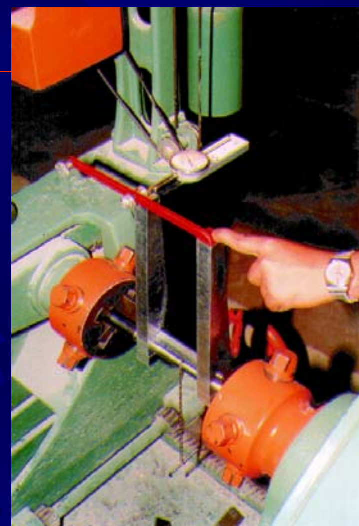
Torsion Test



Material Properties

Torsion Test





Material Properties

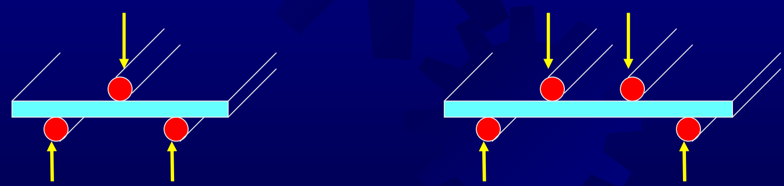
Torsion Test of Reinforced Plastic

Failure

Material Properties

Bend or Flexure Test

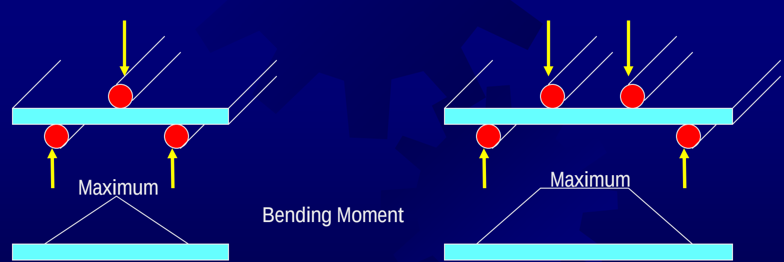
- Commonly used test for Brittle Materials
- Involves a specimen with rectangular cross section supported at its ends
- Load applied vertically, at one or two points – hence referred to as three-point or four-point bending



Material Properties

Bend or Flexure Test

- Stresses are tensile at bottom and compression on top surface. Calculated using beam equations.
- Stress at fracture in bending is known as "Modulus of Rupture"



Bend or Flexure Test

- Modulus of Rupture is given by:

$$\sigma = Mc / I$$

M – bending moment
c – half specimen depth
I – Moment of inertia of cross section

Bend or Flexure Test

- Bend testing is conducted on standard materials, welded materials, and full size parts
- Specimens are tested using various diameter mandrels, as well as different angles of bending, according to customer or specification requirements.

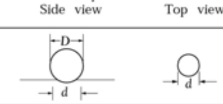
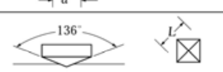
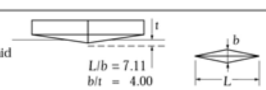
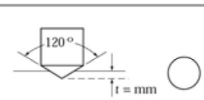
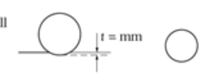
Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Hardness Test

- Hardness is a measure of a material's resistance to indentation or localized deformation
- Provides a general indication of a material's strength as well as its resistance to scratching and wear
- Steel is harder than Al, and so on. The resistance to indentation depends upon the shape of the indentor and the load applied

Hardness Tests

Test	Indenter	Shape of indentation: Side view / Top view	Load, P	Hardness number
Brinell	10-mm steel or tungsten carbide ball		500 kg 1500 kg 3000 kg	$HB = \frac{2P}{(\pi D)(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid		1-120 kg	$HV = \frac{1.854P}{L^2}$
Knoop	Diamond pyramid		25g-5kg	$HK = \frac{14.2P}{L^2}$
Rockwell A, C, D	Diamond cone		kg 60 150 100	HRA, HRC, HRD $= 100 - 500t$
Rockwell B, F, G	$\frac{1}{16}$ in. diameter steel ball		100 60 150	HRB, HRF, HRG $= 130 - 500t$
Rockwell E	$\frac{1}{8}$ in. diameter steel ball		100	HRE $= 130 - 500t$

General characteristics of hardness-testing methods and formulas for calculating hardness. The quantity P is the load applied. *Source*: H. W. Hayden, et al., *The Structure and Properties of Materials*, Vol. III (John Wiley & Sons, 1965).

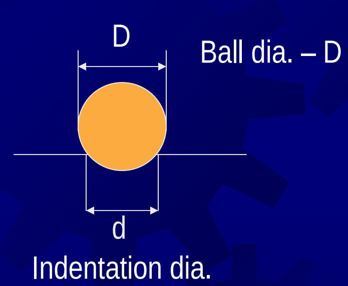
Material Properties

Brinell Hardness Test

- The earliest, introduced around 1900
- Involves pressing a ball against a prepared surface of the specimen
- Uses a 10mm dia. Tungsten-Carbide ball to make the indent and standard loads between 500 to 3000 kg
- The Brinell Hardness Number (HB) is defined as the ratio of the load to the curved surface area of the indentation
- Harder the material, smaller the indentation (!)

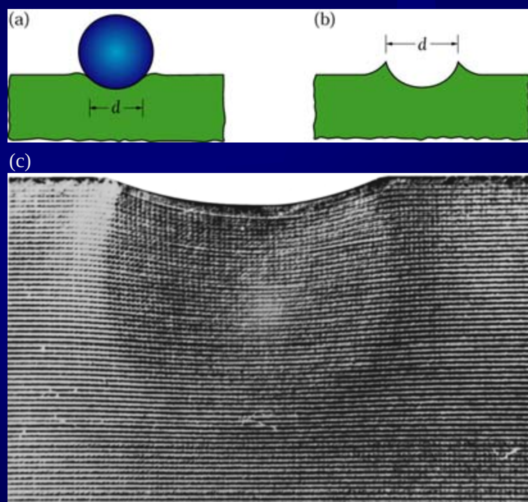
Material Properties

Brinell Hardness Test



$$HB = 2P / (\pi D)[D - (D^2 - d^2)^{1/2}] \text{ kg/mm}^2$$

Brinell Testing



Indentation geometry in Brinell testing:
(a) annealed metal
(b) work-hardened metal
(c) deformation of mild steel under a spherical indenter

Note that the depth of the permanently deformed zone is about one order of magnitude larger than the depth of indentation. For a hardness test to be valid, this zone should be fully developed in the material. *Source*: M. C. Shaw and C. T. Yang.

Material Properties

Rockwell Hardness Test

- Most common, introduced in 1922
- The test measures the depth of penetration rather than the diameter of the indent
- The indentor is first pressed with a smaller load and then with a larger load. The difference in the indentation between the two loads gives an indication of the hardness of the material
- Numerous scales to test a full range of materials from soft to hard (A,C,D – Diamond cone; B,F,G – 1/16” dia ball)

Material Properties

Rockwell Hardness Test

Rockwell Test

Material Properties

Rockwell Hardness Testing Machine

Test Samples

Brinell Hardness Testing Machine

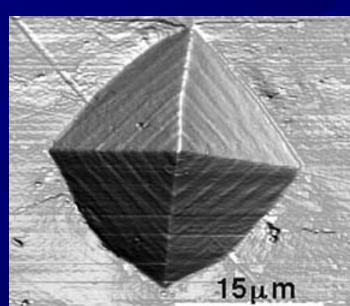
Material Properties

Vickers Hardness Test

- This test utilizes smaller loads and a small diamond tip
- Load ranges from 1kg to 120kg
- Impressions are typically less than 0.5mm depth
- Microscope used to measure the size of the indent made on the sample

Materials in Manufacturing

Hardness Test



Nanoindent (Vickers indenter)

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Mohs Hardness Test

- Developed in 1822, this test is based on the capability of one material to scratch another
- The Mohs Hardness scale is based on a number from 1 to 10, with 1 for talc and 10 for diamond
- A material with a higher Mohs number will scratch one with a lower Mohs number
- Soft metals – 2 to 3; Hardened steels – around 6; Al Oxide (abrasive and cutting tools) 9
- Used mainly by minerologists

Material Properties

Knoop Hardness Test

- Micro-hardness test – Knoop Test This test utilizes much smaller loads
- The Knoop Test utilizes an "elongated" pyramid tip
- Load ranges from 25g to 5kg
- Impressions are typically between 0.01mm to 0.1mm depth
- Microscope used to measure the size of the indent made on the sample

Material Properties

Other Hardness Tests

- Scleroscope – Portable instrument with a diamond tipped indenter (hammer)
  - dropped on the surface of specimen from a fixed height
  - hardness is determined from rebound of the indenter
  - indent is small; used for hardness of large objects
- Durometer – Instrument used for hardness of rubbers, plastics, and similar soft elastic materials
  - indenter with constant load; depth measured after one second
  - hardness is inversely proportional to depth

Material Properties

Specimens – for Hardness Measurement

Risø National Laboratory
Frederiksborgvej 399, P.O. 49, DK-4000 Roskilde

Material Properties

Fatigue

- Various structures and components in manufacturing operation, such as tools, dies, gears, cams, springs, shafts, etc., are subject top rapidly fluctuating (cyclic or periodic) loads, in addition to static loads
- Cyclic Stresses may be caused by these fluctuating mechanical loads on gears
- Thermal stresses may be induced on a die (cool die coming in contact with hot work-pieces)

Material Properties

Fatigue

- Under such circumstances, the part or component will fail at a stress level below that at which failure would occur under static loading
- This phenomenon is called “Fatigue Failure” and is responsible for the majority of failures in mechanical components

Material Properties

Fatigue

- Fatigue is the result of cumulative damage, caused by stresses much lower than the tensile strength of the material
- Fatigue failure begins with the formation of small cracks (invisible to the naked eye) which then propagate on repeated loading until brittle fracture occurs (or the remaining cross section area is unable to take the load)

Material Properties

Fatigue Tests

- Test methods involve testing specimens under various states of stress, usually in a combination of tension and compression in torsion
- Carried out at Various Stress Amplitudes (S) and Number of Cycles (N) it takes for the specimen to fail is noted
  - Stress amplitude – maximum stress in tension and compression to which the specimen is subjected

Material Properties

Fatigue Tests

Test Set-up – Axial

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Fatigue Tests

- Maximum Stress to which a material can be subjected to, without fatigue failure, regardless of number of cycles, is called the “Endurance Limit” or “Fatigue Limit”
- Although many metals have a definite endurance limit, aluminum alloys do not have one !
- For such metals, the fatigue strength is specified at a certain number of cycles

S-N Curves

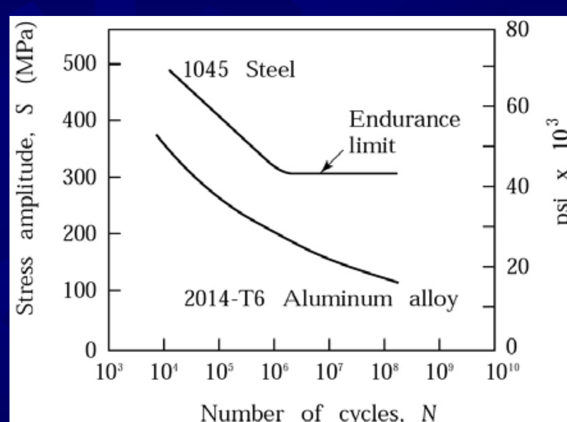
- Shows the stress level 'S' as a function of the number of cycles to failure 'N'
- For steel, curve level off after N = 10^6 cycles.
- There is a fatigue limit or endurance limit, denoted by 'S'
- Fatigue limit can be calculated based on reliability, size, and surface finish
- An idea on number of cycles:

  N = 5000 rpm * 60 min/hr * 24 hr/day * 365 days/yr *10 years = 26 * 10^9 cycles

S-N Curves

Typical *S-N* curves for two metals

Note that, unlike steel, aluminum does not have an endurance limit



Material Properties

Fatigue Tests

Test
Specimens

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Fatigue Tests

Specimens – Before & After
Fatigue Test

Risø National Laboratory
Frederiksborgvej 399, P.O. 49, DK-4000 Roskilde

Material Properties

Fatigue Tests

Specimens – Stress & Deformation Tests

- Regular Leaf Spring and
- Polymer Composite Leaf Spring

Risø National Laboratory
Frederiksborgvej 399, P.O. 49, DK-4000 Roskilde

Materials in Manufacturing

Fatigue Test

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Creep

- Creep is the permanent elongation of a component under a static load, over a period of time
- Phenomenon of metals and certain non-metals (such as plastics and rubbers) and it can occur at any temperature.

  Best example is Lead – which creeps under tensile load at room temperature itself !
- Especially important at high temperature applications – turbine blades, jet engines, etc.

Material Properties

Creep

- Creep/stress rupture tests are conducted at temperatures up to +2200°F to either ASTM E139 (creep and smooth-bar stress rupture) or ASTM E292 (notch tests)
- Temperature and creep readings are recorded by computers and continuously monitored to ensure utmost accuracy
- Specimens fail by necking and fracture as in a tension test – called "rupture" or "creep rupture"
- Strain can also be measured by attaching strain gages to the specimen

Material Properties

Creep

- Stress and creep rupture tests are also conducted in various environments under vacuum or inert atmospheric conditions. Maximum temperature for these tests is in excess of +1700°F
- Tests are usually performed on materials that exhibit excessive corrosion at elevated temperatures in regular atmospheric environment
- A section of the creep test specimen can also be strain-gaged to measure the amount of strain during test

Materials in Manufacturing

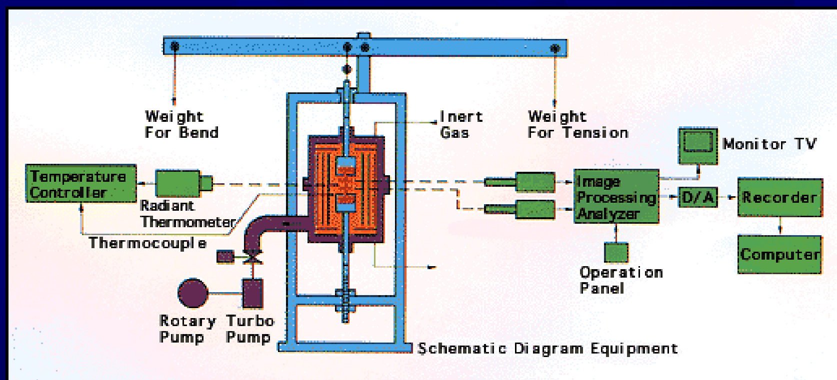
Creep testing machines

- Creep testing machines for tensile, compressive or bending in vacuum, inert gas or open air
- Creep deformation is measured by using special devised closed circuit camera
- Temperature is measured by thermocouple and infrared radiation thermometer.
- Loading capacity is 3 ton maximum.

Japan Ultra-high Temperature Materials Research Center/Research Institute

Material Properties

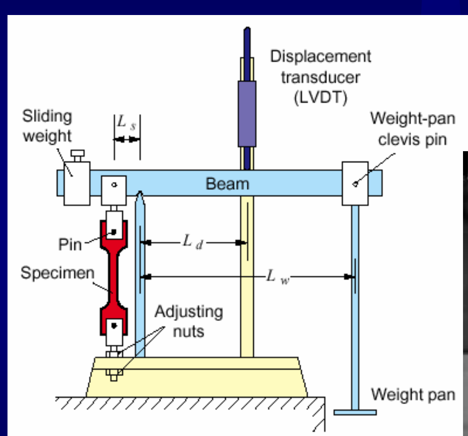
Creep



Japan Ultra-high Temperature Materials Research Center/Research Institute

Material Properties

Creep

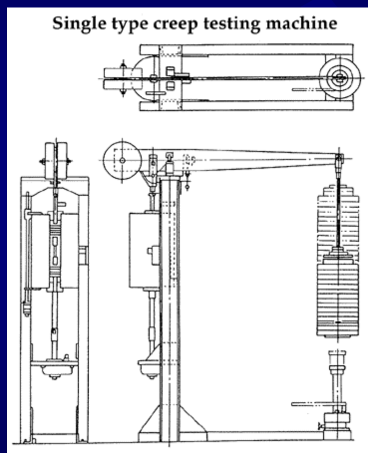


Dead weight Creep Machine

Specimen undergoing Creep in tension

Material Properties

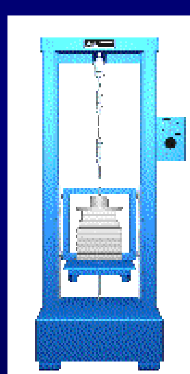
Creep



National Research Institute
Ibaraki, Japan

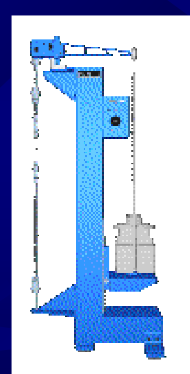
Material Properties

Creep



Direct Loading

Lever Arm Loading



From: Applied Test Systems, Butler, PA

Material Properties

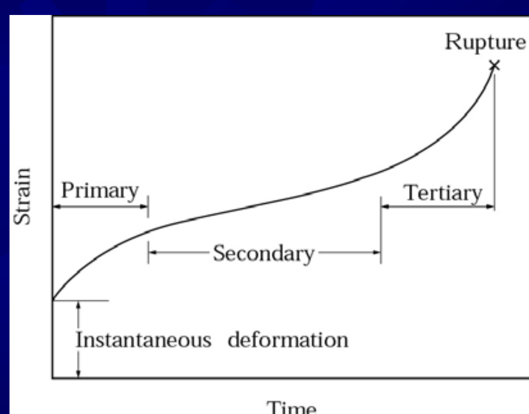
Creep Test

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Creep Curve

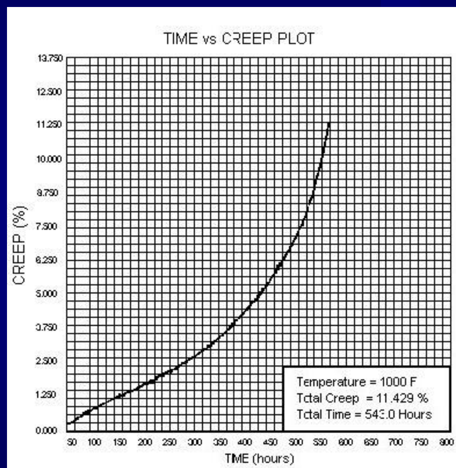
Schematic illustration of a typical creep curve.

The linear segment of the curve (secondary) is used in designing components for a specific creep life.



Material Properties

Creep

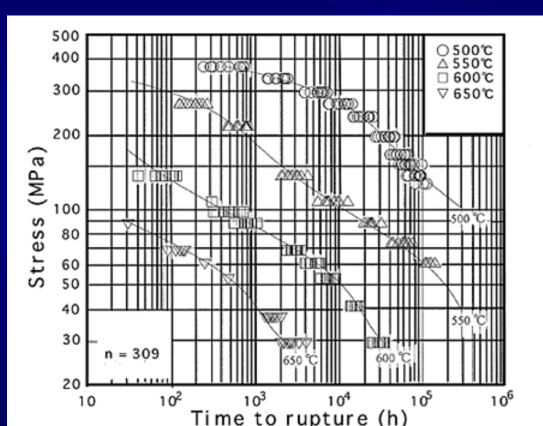


An actual plot of creep vs. time

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Creep



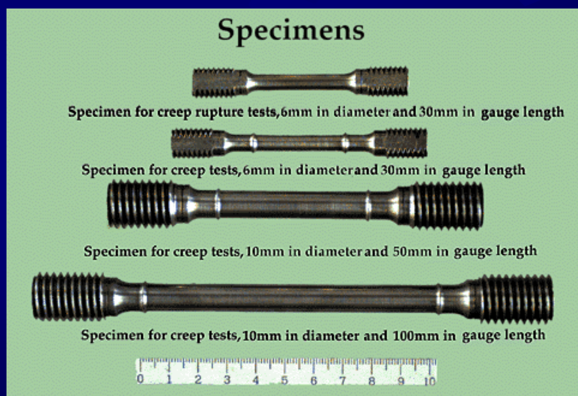
Creep Rupture Data –

variation with stress and temperature

National Research Institute Ibaraki, Japan

Material Properties

Creep



Creep Test Specimens

National Research Institute
Ibaraki, Japan

Material Properties

Creep

Bank of Creep Testing Machines

Westmoreland Mechanical Testing & Research, Inc.,
Youngstown, PA

Material Properties

Impact

- In many manufacturing operations, materials are subject to impact loading – drop forging is one such example
- Toughness – The ability of the material to withstand an Impact

Material Properties

Impact

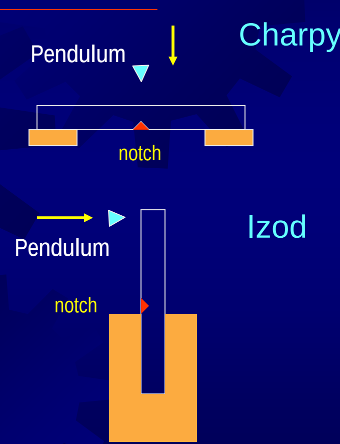
- Materials that have high impact resistance are generally those that have higher strength and ductility and hence high toughness
- Sensitivity to surface defects (called Notch Sensitivity) is also important because it significantly lowers impact toughness

Impact Test

- Typical Impact test consists of placing a notched specimen in an impact tester and breaking it with a swinging pendulum
- Measures the amount of energy absorbed by the material from a sudden intense “blow”
- Used to evaluate the “Brittleness” property

Charpy & Izod Impact Tests

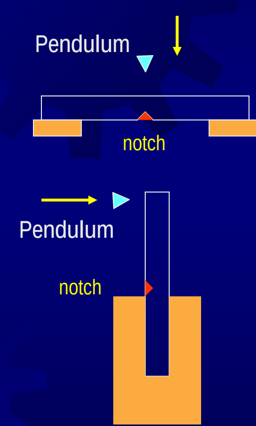
- In the Charpy test, the specimen is supported at both ends
- In the Izod test, it is supported at one end like a cantilever beam



Material Properties

Charpy & Izod Impact Tests

- From the amount of swing of the pendulum, the energy dissipated in breaking the specimen can be obtained
- This energy is the Impact Toughness of the material
- Particularly useful in determining the ductile-brittle transition temperature of materials



Material Properties

Charpy & Izod Impact Tests

Izod test

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA

Material Properties

Charpy Test

Westmoreland Mechanical Testing & Research, Inc., Youngstown, PA