بسم الله الرحمن الرحيم

Benha University
Shoubra Faculty of Engineering

Energy & sustainable energy Dep.
1st year

04.04.2019 – Week 8

Introduction to Materials Tests

Dr. Mahmoud Khedr

Outline

- Why Material Failure
- Introduction to mechanical fundamentals
- Testing machines
- Strain gauges
- Materials Characterization via microscopes
- Materials classification, mechanical definitions & loading types
- Ductile & Brittle Failure

Material Property

Property	Tests
Hardness	Micro/Macro hardness tests
Strength Ductility (elongation, area of reduction)	Tension tests
Creep (elevated-temperature strength)	Creep tests
Torsion	Torsion tests
Toughness (resistance to failure)	Impact tests Fracture toughness tests
Fatigue	S-N fatigue tests Fatigue crack growth tests

Why Material Failure

Seven of the Liberty ships built during the world war II has broken completely in two as a result of brittle fractures.

•Over 1000 of approximately 5000 merchant ships built during World War II had developed cracks of considerable size by 1946.

Why Material Failure

The bridge building industry did not pay particular attention to the possibility of brittle failure until the failure of Point Pleasant bridge in 1967.

The bridge collapsed without warning, costing 46 lives.

INTRODUCTION to mechanical fundamentals

- **1-1. Scope of materials testing**

The current course is concerned primarily with the response of metals to forces or loads. It is a combination of many disciplines and many approaches to the problem of understanding the response of materials to forces. On the one hand is the approach used in reference to strength of materials and in the theories of elasticity and plasticity, where a metal is considered to be a homogeneous material whose mechanical behavior can be rather precisely described on the basis of only a very few material constants. This approach is the basis for the rational design of structural members and machine parts.

INTRODUCTION to mechanical fundamentals

- **1-2. Strength of Materials—Basic Assumptions**

The internal resisting forces are usually expressed by the stress (*is defined as force per unit area "**σ**". The companion term strain "**ε**" is defined as the change in length per unit length. More complete definitions will be given later.*) acting over a certain area, so that the internal force is the integral of the stress times the differential area over which it acts. In order to evaluate this integral, it is necessary to know the distribution of the stress over the area of the cutting plane. The stress distribution is arrived at by observing and measuring the strain distribution in the member, since stress cannot be physically measured.

INTRODUCTION to mechanical fundamentals

- **1-3. Elastic and Plastic Behavior**

Experience shows that all solid materials can be deformed when subjected to external load. It is further found that up to certain limiting loads a solid will recover its original dimensions when the load is removed.

The recovery of the original dimensions of a deformed body when the load is removed is known as elastic behavior. The limiting load beyond which the material no longer behaves elastically is the elastic limit. If the elastic limit is exceeded, the body will experience a permanent set or deformation when the load is removed. A body which is permanently deformed is said to have undergone plastic deformation.

INTRODUCTION to mechanical fundamentals

- **1-4. Average Stress and Strain**

σ = P/A.

ε = δ/Lo.

E = σ/ε = Constant. The constant **E** is the modulus of elasticity, or Young's modulus.

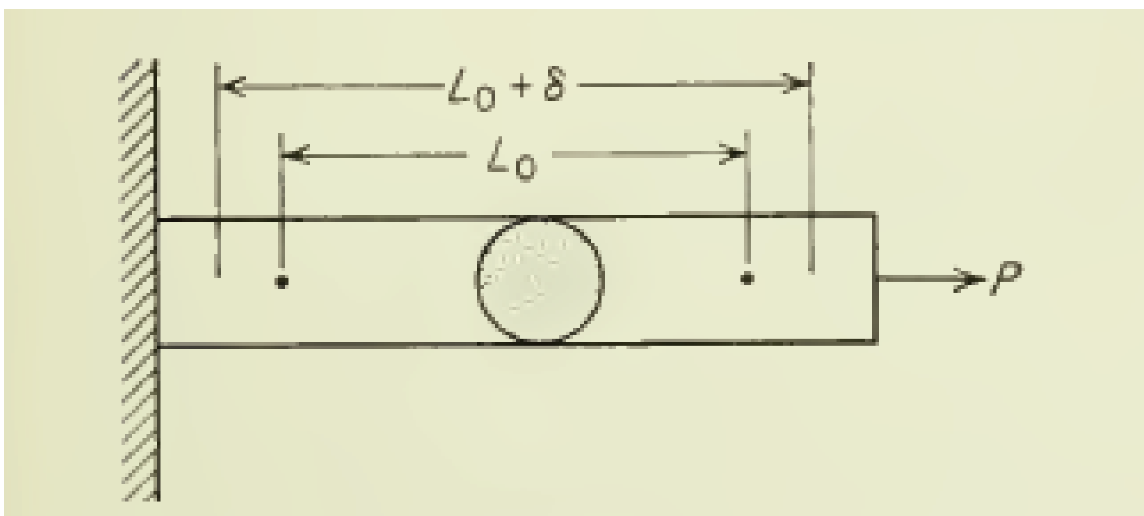


Fig. 1-1. Cylindrical bar subjected to axial load.

INTRODUCTION to mechanical fundamentals

- **1-5. What Constitutes Failure?**

Structural members and machine elements can fail to perform their intended functions in three general ways:

1. Excessive elastic deformation; **buckling.**
2. Yielding, or excessive plastic deformation; **creep.**
3. Fracture; **Fatigue, presence of hydrogen**.

- **Factor of safety**.

Benha University
Shoubra Faculty of Engineering

Energy & sustainable energy Dep.
1st year

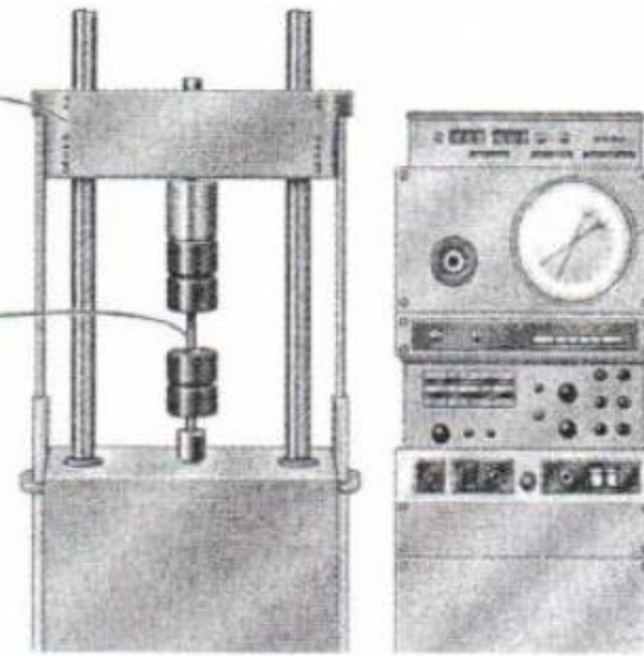
04.04.2019 – Week 8

Testing machines

Dr. Mahmoud Khedr

Testing Machines

1. The mechanical properties of materials used in engineering are determined by experiments performed on small specimens.
2. These experiments are conducted in laboratories equipped with testing machines.



Hydraulic Universal Testing Machine

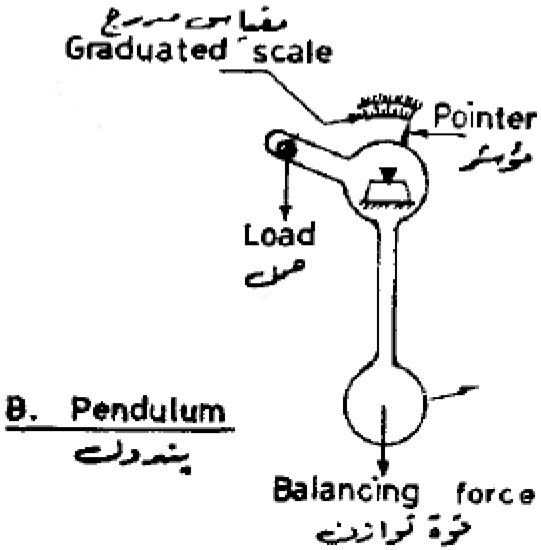
Testing Machines

Hydraulic Universal Testing Machines consist of two major portions:

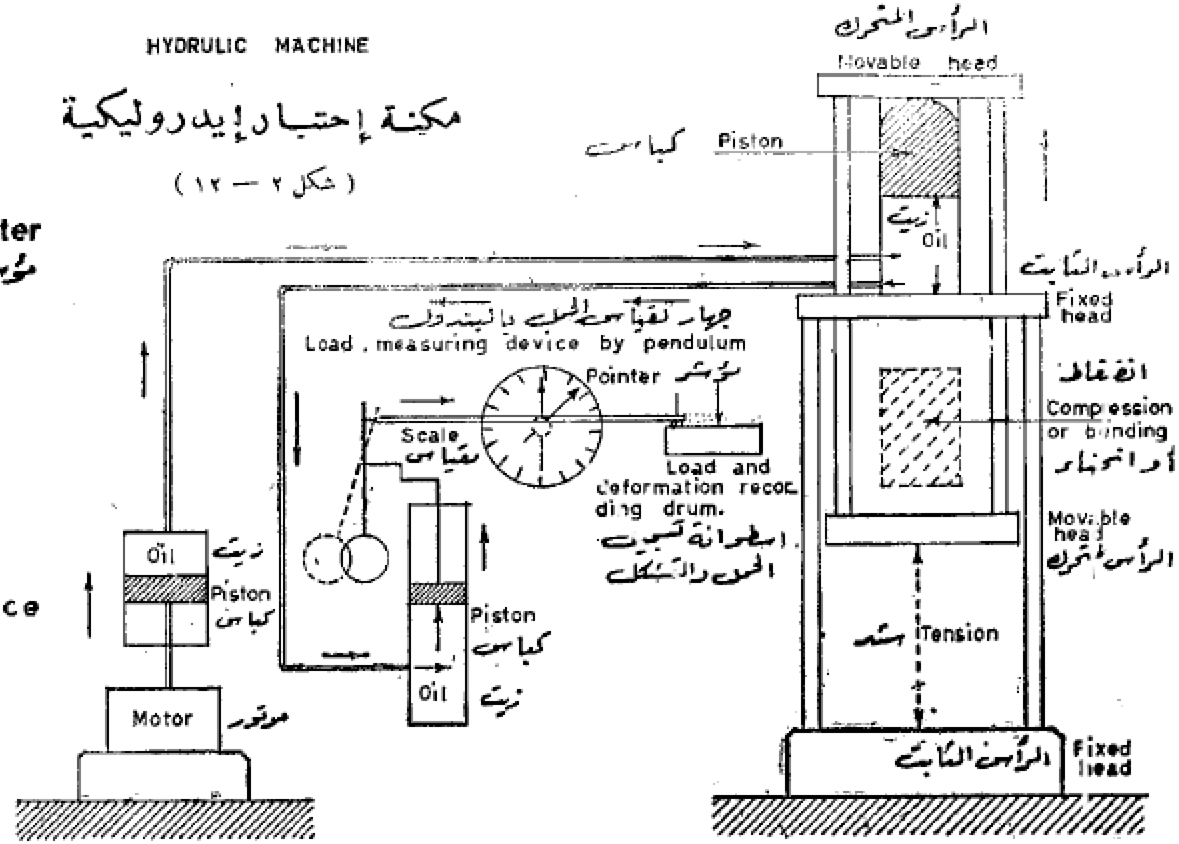
1. ***Loading part:*** It consists of fixed head "that does not move" and a movable head that moves using hydraulic oil pressure works on electric power. The oil pressure forces the movable jaw to move in gradual and easy-to-control motion. The test specimen is attached to both heads using either hydraulic or mechanical jaws. Depending upon the direction of motion of the movable head and the location of the test specimen, the specimen is subjected to tensile, compressive or bending stresses.

2. ***Load balancing and measuring part:*** This part consists of a pendulum where the oil pressure is exerting a fore on the pendulum that forces it to rotate around a pin all the way up until it reaches a balance state. Depending on the weight and length of the pendulum, the maximum capacity "maximum applied load " of the machine is changed. The pendulum method happens instantaneously giving the load value directly on the machine grading.

Testing Machines



Pendulum load balancing system



Schematic for a universal testing machine

Testing Machines

Advantages of "Hydraulic Universal Testing Machines":

1. ***Easy and quick load application*** with accurate control in loading rate by simply controlling the speed of movement of the moving cross head. This is carried out by controlling the speed of oil entering the cylinder.
2. ***Free of vibrations*** and noise.

Disadvantages of "Hydraulic Universal Testing Machines":

1. ***Frequent maintencne*** It requires frequent maintenance for oil change. If air bubbles enter the oil circuit may cause lose of oil pressure.

Testing Machines

Requirement in the “Hydraulic Universal Testing Machines”:

1. ***Accuracy:*** The machine should be accurate in measuring the applied load on the specimen with an accuracy of +1% of the value of the actual load applied on the specimen at any time.

2. ***Sensetivity:*** The machine should be sensitive to register small changes in the applied load of no less that 0.05% of the maximum capacity of the testing machine.

3. ***No Rocking***, No ***Rolling*** and no ***Twisting***: the machine should be free of these three action so that the state of the applied load is not altered.

4. No heavy vibrations or jerking motion.

5. Load is applied gradually, rate of loading could be controlled easily, with no sudden movements.

Benha University
Shoubra Faculty of Engineering

Energy & sustainable energy Dep.
1st year

04.04.2019 – Week 8

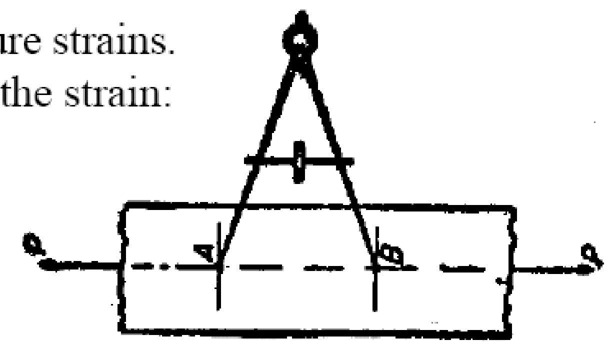
Strain gauges

Dr. Mahmoud Khedr

Strain gauges

1. Strain gauges are devices to measure deformation or linear strains for a definite length of the test specimen named a *gauge length*.
2. Some devices may measure deformation, others may measure strains.
3. The observed *deformation per unit of length* of the gage as the strain:

$$\varepsilon = \frac{\Delta L}{L_0}$$



Gauge Length

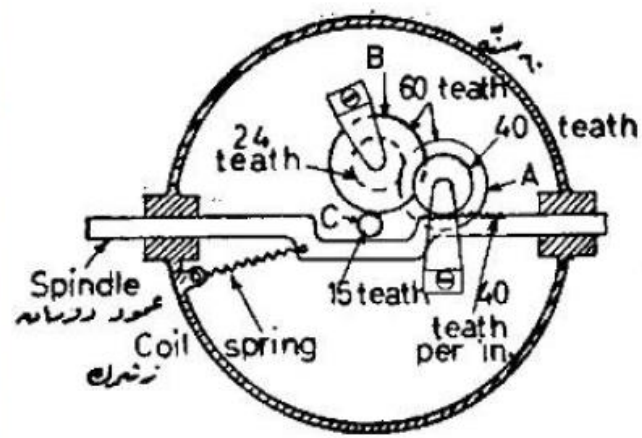
4. Strain is a *dimensionless* quantity. but it is customary to refer to it as a having the dimension of mm/ mm or mm/m (millie-strain or μm/m (micro-strain).
5. Deformation in specimens under loading is extremely small and can not be measured accurately unless they are ***magnified***.
6. If the magnification method is done mechanically then strain gauges are called *mechanical strain gauges*.
7. If the magnification method is electrically done then strain gauges are called *electrical strain gauges.*

Mechanical strain gauges

Mechanical strain gauges may use either:

1. ***Dial Strain Gauges:*** It uses gears with different teeth number.

2. Extensio-metre: It uses gears an arms.

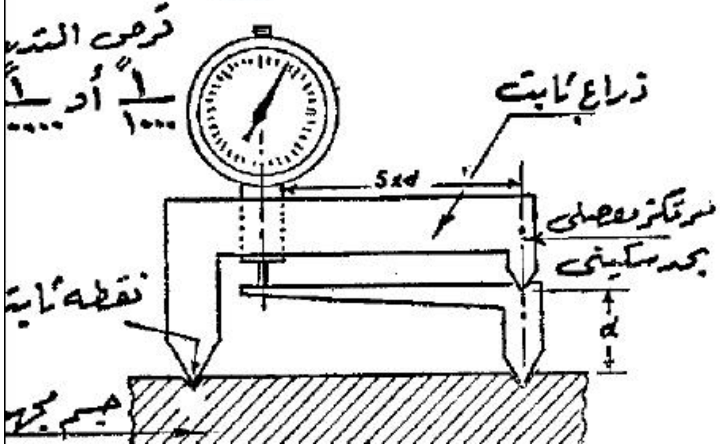


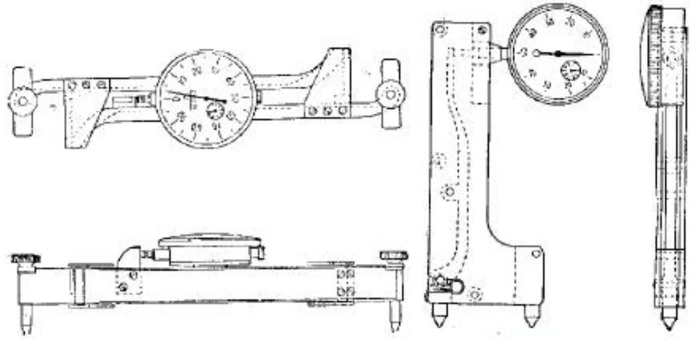
TYPICAL DIAL_ INDICATOR MECHANISM

Mechanical strain gauges

Mechanical strain gauges may use either:

1. Dial Strain Gauges: It uses gears with different teeth number.
2. **Extensiometre:** It uses gears an arms.





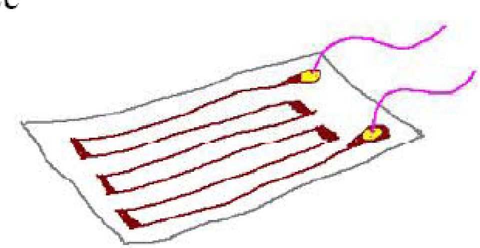
Electrical strain gauges

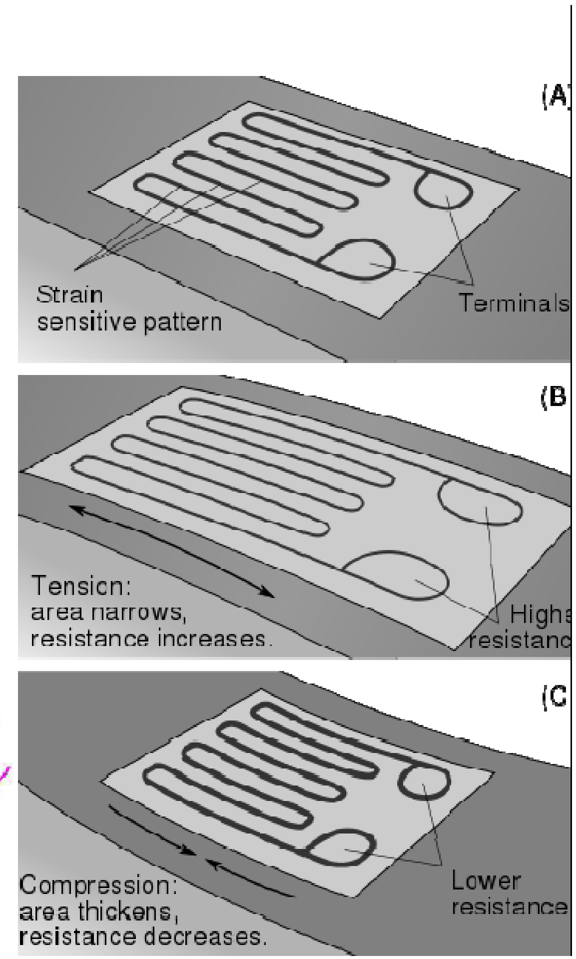
An ***electrical strain gauge*** is a device used to measure the strain of an object.
The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is ***glued*** to the object by a suitable adhesive. As the object is deformed, the foil is deformed, causing its ***electrical resistance to change***. This resistance change, usually measured using a ***Wheatstone bridge***, is related to the strain by the quantity known as the gauge factor.
The gauge factor *GF* is defined as:

$$GF = \frac{\Delta R/R}{\varepsilon}$$

where

ΔR	is the change in resistance caused by strain,
R_G	is the resistance of the un-deformed gauge, and
ε	is strain.





Benha University
Shoubra Faculty of Engineering

Energy & sustainable energy Dep.
1st year

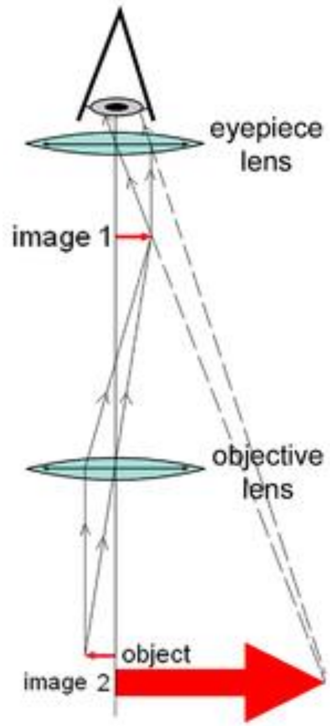
04.04.2019 – Week 8

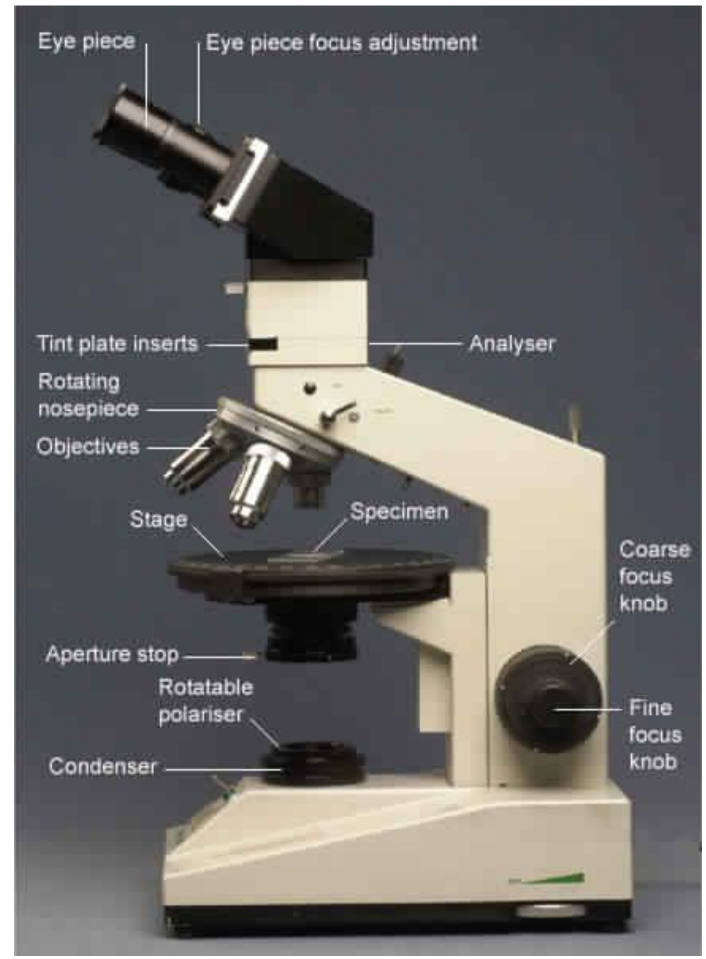
Materials Characterization

Dr. Mahmoud Khedr

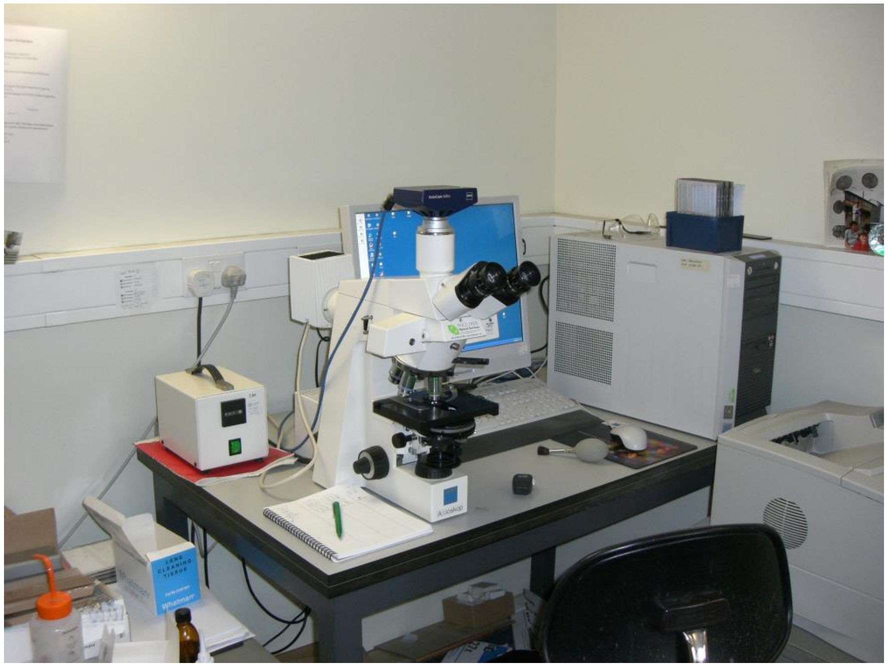
Optical microscopy (OM)

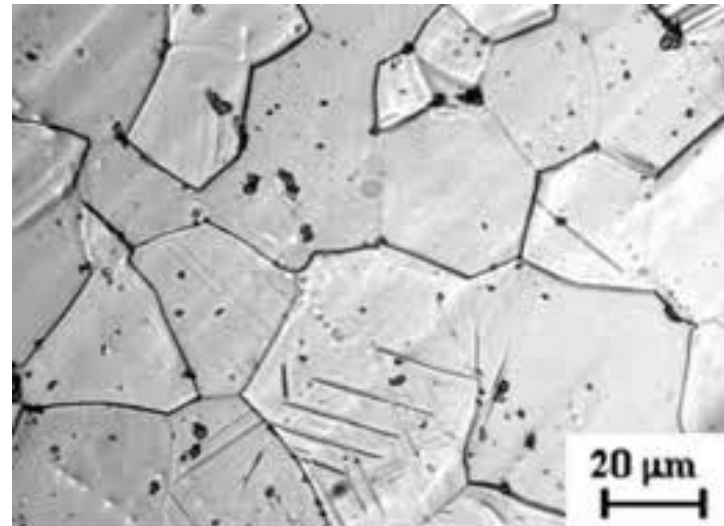
- Logical Max. zoom is 1000x.
- Characterizes the optical microstructure
- Sample dimensions!

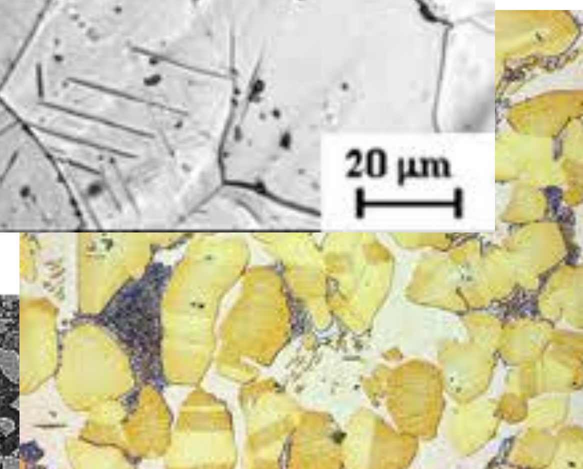


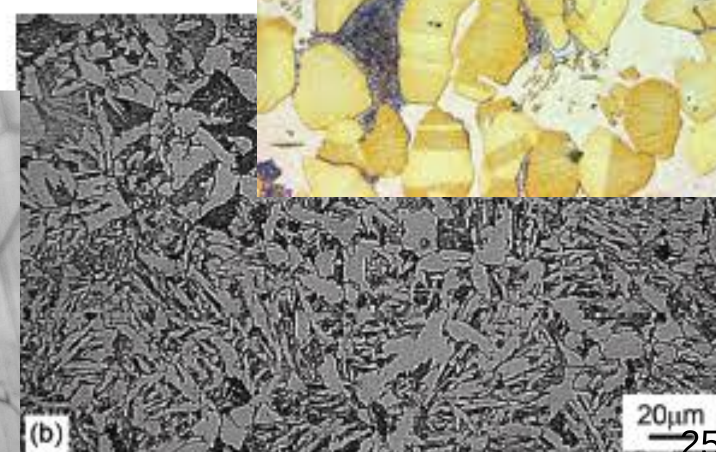


Optical microscopy (OM)

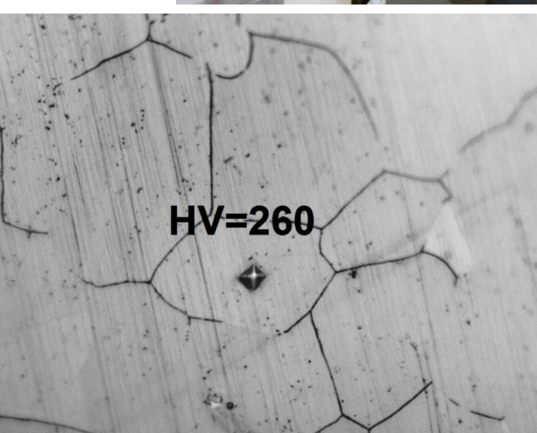


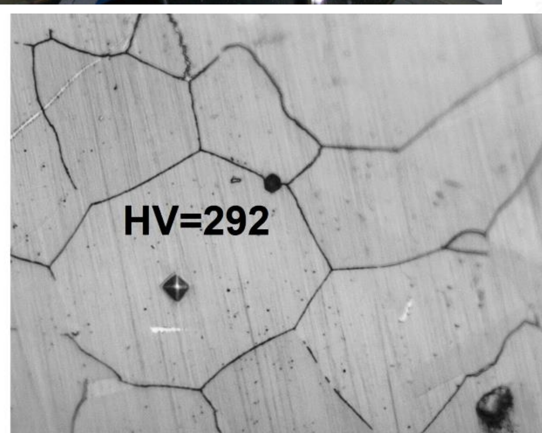






. Microstructure of samples (a) normalized and (b) air cooled (Nital 2% etching).



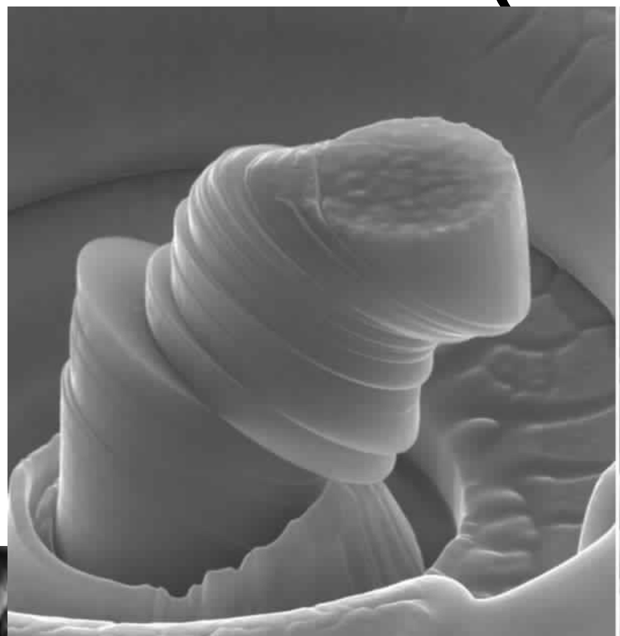


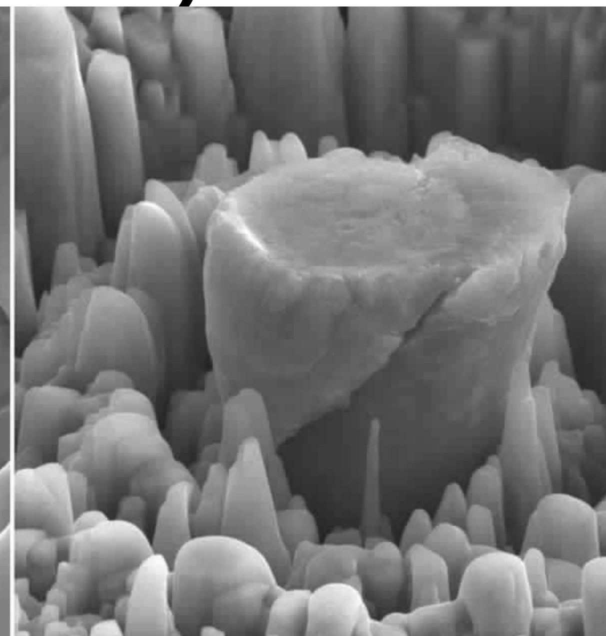
Scanning Electron microscopy (SEM)

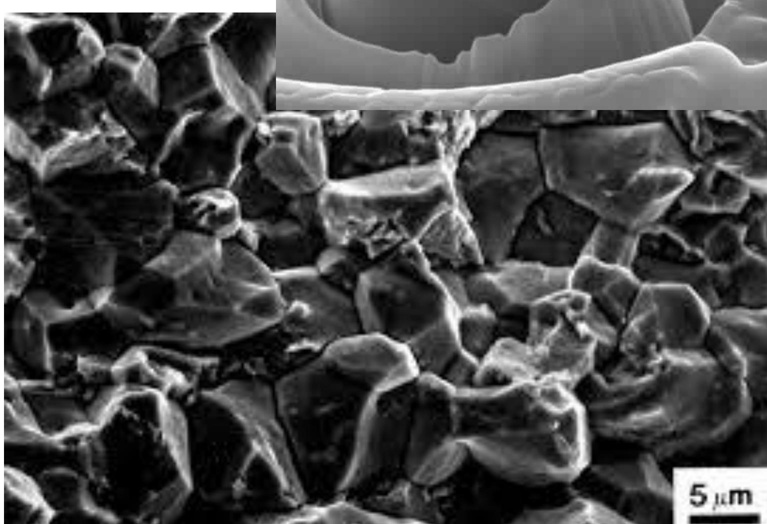
Logical max. zoom !

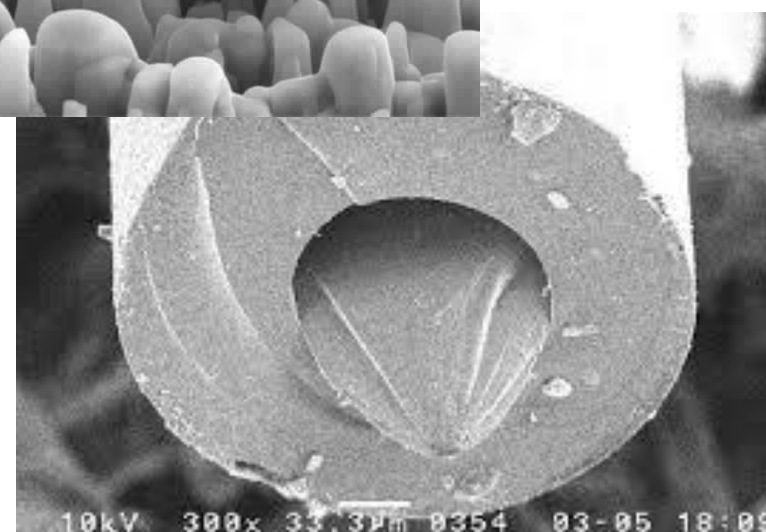
Sample dimensions !

Scanning Electron microscopy (SEM)





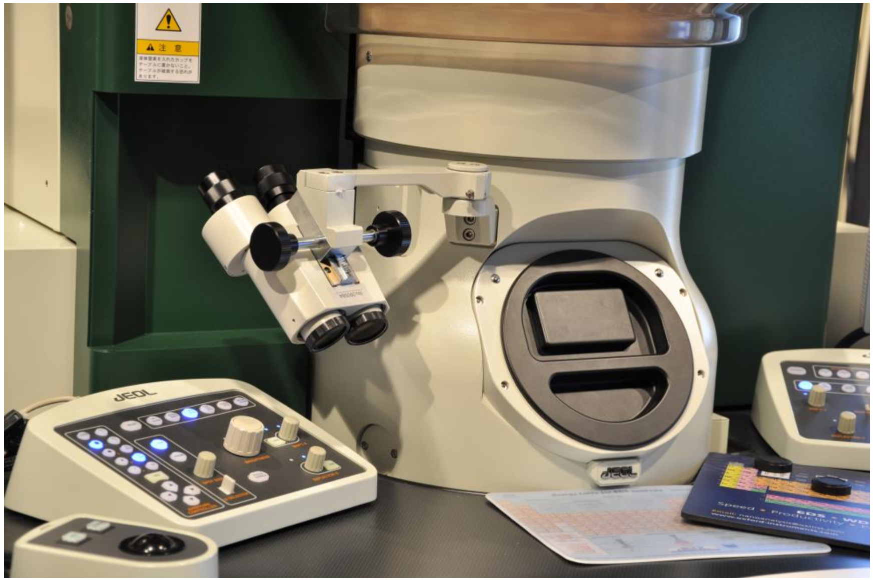




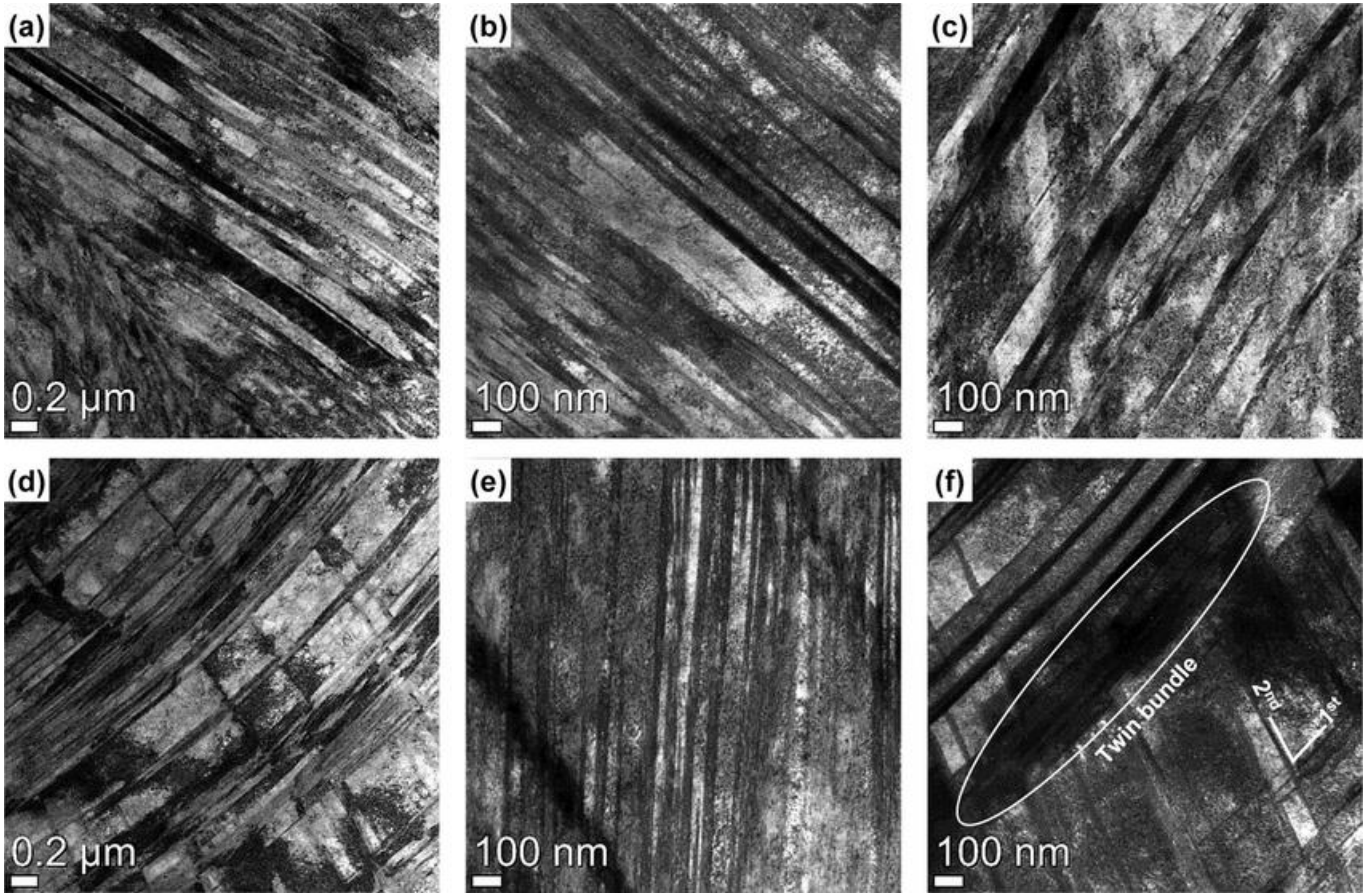
Transmission Electron microscopy (TEM)

Logical max. zoom !

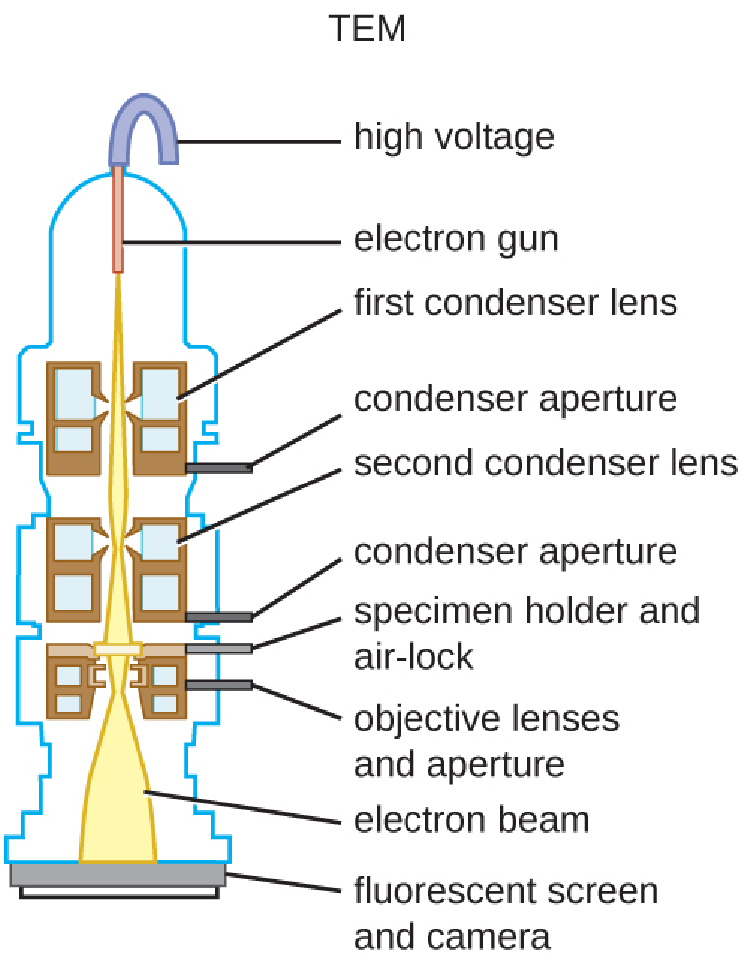
Sample dimensions !

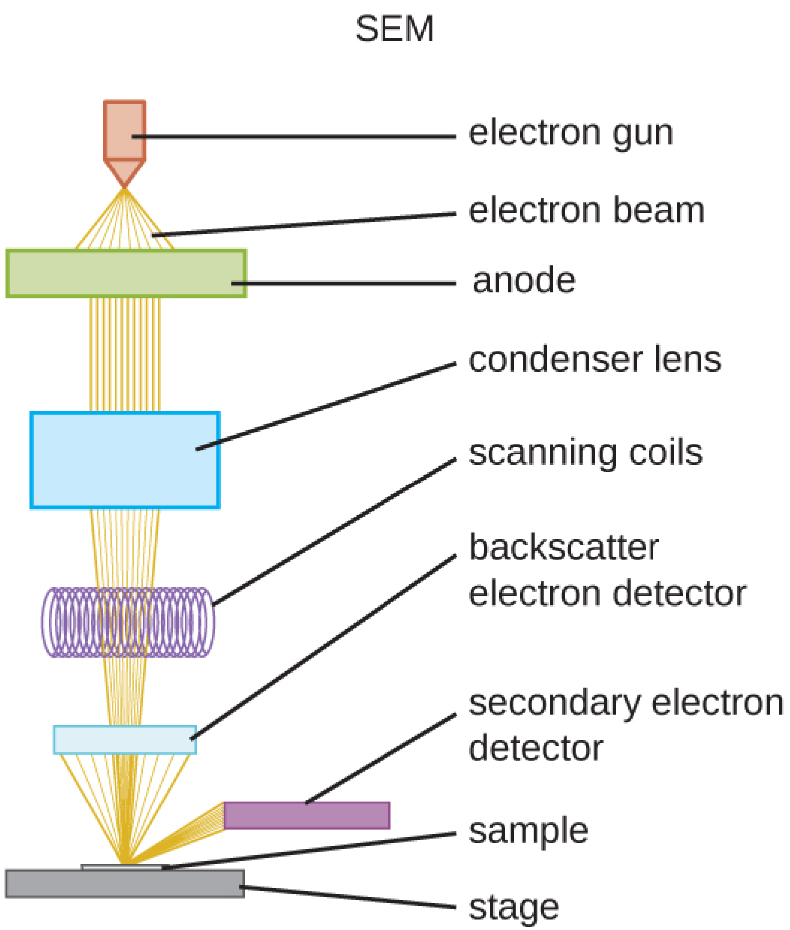


Transmission Electron microscopy (TEM)



TEM vs. SEM

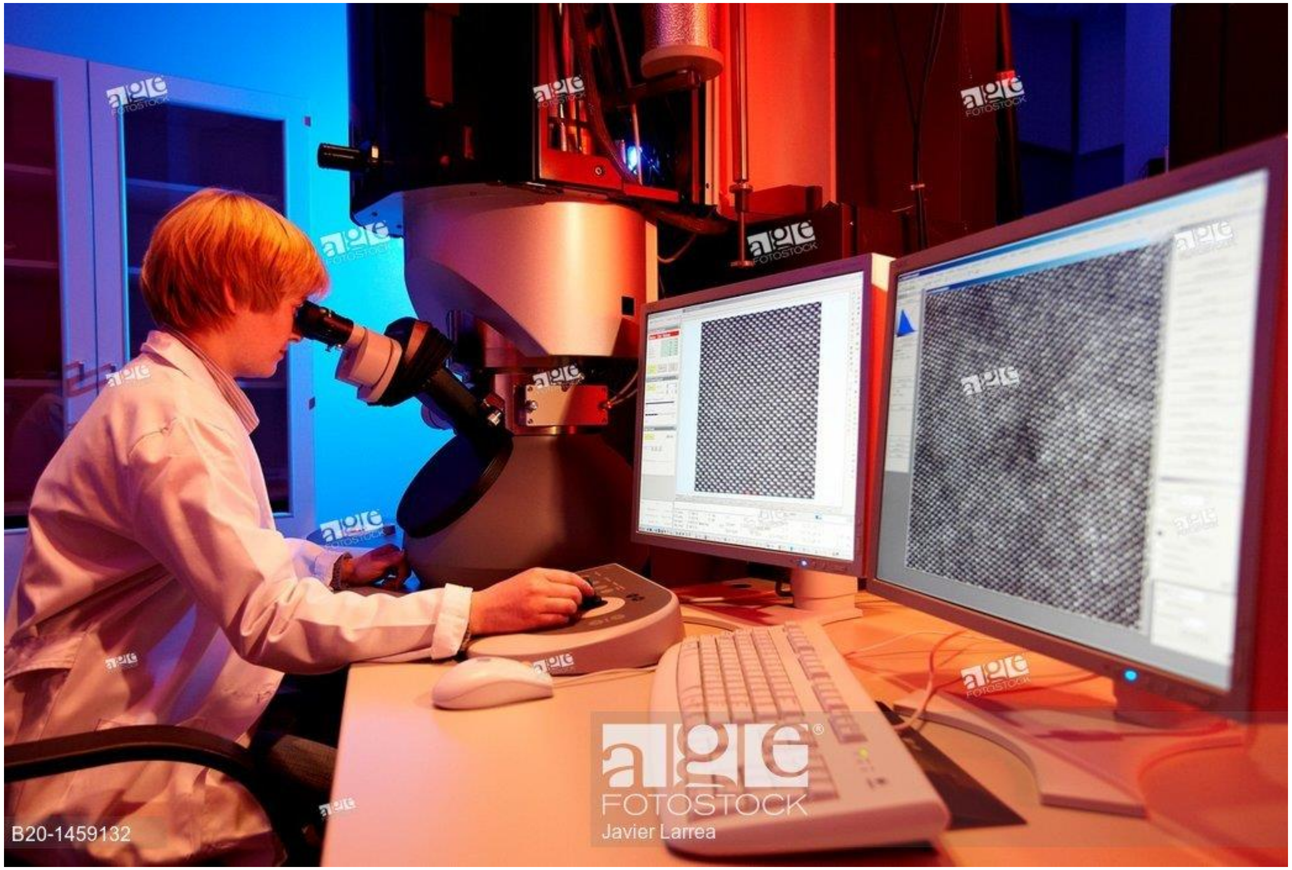

TEM
high voltage
electron gun
first condenser lens
condenser aperture
second condenser lens
condenser aperture
specimen holder and
air-lock
objective lenses
and aperture
electron beam
fluorescent screen
and camera


SEM
electron gun
electron beam
anode
condenser lens
scanning coils
backscatter
electron detector
secondary electron
detector
sample
stage

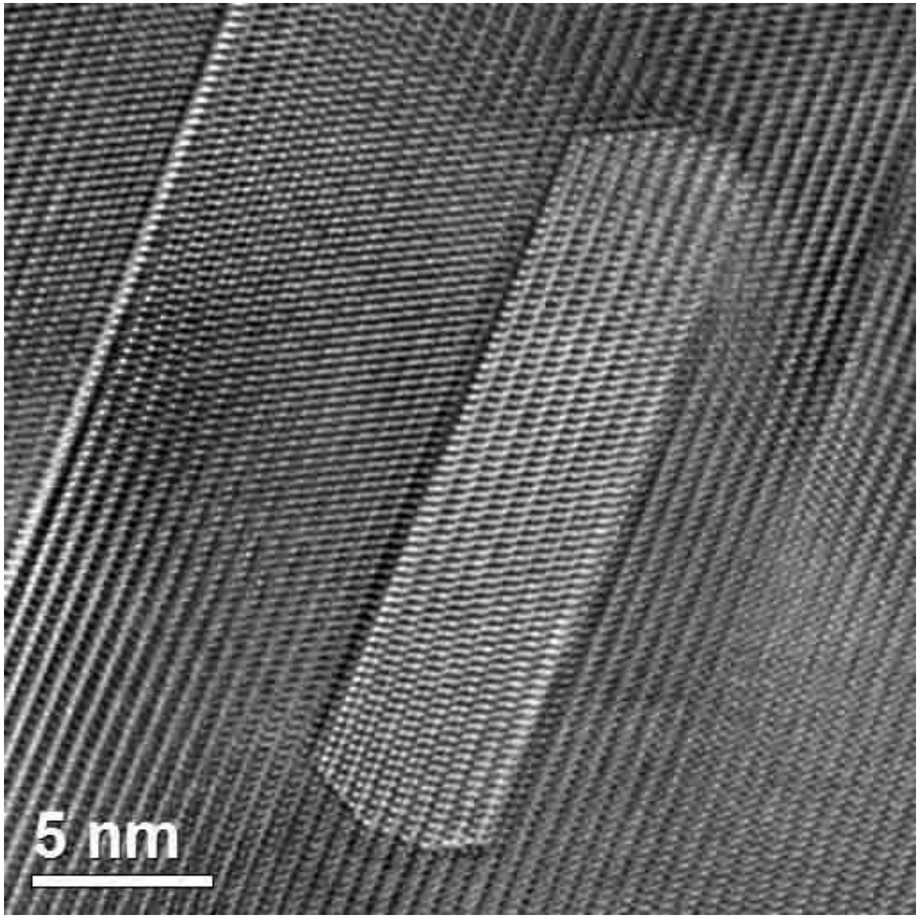
High Resolution Transmission Electron microscopy (HRTEM)

Max. zoom
!

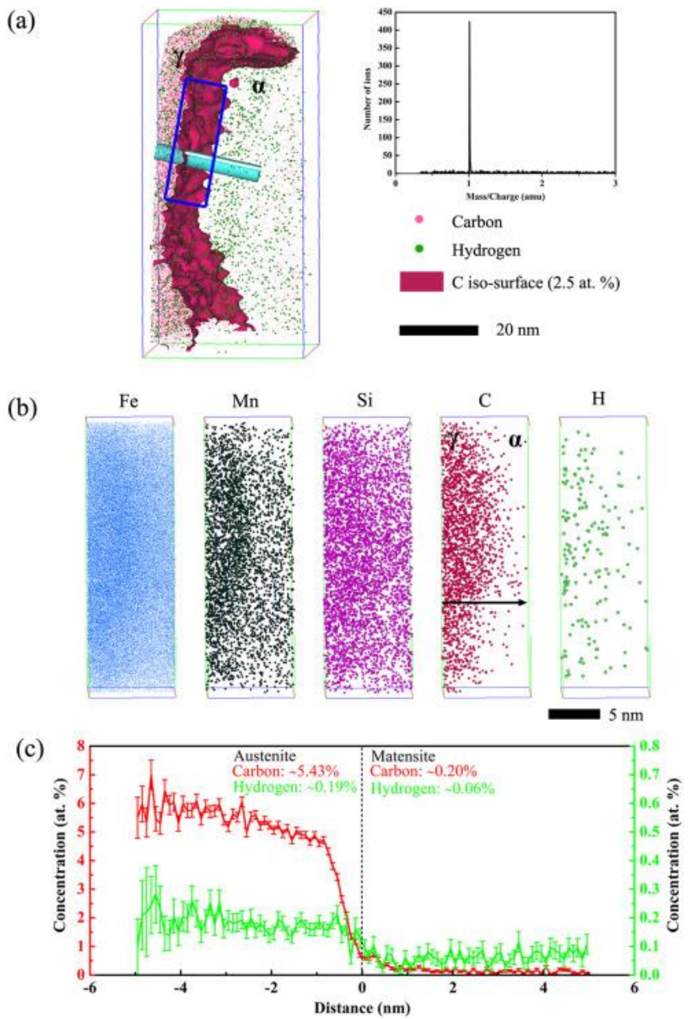
Sample
dimensions
!



High Resolution Transmission Electron microscopy (HRTEM)



3D atomic probe tomography (3DAPT)



Comparison between OM, SEM & TEM

Source: Metals Handbook, vol.10, ASM

	Optical microscope	Scanning electron microscope	Transmission electron microscope
Emission	Light	Electron beam	Electron beam
Medium	Atmosphere	Vacuum $<10^{-4}$ Pa	Vacuum$<10^{-5}$Pa
Resolution	~ 200 nm	Approx. 5 nm	Approx. 0.14 nm
Contrast	Absorption reflection	Secondary electron effect	Scattering / diffraction
Lens	Optical glass lens	Electromagnetic lens	Electromagnetic lens
Depth of focus	Shallow	Very deep	Deep
Magnification change method	Lens replacement	Scanning width	Excitation of magnifying lenses
Specimen thickness	Usually 0.5 µm min.	Usually 10 mm max.	Usually 1 µm max.
Specimen preparation	Easy	Relatively easy	No easy

Benha University
Shoubra Faculty of Engineering

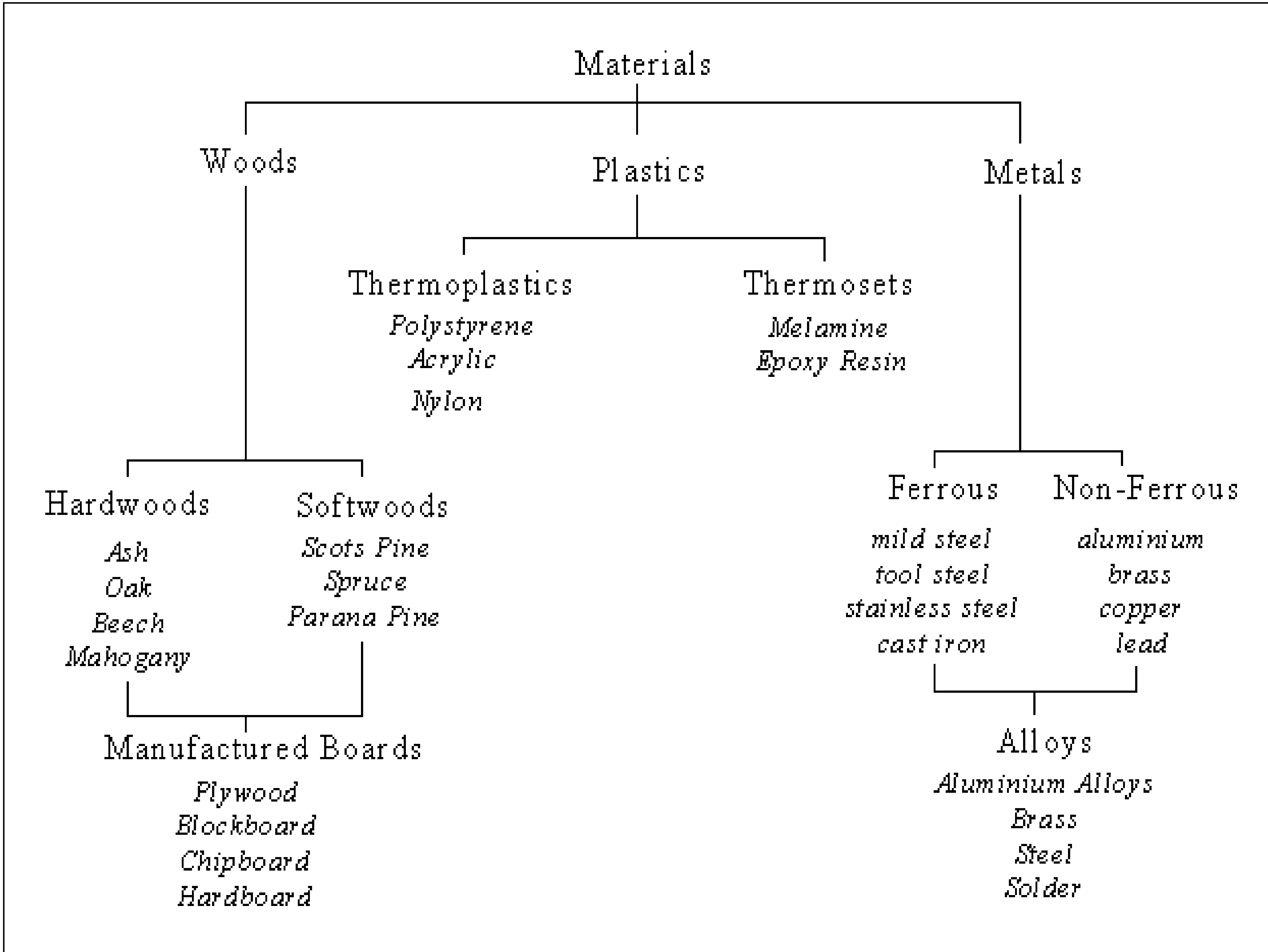
Energy & sustainable energy Dep.
1st year

04.04.2019 – Week 8

Materials classification, mechanical definitions & loading types

Chapter 6 of Materials Science and Engineering
Author - William D. Callister

Dr. Mahmoud Khedr


Materials
Woods
Plastics
Metals
Thermoplastics
Polystyrene
Acrylic
Nylon
Thermosets
Melamine
Epoxy Resin
Hardwoods
Ash
Oak
Beech
Mahogany
Softwoods
Scots Pine
Spruce
Parana Pine
Manufactured Boards
Plywood
Blockboard
Chipboard
Hardboard
Ferrous
mild steel
tool steel
stainless steel
cast iron
Non-Ferrous
aluminium
brass
copper
lead
Alloys
Aluminium Alloys
Brass
Steel
Solder

Metals

- Metals are… Solid at room temperature, except mercury, which is liquid !
- Metals have… very high melting point.
- Metals are… shiny when they cut.
- Metals are… good conductors of heat and electricity.
- Metals are… usually strong & malleable so they can be formed.

Metals

Ferrous

Containing iron & almost all are magnetic.
e.g. mild-steel, cast-iron, tool-Steel etc.

Non-Ferrous

Do not contain iron.
e.g. Aluminium, copper, silver, gold, lid, tin etc.

Alloys

A mixture of metals, or a metal & small amount of other substance

Ferrous Alloys

e.g.
stainless steel
steel + chromium

Non-Ferrous Alloys

e.g. brass (copper + zinc)
bronze (copper + tin)

METALS & ALLOYS

Metals are available in **pure** or **alloy** form.

Pure Metals such as pure aluminium or pure copper, contain only one type of metal. They are not mixed with any other metal.

Alloys are mixture of two or more pure metals.

Alloys tend to have **better strength properties** than pure metals.

Alloys and pure metals often have **special physical properties**.

Mechanical Properties

1. Strength - The ability of a material to stand up to forces being applied without it bending, breaking, shattering or deforming in any way.

2. Elasticity - The ability of a material to absorb force and flex in different directions, returning to its original position.

3. Plasticity - The ability of a material to be change in shape permanently.

4. Ductility - The ability of a material to change shape (deform) usually by stretching along its length.

Mechanical Properties

5. Tensile Strength – The ability of a material to stretch without breaking or snapping.

6. Malleability - The ability of a material to be reshaped in all directions without cracking.

7. Toughness - A characteristic of a material that does not break or shatter when receiving a blow or under a sudden shock.

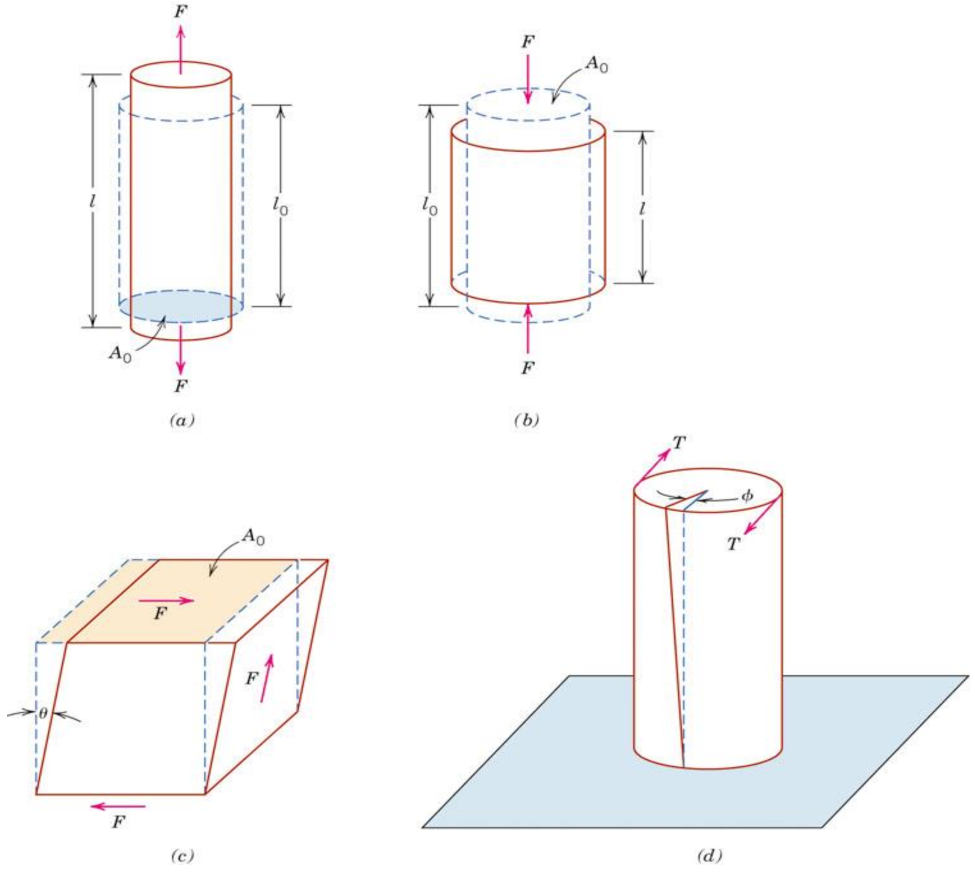
8. Conductivity - The ability of a material to conduct electricity.

1. Hardness – The ability of a material to resist scratching, wear and tear & indentation.

Mechanical Properties

- Stiffness - Elastic Modulus or Young's Modulus (MPa)
- Strength - Yield, Ultimate, Fracture, Proof, Offset Yield. Measured as stress (MPa)
- Ductility - Measure of ability to deform plastically without fracture - Elongation, Area Reduction, Fracture Strain
- Toughness, Resilience - Measure of ability to absorb energy (J/m^3).
- Hardness - Resistance to indentation/abrasion (Rockwell, Brinell, Vickers.)

Types of load



Benha University
Shoubra Faculty of Engineering

Energy & sustainable energy Dep.
1st year

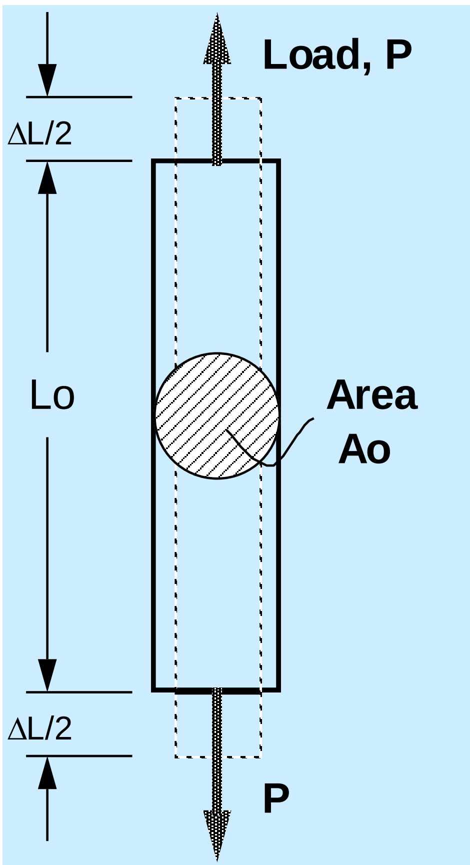
04.04.2019 – Week 8

Tensile Testing

Chapter 6 of Materials Science and Engineering
Author - William D. Callister

Dr. Mahmoud Khedr

Mechanical Properties

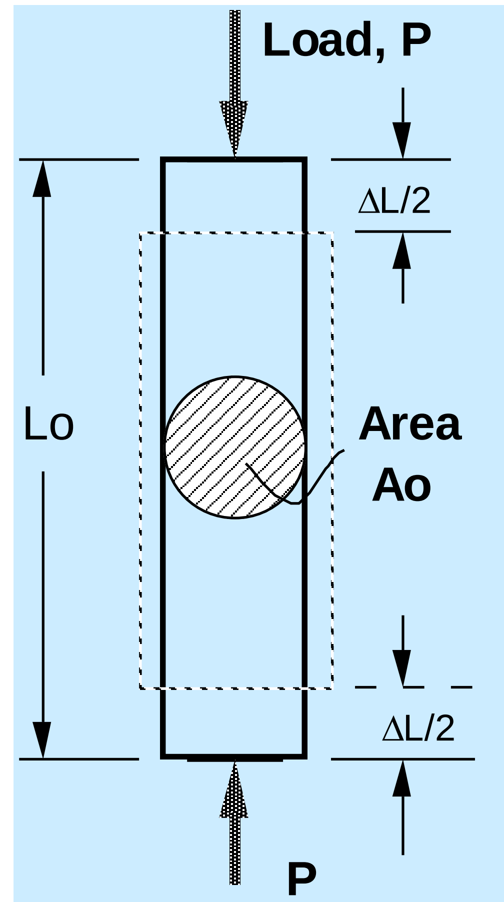


Engineering Stress

$$\sigma = \frac{F}{A_o}$$

$$e = \frac{\Delta L}{L_o}$$

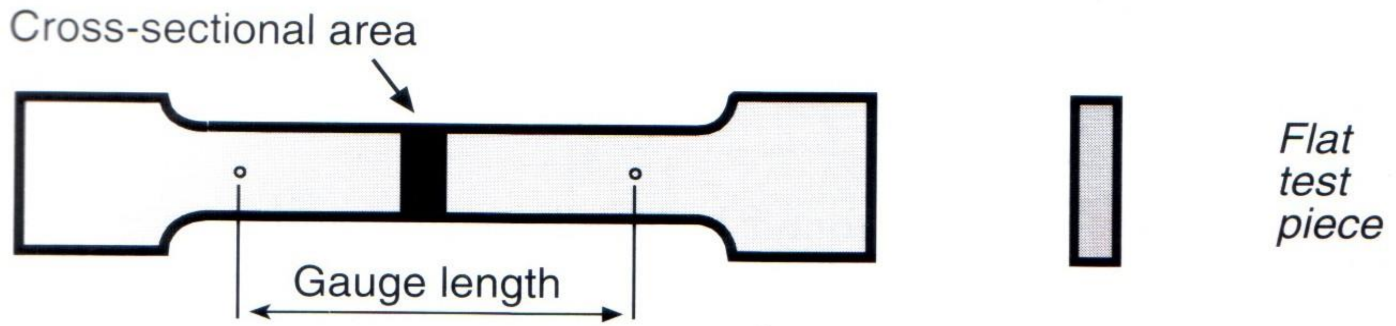
Engineering Strain

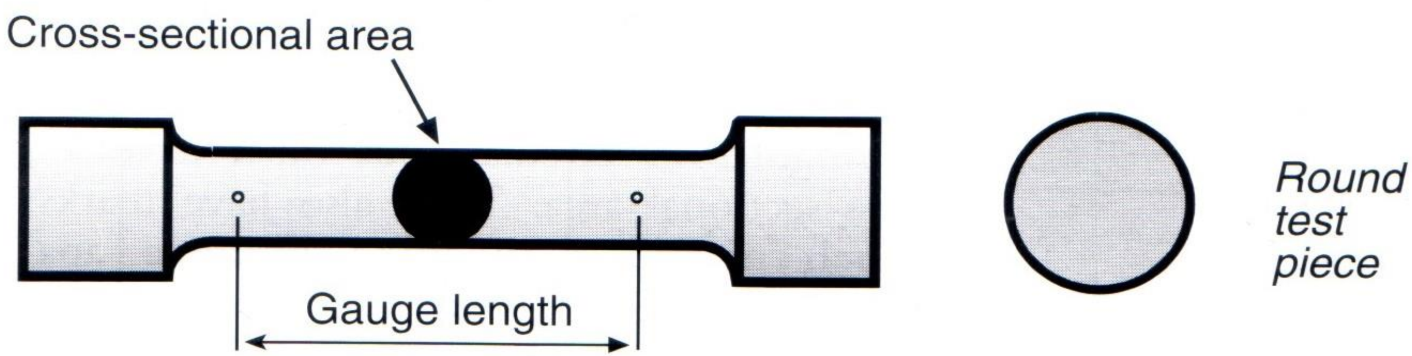


Direct Stress - Tension

Direct Stress - Compression

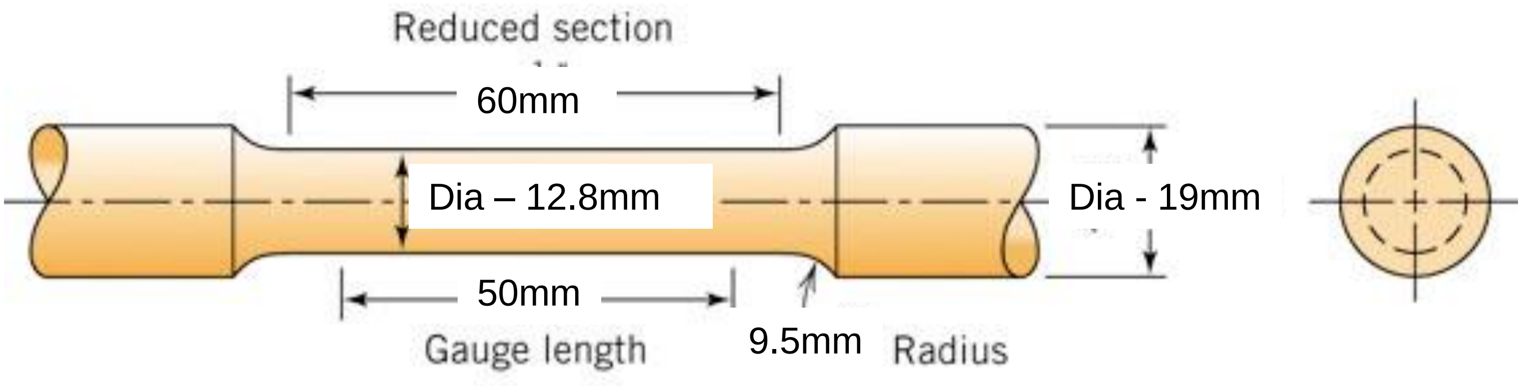
Tensile test specimens

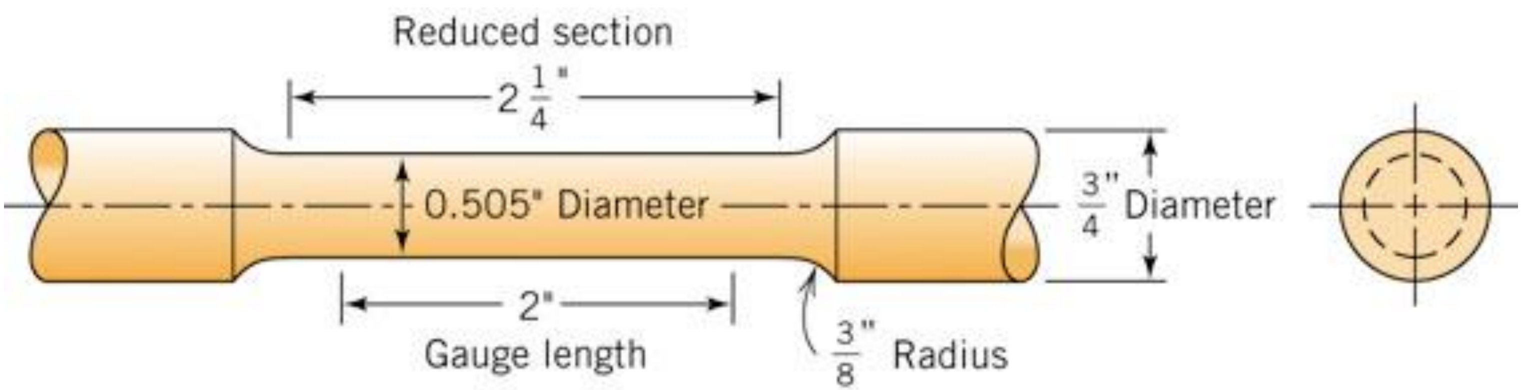




Standard lengths are given below. As well as gauge length, minimum parallel, and total lengths, radii, width, and for round pieces, diameter, are also specified

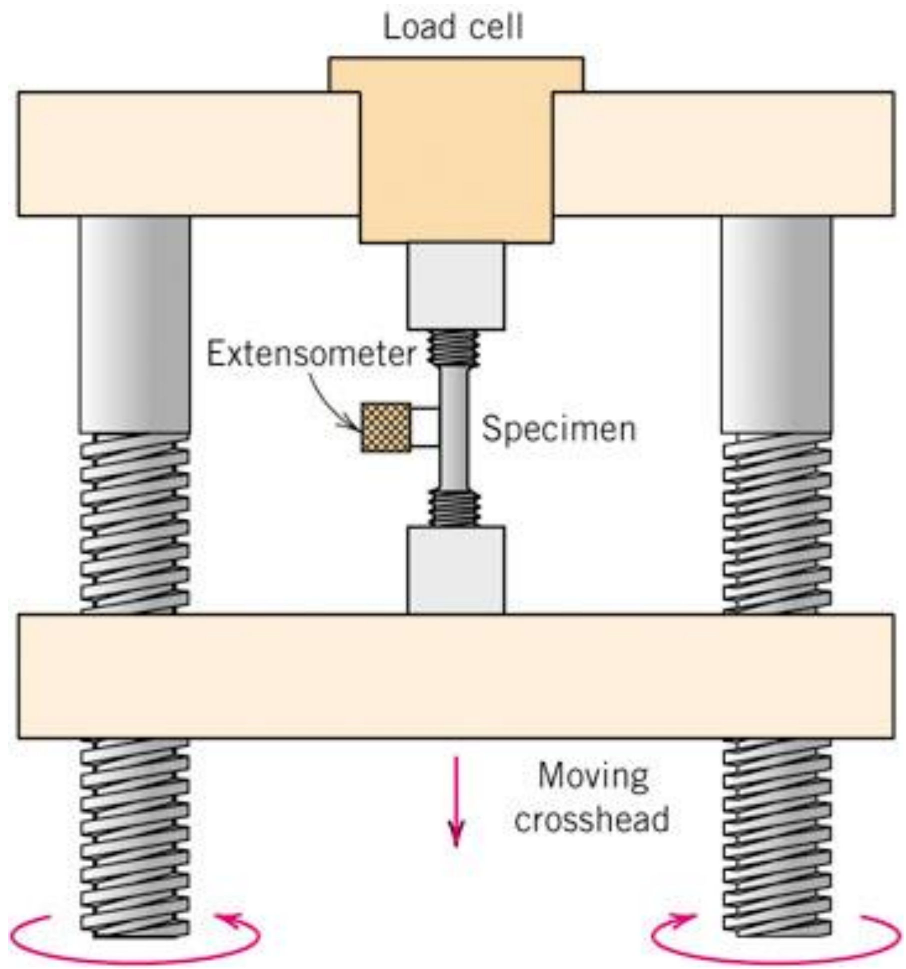
Example of a typical tensile specimen





Tension test

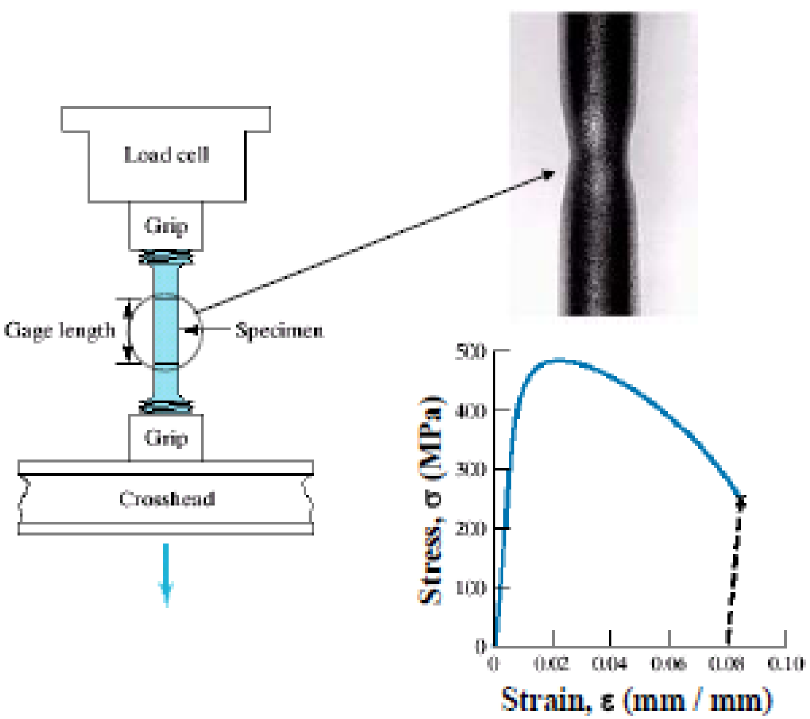
Typical Universal Testing Machine



Tension test

Introduction

To understand and describe how materials deform (elongate, compress, twist) or break as a function of applied load, time, temperature, and other conditions we need first to discuss standard test methods and standard language for mechanical properties of materials.



Concepts of Stress and Strain (tension and compression)

To compare specimens of different sizes, the load is calculated per unit area.

Engineering stress: $\sigma = F / A_o$

F is load applied perpendicular to specimen cross-section; A_0 is cross-sectional area (perpendicular to the force) **before** application of the load.

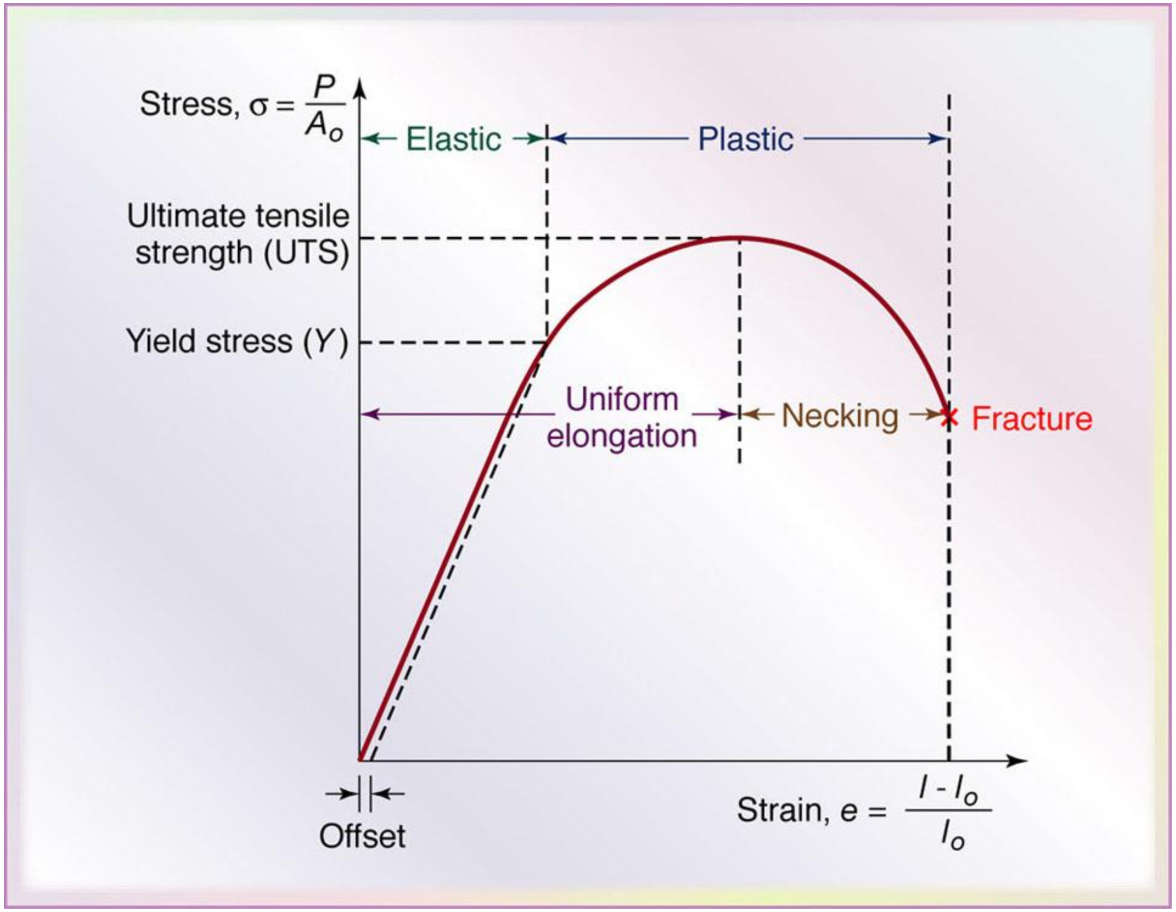
Engineering strain: $\varepsilon = \Delta l / l_o \quad (\times 100\ \%)$

Δl is change in length, l_o is the original length.

These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area A_0 and of different length l_0.

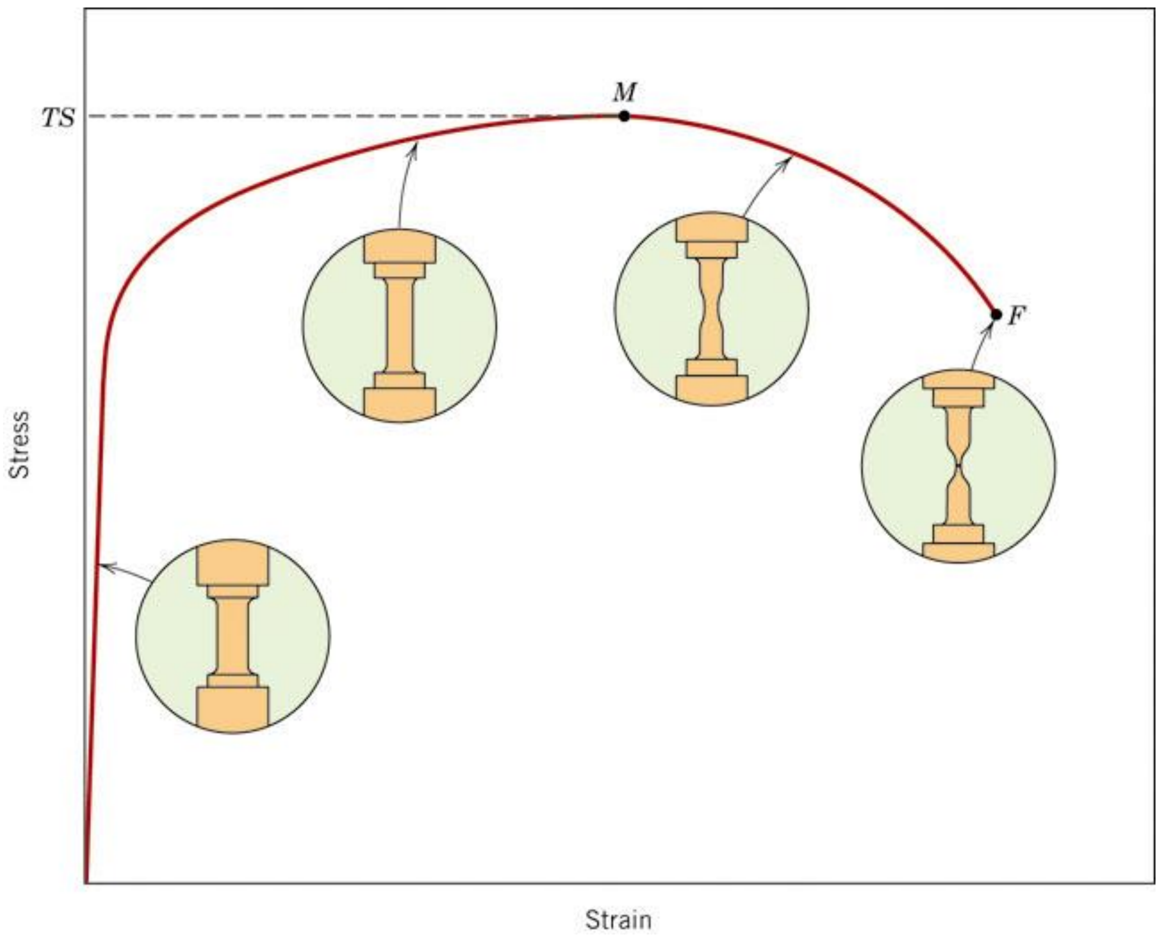
Stress and strain are positive for tensile loads, negative for compressive loads

Tension Test Stress-strain Curve

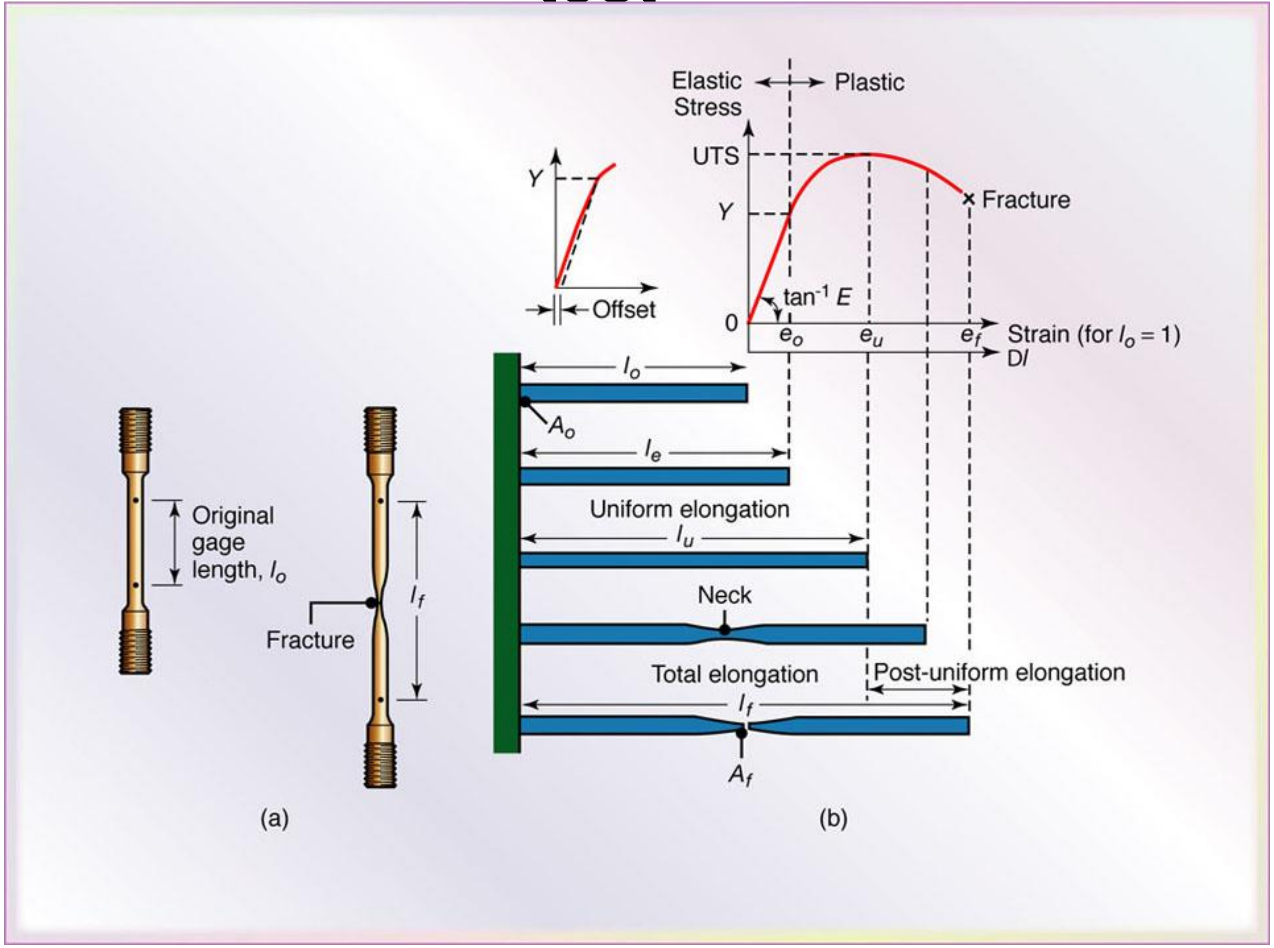


A typical stress-strain curve obtained from a tension test, showing various features

Evolution of tensile-test Specimen during tensile test

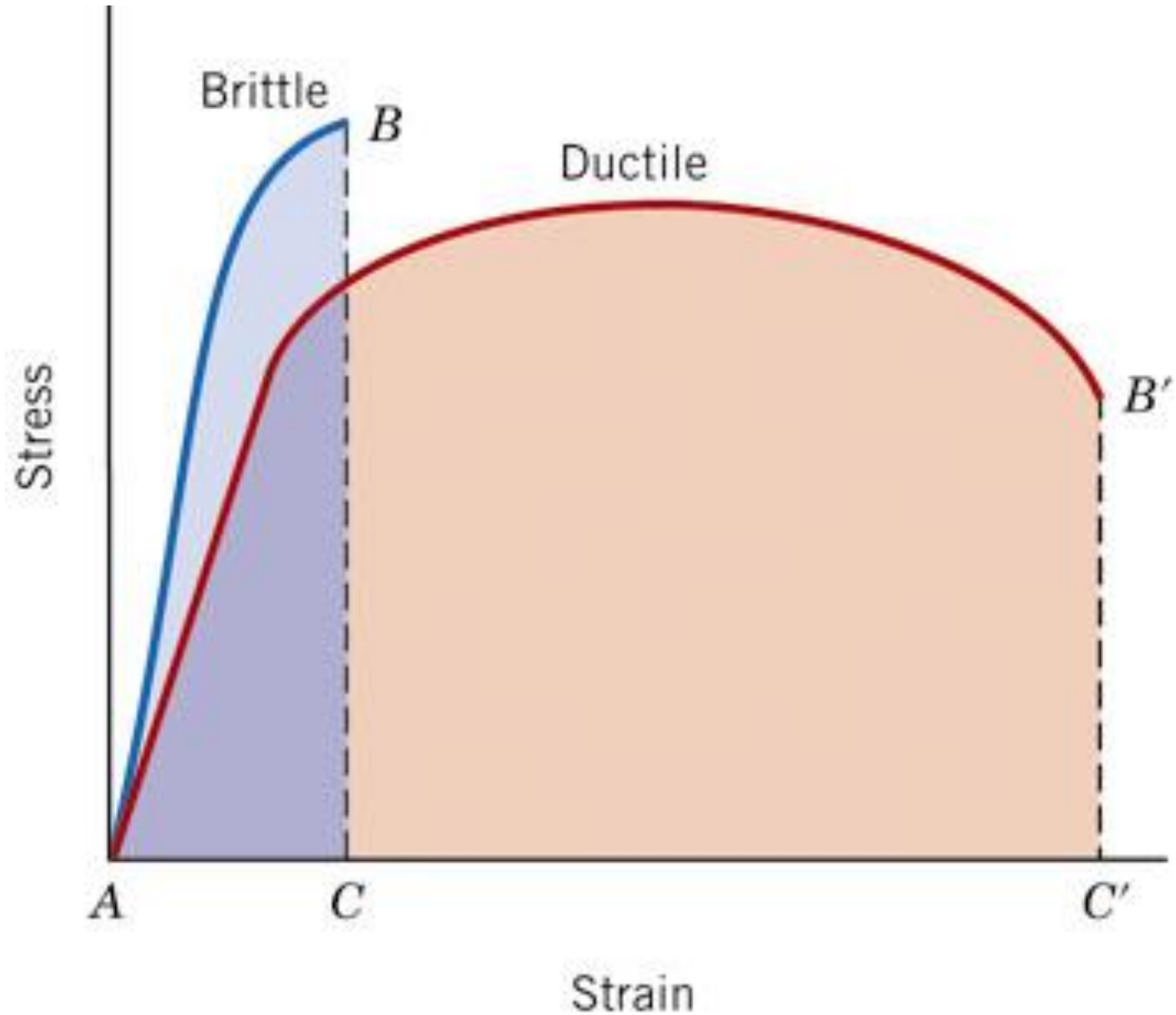


Evolution of tensile-test Specimen during tensile test

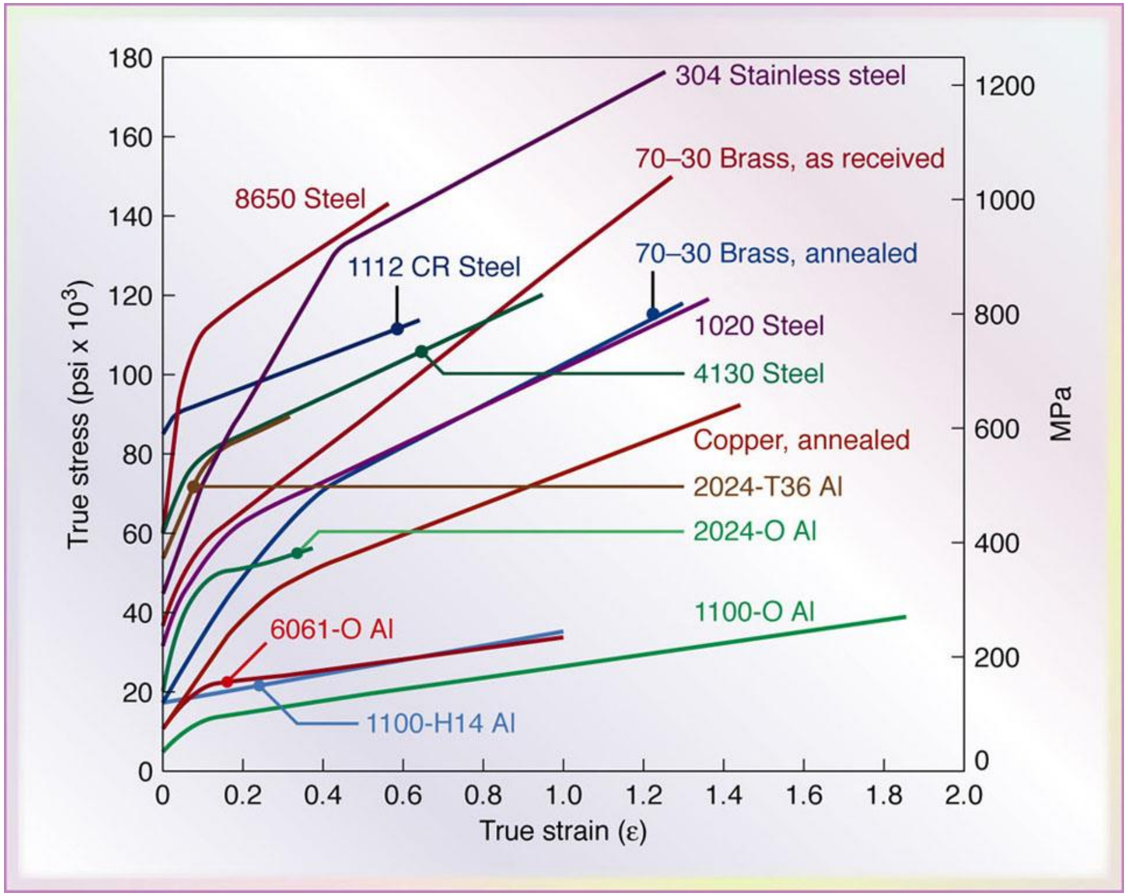


(a) A standard tensile-test specimen before and after pulling, showing original and final gage lengths.
(b) A tensile-test sequence showing different stages in the elongation of the specimen.

Brittle ‘vs’ Ductile



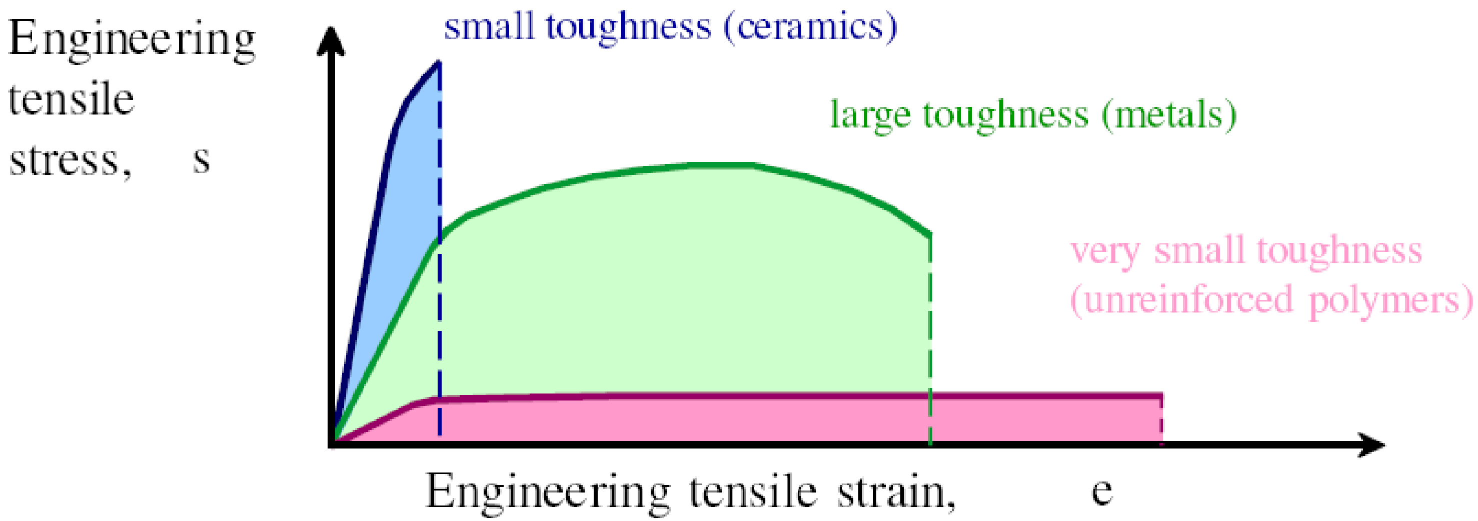
True Stress-strain Curves



True stress-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 thus each curve starts at the yield stress, Y, of the material

Toughness

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Benha University
Shoubra Faculty of Engineering

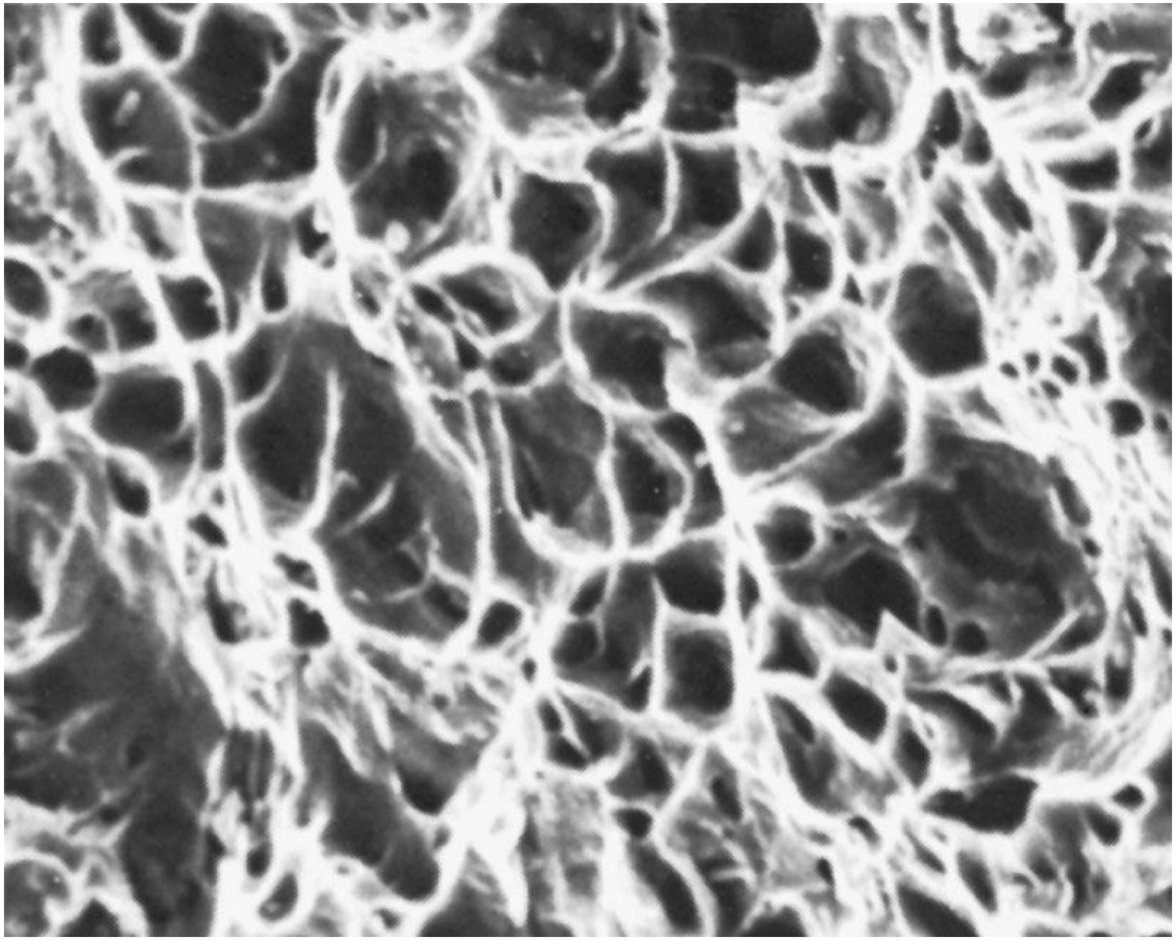
Energy & sustainable energy Dep.
1st year

04.04.2019 – Week 8

Ductile & Brittle Failure

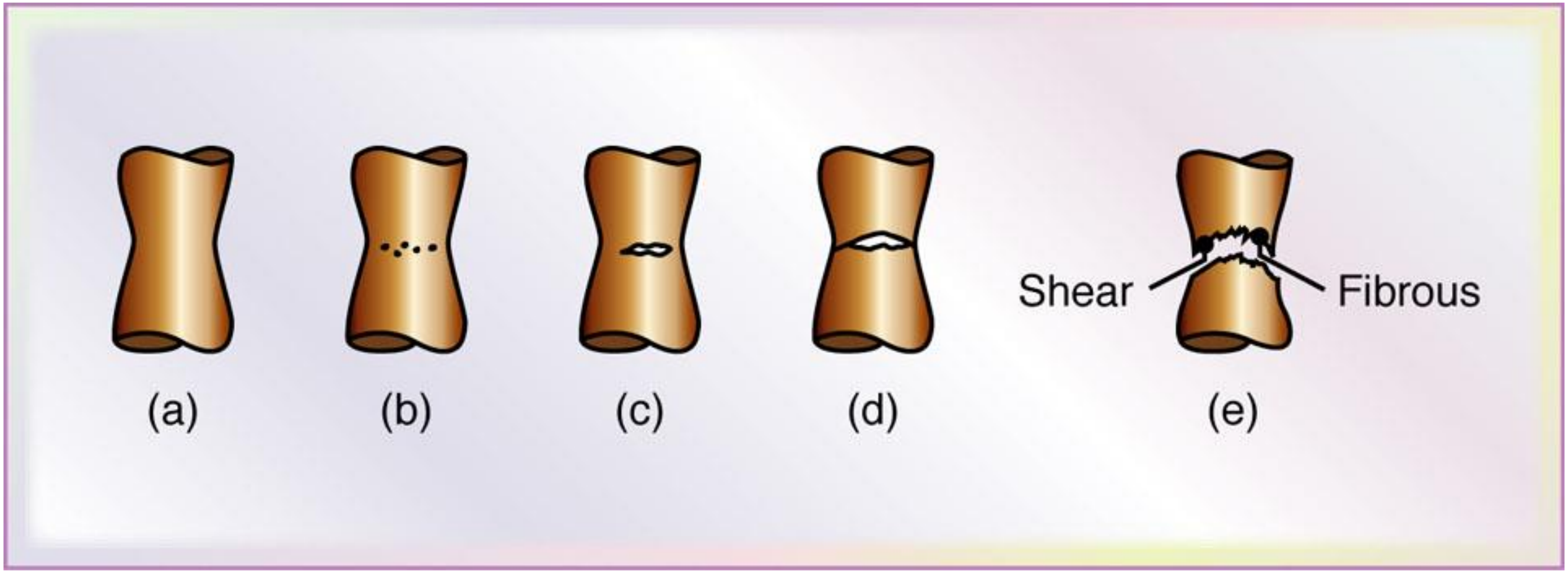
Dr. Mahmoud Khedr

Ductile Fracture in Low-carbon Steel



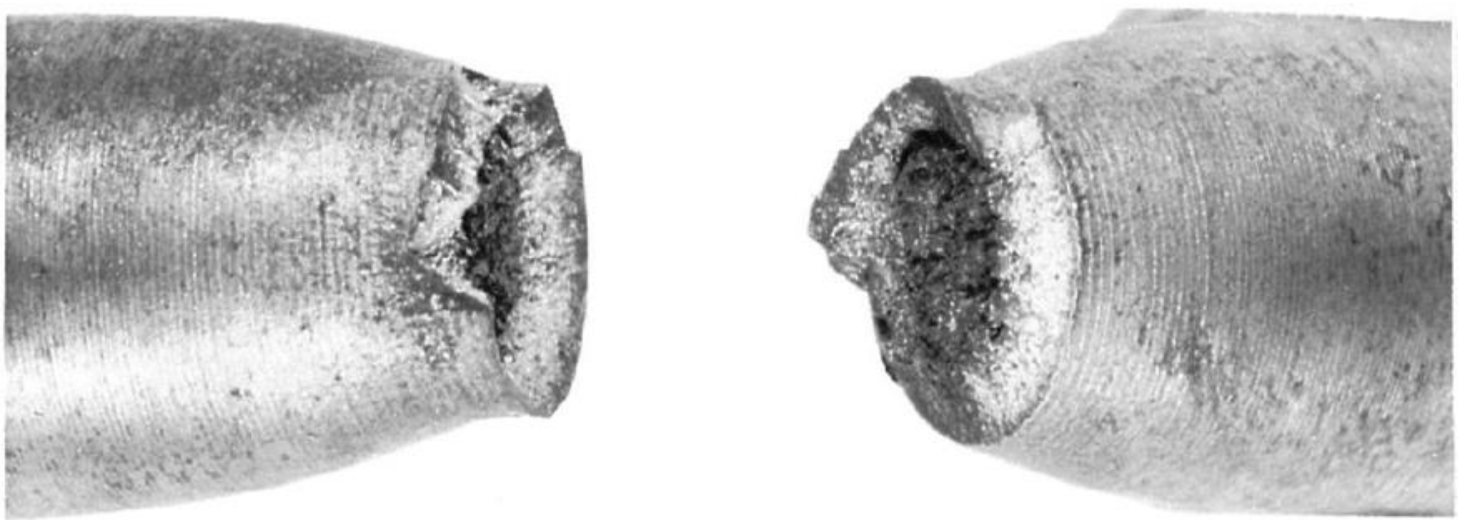
Surface of ductile fracture in low carbon steel, showing dimples. Fracture usually is initiated at impurities, inclusions, or preexisting voids (microporosity) in the metal. *Source*: Courtesy of K. H. Habig and D. Klaffke

Progression of a ductile Fracture



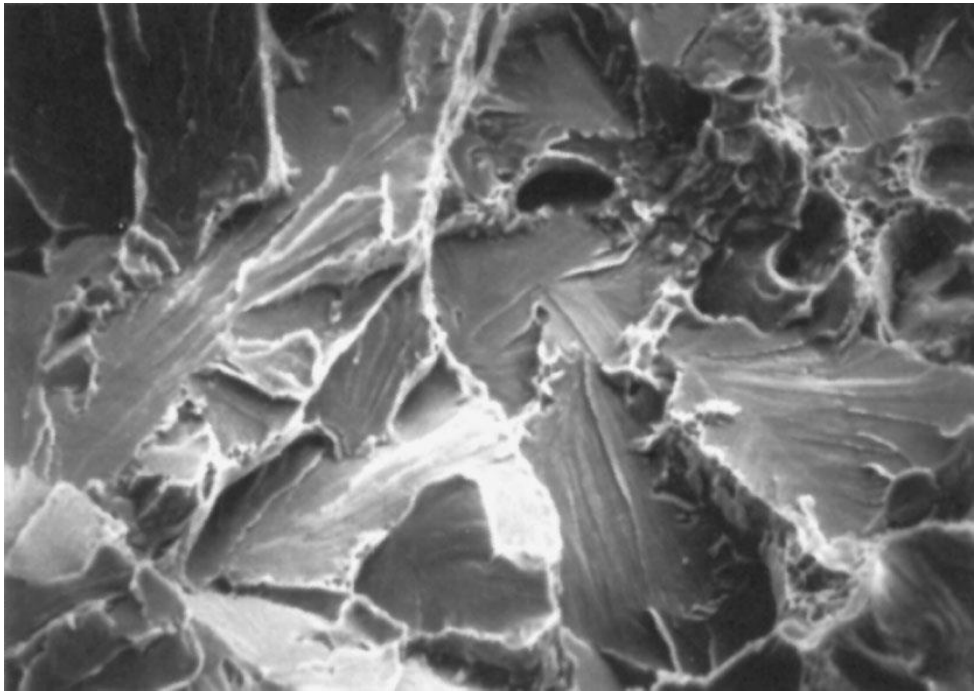
(a) early stage of necking
(b) small voids begin to form within the necked region
(c) voids coalesce, producing an internal crack
(d) the rest of the cross-section begins to fail at the periphery, by shearing
(e) the final fracture surfaces, known as cup- (top fracture surface) and cone- (bottom surface)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

Tension test sample after fracture

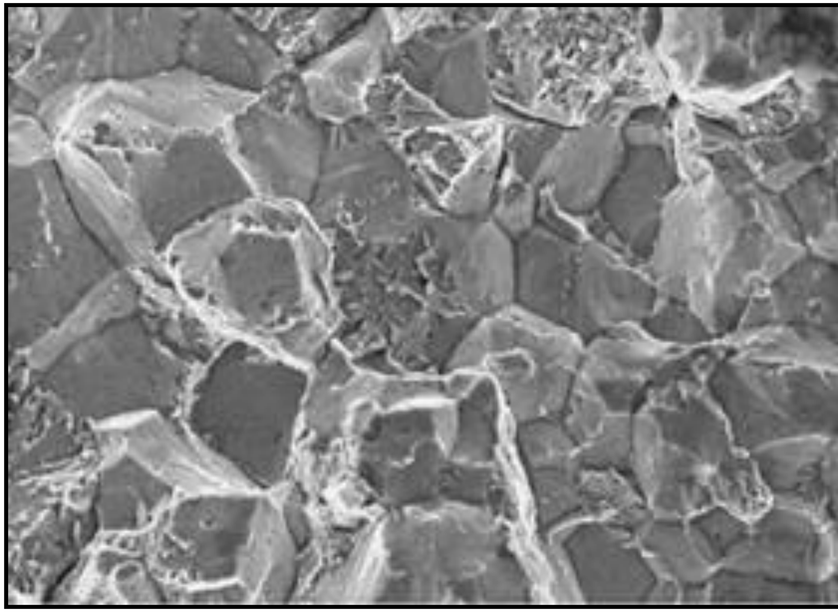


Localized deformation of a ductile material during a tensile test produces a necked region. The micrograph shows necked region in a fractured sample

Brittle Fracture Surface of Steel

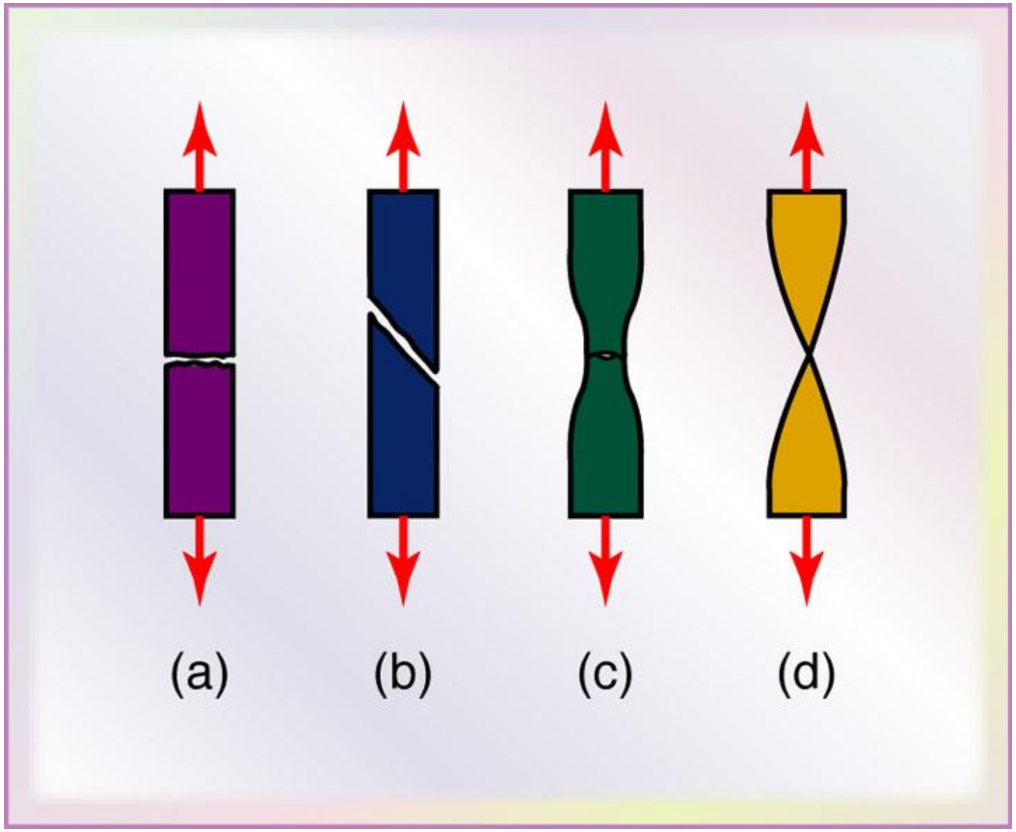


Fracture surface of steel that has failed in a brittle manner. The fracture path is transgranular (through the grains). Magnification: 200x. *Source:* Courtesy of B. J. Schulze and S.L. Meinley and Packer Engineering Associates, Inc.



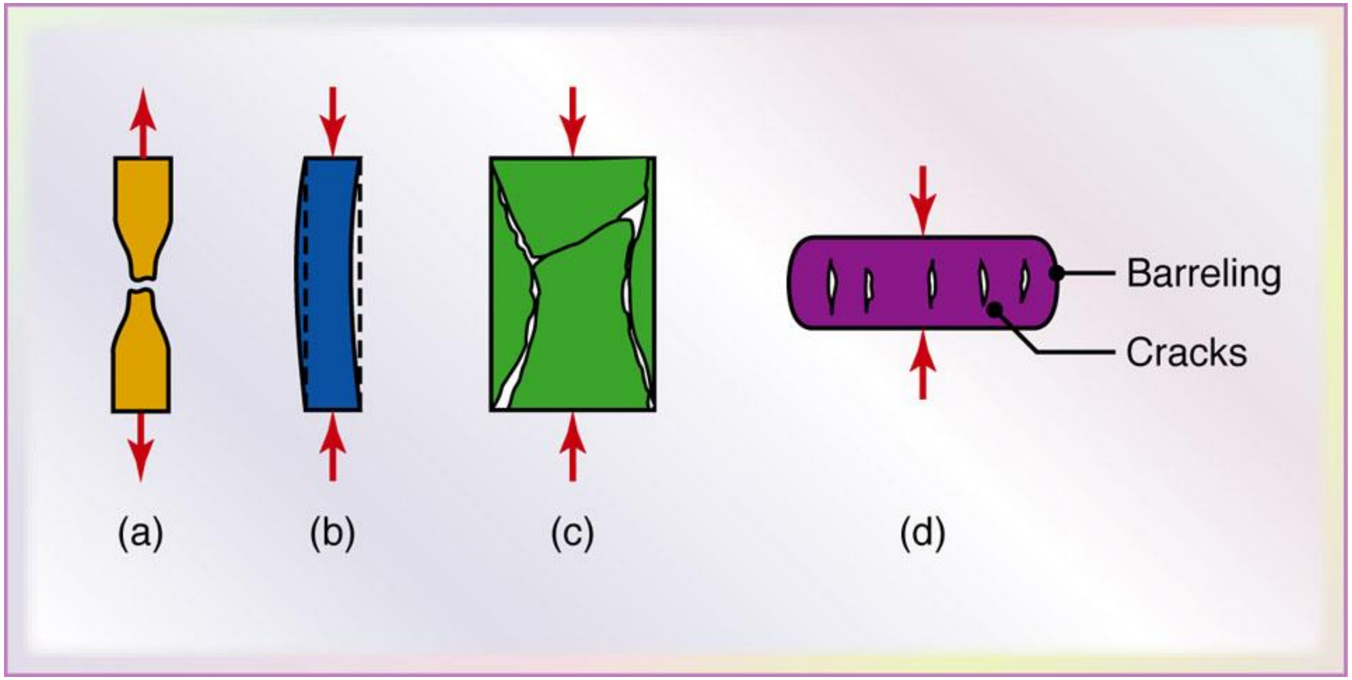
A brittle fracture surface . The fracture path is intergranular (through the grain boundaries).

Fracture Types in Tension



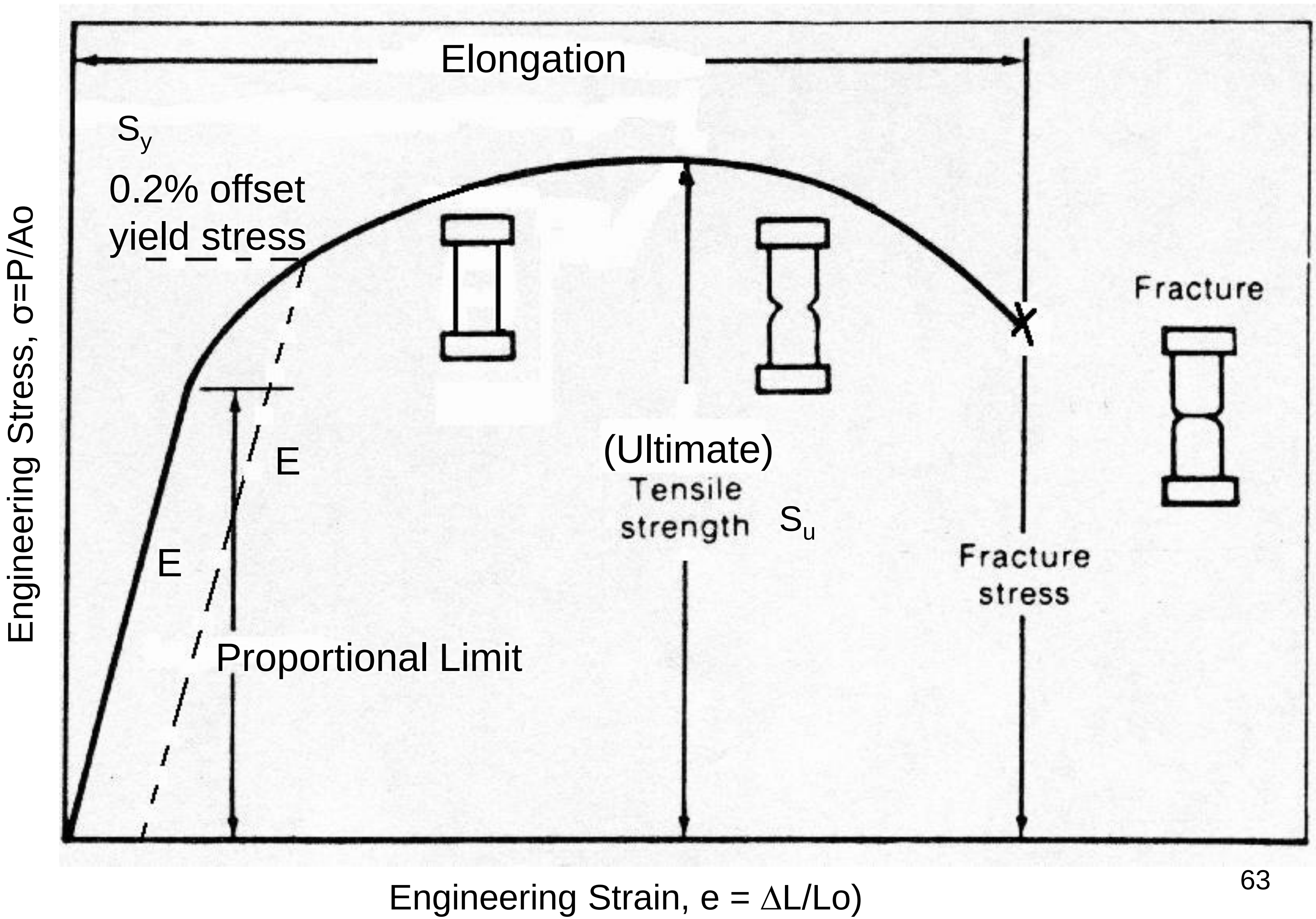
(a) brittle fracture in polycrystalline metals
(b) shear fracture in ductile single crystals
(c) ductile cup-and-cone fracture in polycrystalline metals
(d) complete ductile fracture in polycrystalline metals, with 100% reduction of area.

Material Failures

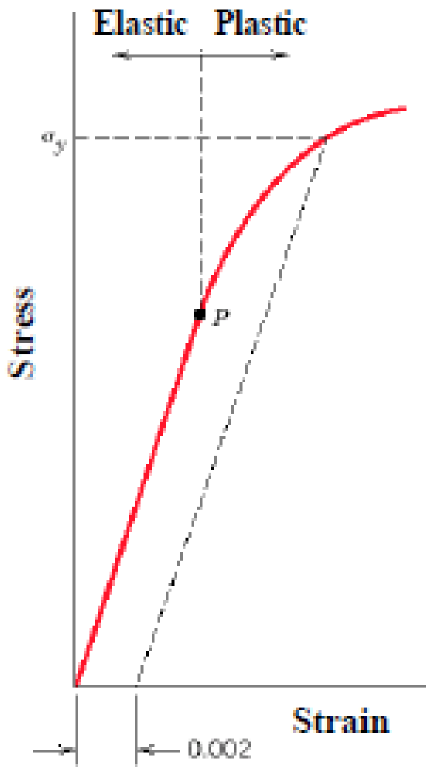


(a) necking and fracture of ductile materials;
(b) buckling of ductile materials under a compressive load;
(c) fracture of brittle materials in compression;
(d) cracking on the barreled surface of ductile materials in compression

Engineering Stress-Strain Curve



Stress-Strain Behavior



Elastic deformation

Reversible: when the stress is removed, the material returns to the dimension it had before the loading.

Usually strains are small (except for the case of plastics).

Plastic deformation

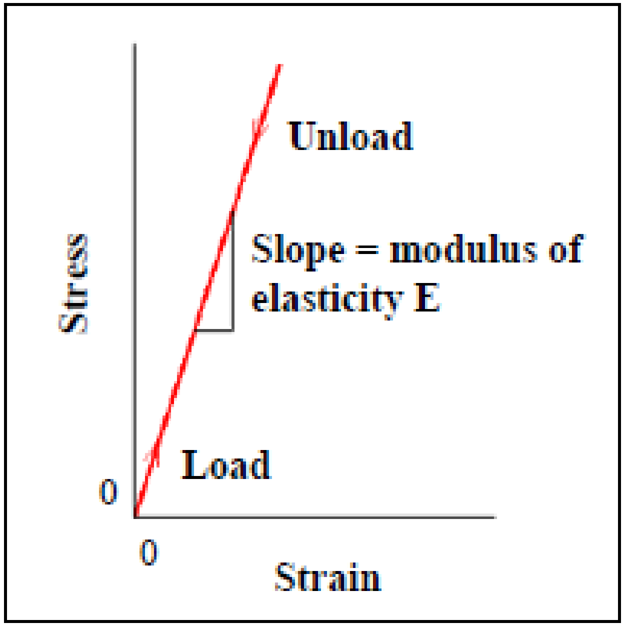
Irreversible: when the stress is removed, the material does not return to its previous dimension.

Stress-Strain Behavior: Elastic deformation

In tensile tests, if the deformation is elastic, the stress-strain relationship is called Hooke's law:

$$\sigma = E\,\varepsilon$$

E is **Young's modulus** or **modulus of elasticity**, has the same units as σ, N/m^2 or Pa



Higher E → higher "stiffness"

Engineering Stress-Strain Curve

- Express Load in Newtons (N) and Area in mm^2 to get Stress in MPa.

$$\frac{N}{mm^2} \cong MPa$$

- Mechanical properties of metals are almost always given in MPa or ksi.

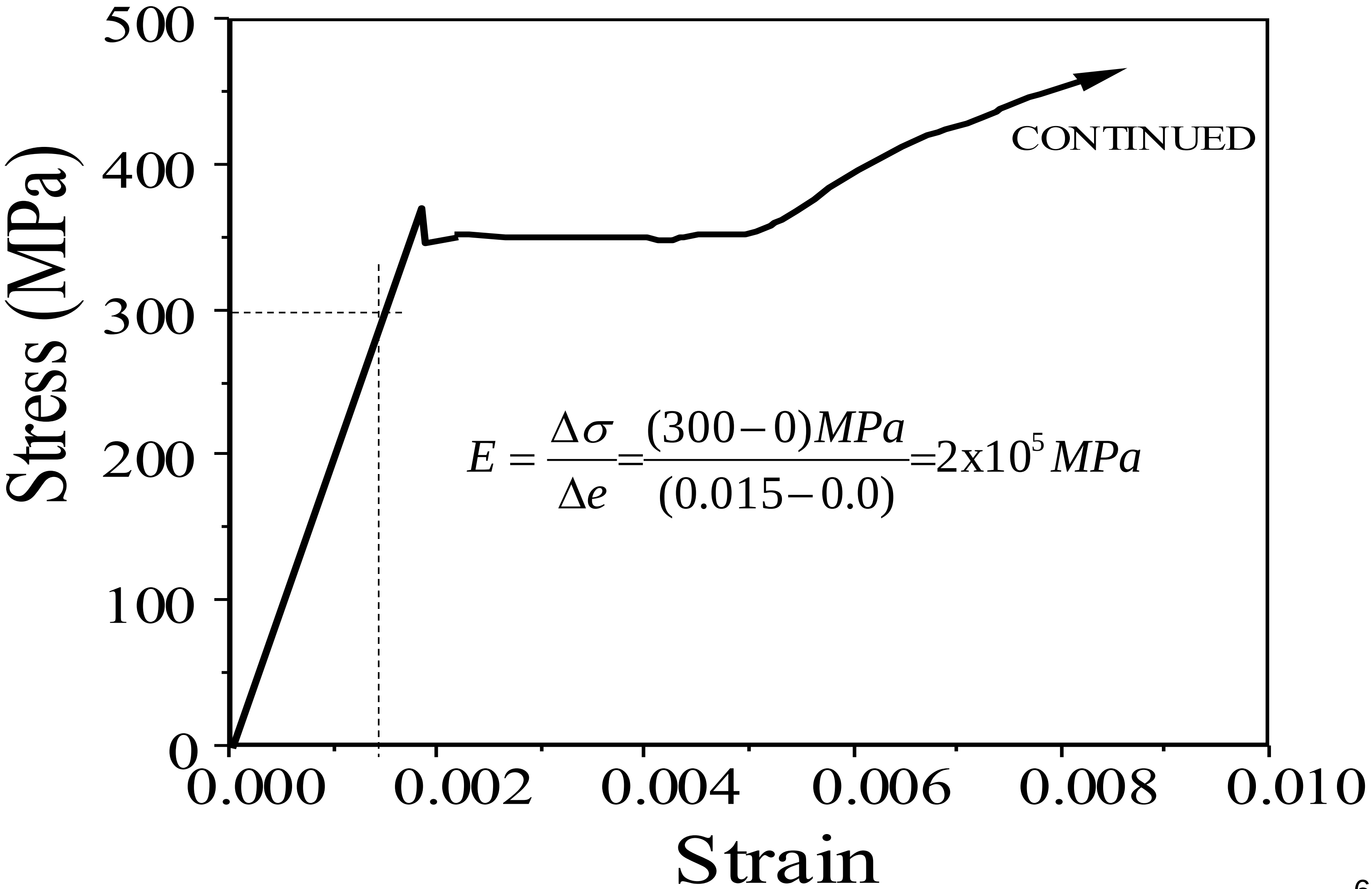
- 1000 psi = 1 ksi = 6.89 MPa

Hooke's law – Elastic deformation

- Elastic deformation is not permanent; it means that when the load is removed, the part returns to its original shape and dimensions.
- For most metals, the elastic region is linear. For some materials, including metals such as cast iron, polymers, and concrete, the elastic region is non-linear.
- If the behavior is linear elastic, or nearly linear-elastic, Hooke's Law may be applied:
- Where E is the modulus of elasticity (MPa)

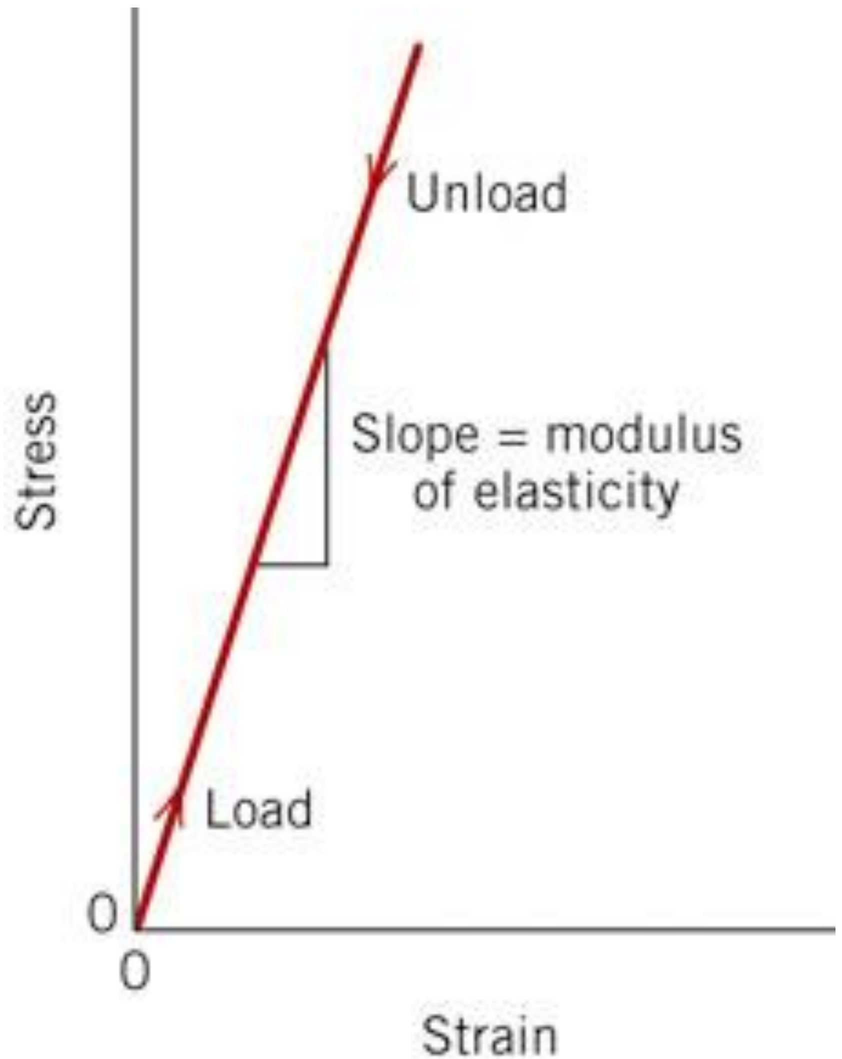
$$\sigma = Ee$$

Modulus of elasticity – Stiffness (E)

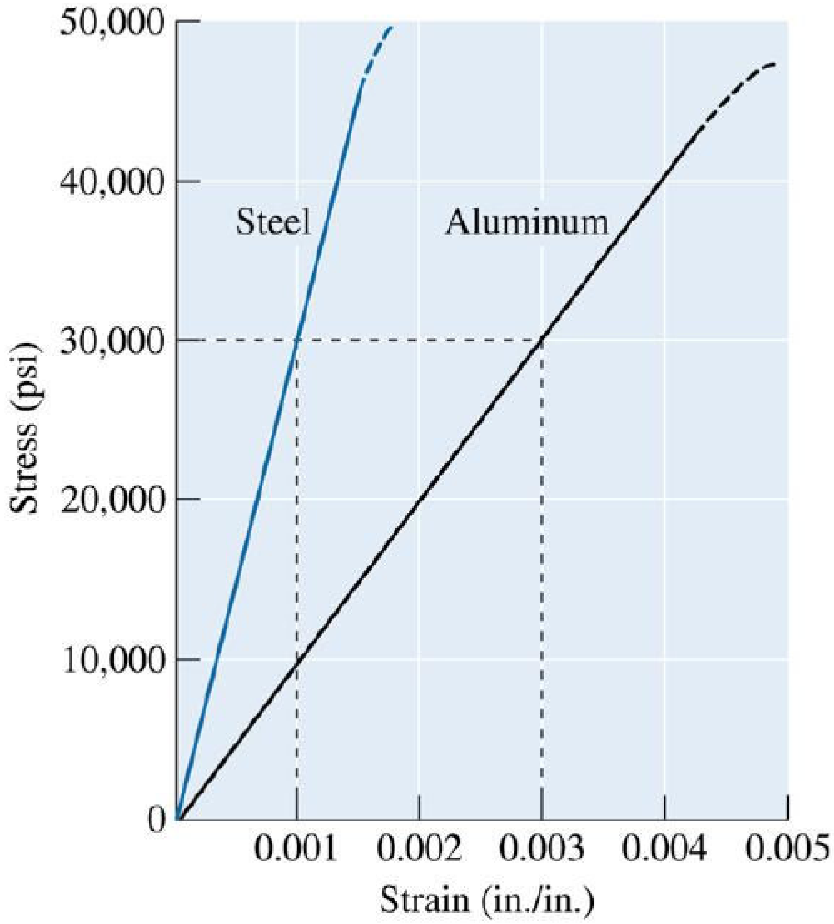


$$E = \frac{\Delta\sigma}{\Delta e} = \frac{(300-0)MPa}{(0.015-0.0)} = 2x10^5\,MPa$$

Stress / Strain Curve

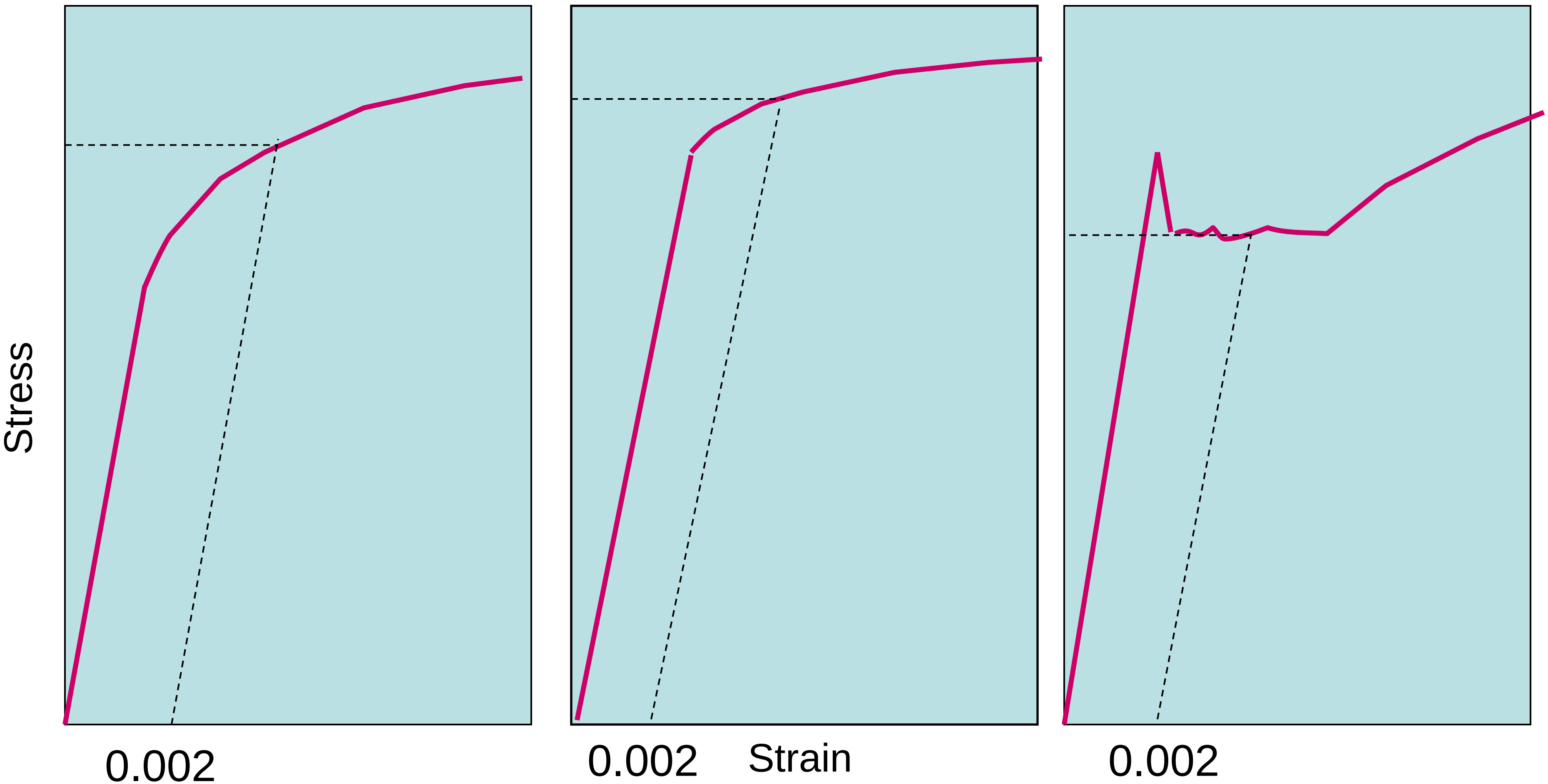


Stiffness of St vs. Al



Comparison of the elastic behavior of steel and aluminum. For a given stress, aluminum deforms elastically three times as much as does steel.

Yield stress - Plastic deformation

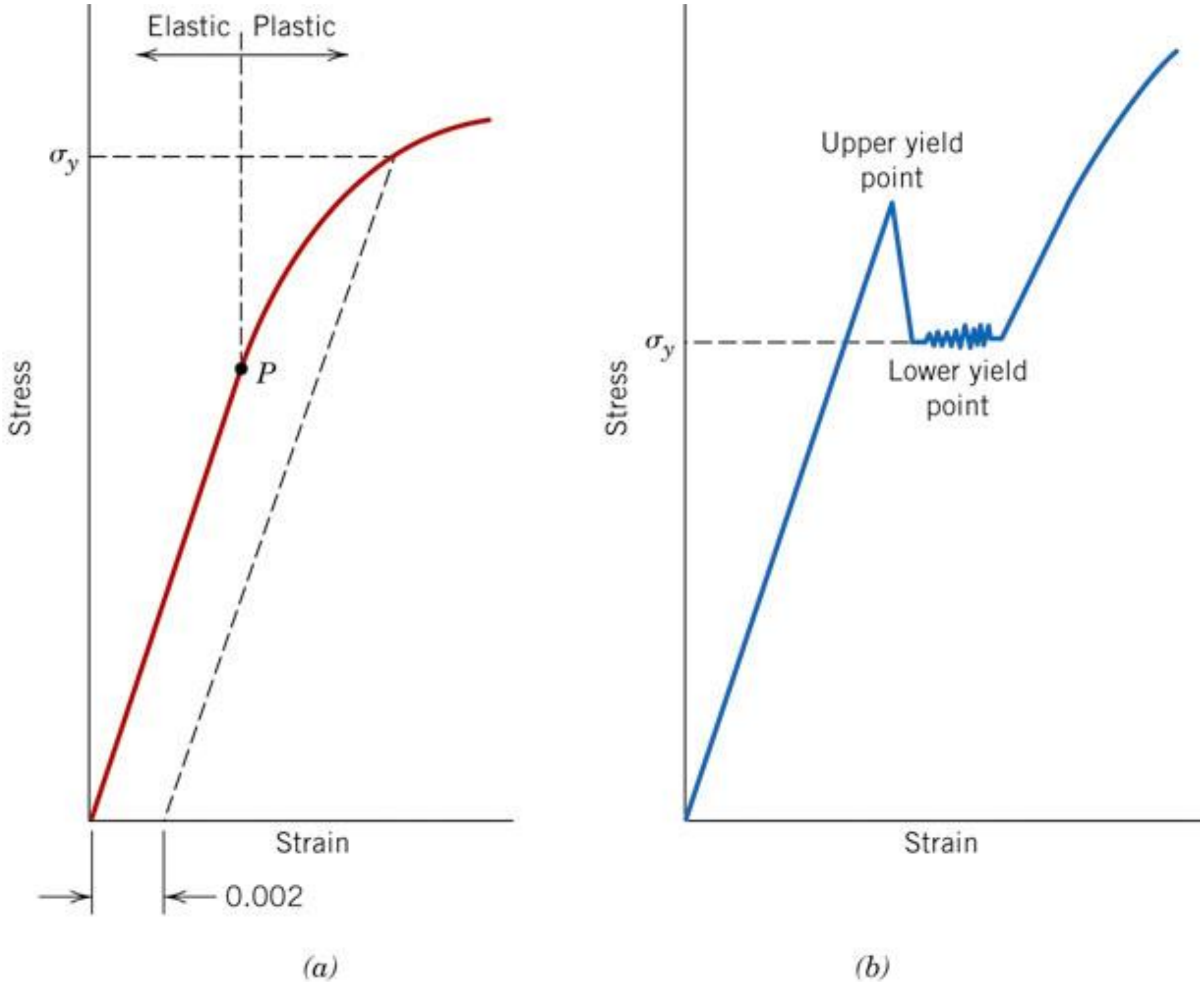


Most Metals - Al, Cu

Al-Alloys

Low carbon Steel

Comparison

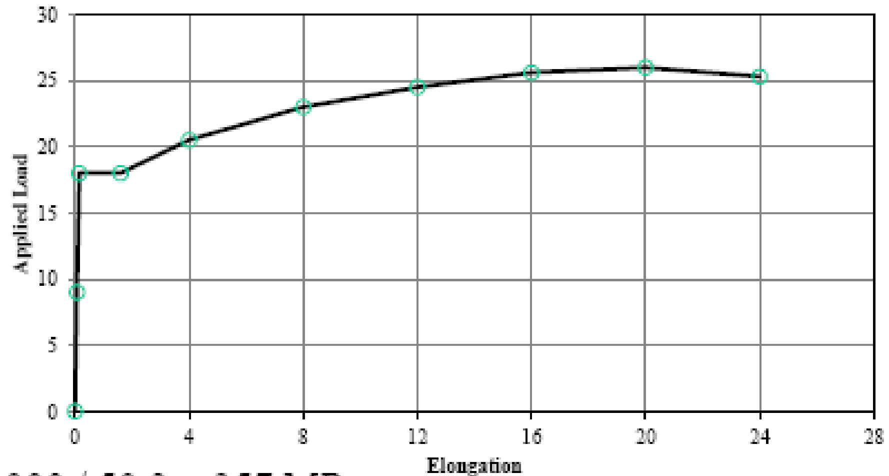


Elastic
Plastic
σ_y
P
Stress
Strain
0.002
(a)
Upper yield point
σ_y
Lower yield point
Stress
Strain
(b)

Solved Example

A static tension test was carried out on a plain steel rebar with circular cross section of diameter 8 mm. If the load-elongation readings were given the following table, then draw the load-deformation relation. Calculate the yield strength, the UTS 'ultimate tensile strength' and the percentage of elongation of the specimen.

Load (kN)	**0.0**	**9.0**	**18.0**	**18.0**	**20.5**	**23.0**	**24.5**	**25.6**	**26.0**	**25.3**
Elongation (mm)	**0.00**	**0.072**	**0.144**	**1.6**	**4.0**	**8.0**	**12.0**	**16.0**	**20.0**	**24.0**



Long Proportional Specimens:
gauge length = Lo = 10 do = 10*8 = 80 mm

Original Cross Sectional Area =
$Ao = \pi\, d^2 / 4 = \pi\, (8)^2 / 4 \quad = 50.30\ mm^2$

Yield Stress = σy = P_y / A_o = 18.0 * 1000 / 50.3 = 357 MPa

Ultimate Tensile Strength = UTS = = P_{max} / A_o = 26.0 * 1000 / 50.3 = 516= MPa

Percent age of elongation = $\frac{L_f - L_o}{L_o} \times 100 = \frac{24}{80} \times 100 = 30\%$