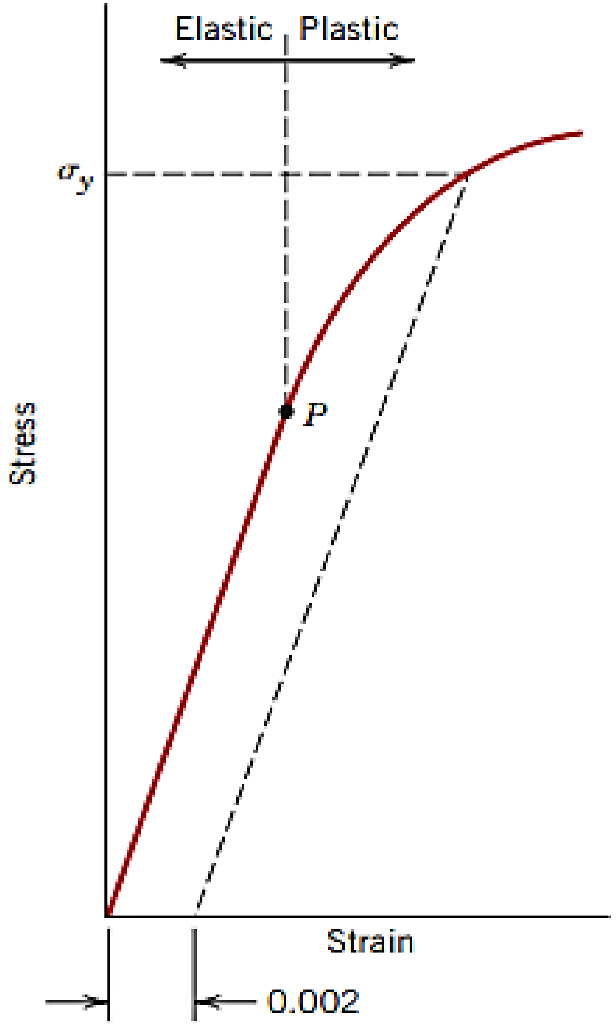
Plastic Deformation

- **Plasticity** is the ability of a **solid** material to undergo **deformation**, a non-reversible change of shape in response to applied forces. For example, a solid piece of metal being bent or pounded into a new shape displays plasticity as permanent changes occur within the material itself.
- In engineering, the transition from **elastic** behavior to **plastic** behavior is called **yield**.
- A totally brittle solid will fracture, either **suddenly** (like glass) or **progressively** (like cement or concrete).
- Most engineering materials do something different; they deform **plastically** or change their shapes in a **permanent way**.
- It is important to know **when**, and **how**, they do this.

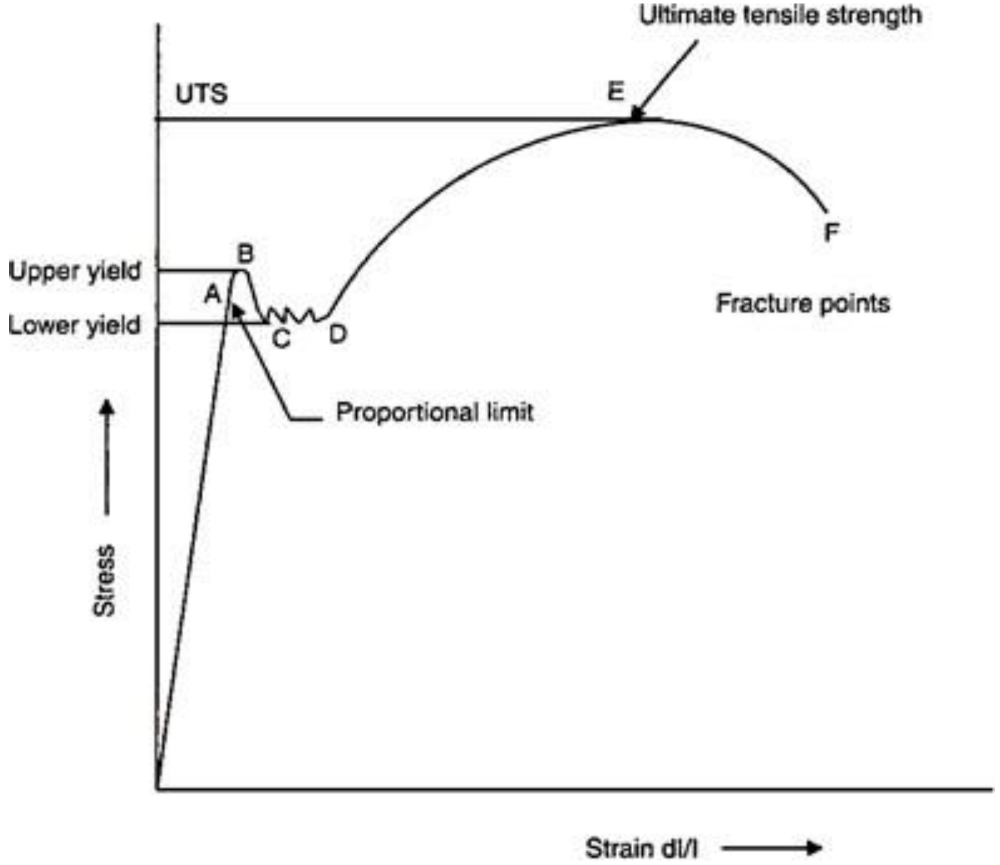
- It is desirable to know the **stress level** at which plastic deformation begins, or where the phenomenon of **yielding** occurs.



- For metals that show gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the **proportional limit**, as indicated by point P in the figure.
- To determine precisely this point, a straight line is constructed **parallel to the elastic portion** of the stress–strain curve at some specified strain offset, usually **0.002**.
- The stress corresponding to the **intersection** of this line and the stress–strain curve as it bends over in the plastic region is defined as the **yield strength** (elastic limit) σ_y

Plastic behavior in tension

- For metals that display the behaviour shown in the figure, the yield strength is taken as the **average stress** that is associated with the lower yield point.

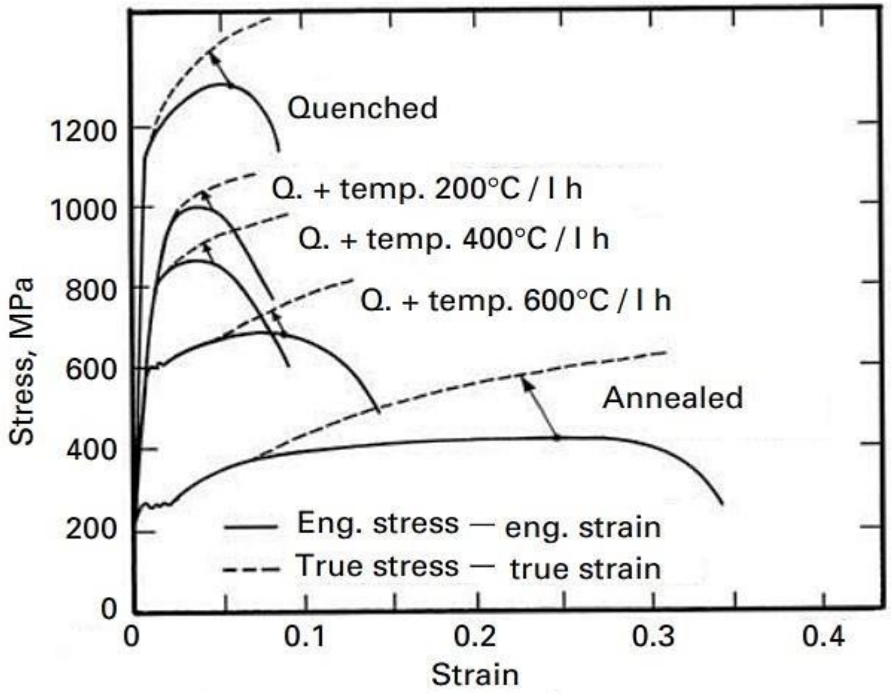


Tensile strength

- The properties of steel are highly dependent upon **heat treatment**.
- **Quenching** produces a hard, martensitic structure, which is gradually softened by tempering treatments at higher temperatures.
- The tensile strength TS is the stress at the maximum on the engineering stress–strain curve

- At this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck

✓ **Quenching** is the process of heating the workpiece to an **appropriate temperature** and maintained for a period of time. Then immersed in a quenching medium for rapid cooling. Quenching can refine grains and improve hardness, strength, wear resistance.

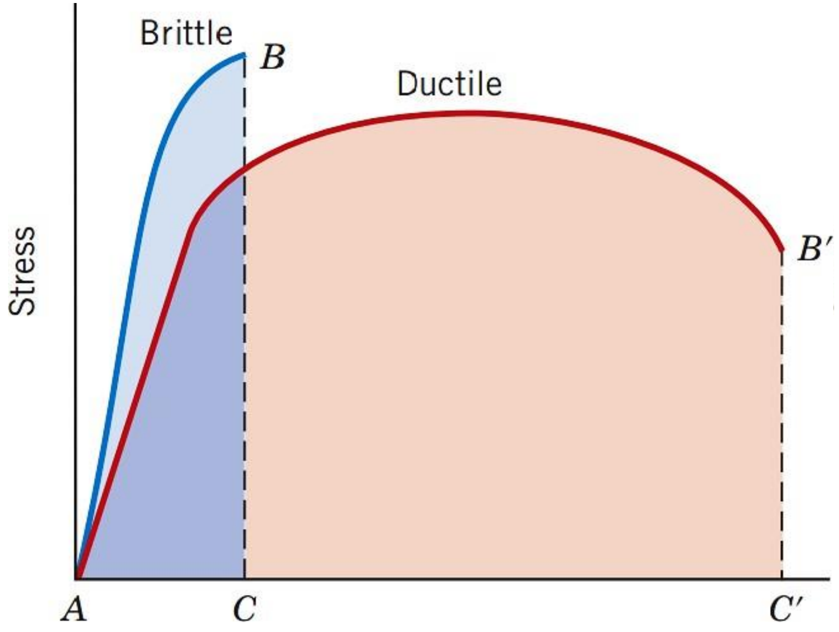


✓ **Annealing** is the process of heating a material **above** the **critical temperature** and maintaining the temperature for a specified period of time, then allowing the material to slowly cool down inside the furnace itself without any forced means of cooling. Annealing results in **increasing ductility** and **reducing the hardness**.

✓ **Tempering** is the process of heating a material **below** its lower critical temperature for a specified amount of time and then rapidly cooling in a certain way. Tempering **relieves** internal stresses and **adjusts** hardness, strength, plasticity and toughness to meet the different performance requirements of workpiece.

Ductility

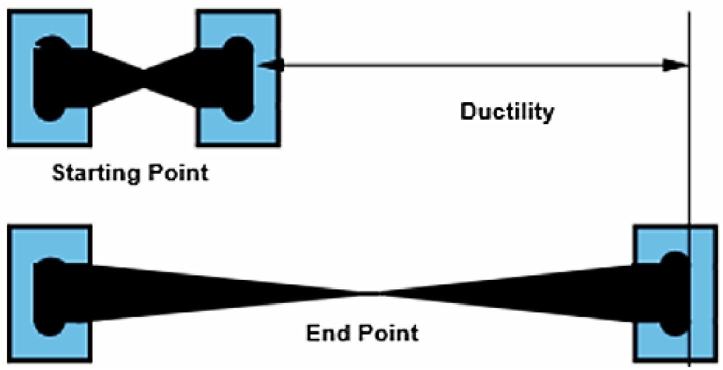
- Measure of the **degree of plastic deformation** that has been sustained at fracture (i.e. **plastic strain to fracture**).
- Material with very little or no plastic deformation upon fracture is termed brittle.
- Brittle materials approximately have a fracture strain < 5%.
- Percent- elongation (**%EL**) or percent reduction in area (**%RA**) can be used to express ductility.



$$\%EL = \left(\frac{l_f - l_o}{l_o}\right) \times 100$$

percentage of **plastic strain** at fracture

$$\%RA = \left(\frac{A_f - A_o}{A_o}\right) \times 100$$



Ductility

- The ductility of materials is important because:
  - ➢ it indicates to a designer the degree to which a structure will deform **plastically before fracture**.
  - ➢ it specifies the degree of **allowable deformation** during fabrication operations.

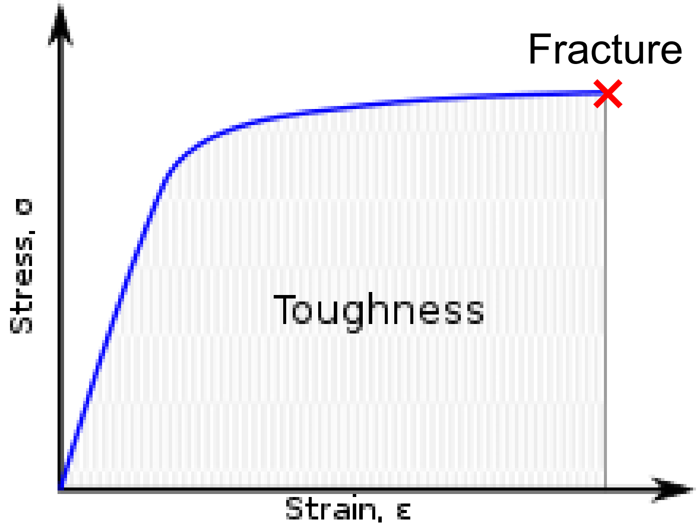
- Mechanical properties of metals obtained from tensile stress–strain tests are sensitive to:
  - ➢ prior deformation.
  - ➢ the presence of impurities.
  - ➢ heat treatment to which the metal has been subjected.

☹ yield and tensile strengths ⬇ when temperature ⬆

☺ ductility ⬆ when temperature ⬆

what is the elasticity !!!

Toughness

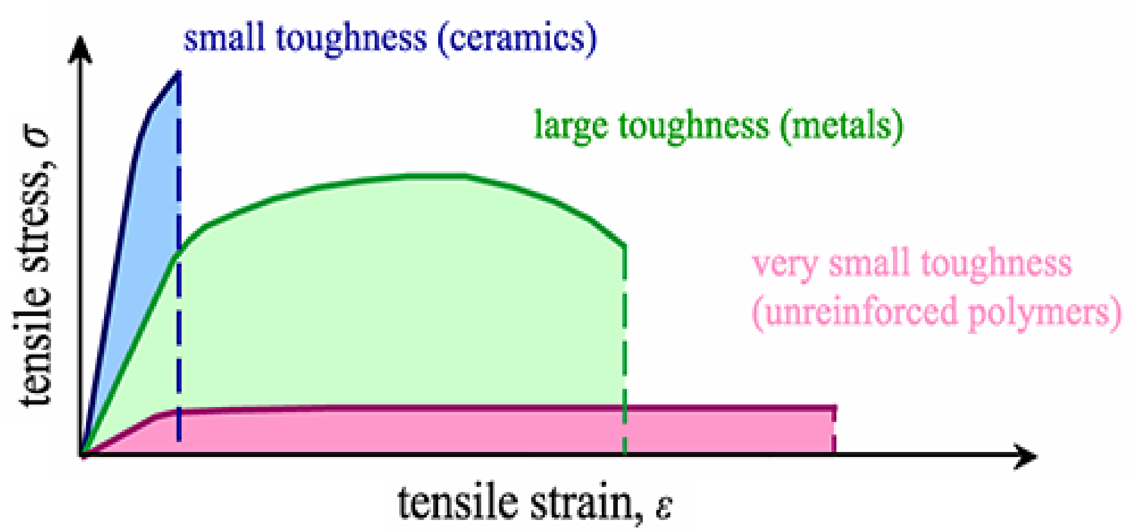


- Toughness is a fundamental material property measuring the ability of a material to **absorb energy** and withstand shock up **to fracture**; that is, the ability to absorb energy in the **plastic** range. In other words, toughness is the **amount of energy** per unit volume that a material can absorb **before rupturing** and is represented by the area under the (tensile) stress-strain curve.
- One must make the distinction between **impact toughness**, which most often occurs under **high** strain-rate loading above the yield point, and **fracture toughness**, which generally occurs under **lower** strain-rate loading.
- **Tough** materials can absorb a considerable amount of energy before fracture, while **brittle** materials absorb very little.
- A material with **high strength** and **high ductility** will have **more toughness** than a material with low strength and low ductility.

Toughness

- **WHAT** do you say about the following "brittle materials may be strong, but they are not tough" and **WHY** ?

- The **lower** the **hardness** and **strength**, the **higher** the **ductility** and **toughness** of a microstructure. However, embrittlement phenomena (e.g., quench embrittlement, temper embrittlement) are **exceptions** to this rule.



- **Impact toughness** testing evaluates the effect of **high strain-rate** loading and the energy absorbed by a sharped notched specimen for fractur under an impact.

- **Fracture toughness** testing evaluates stress intensities required to propagate unstable fracture in front of a sharp crack under conditions of maximum constraint of plastic flow.

True Stress and Strain

- For a cylindrical specimen under tensile test, As the applied force F increases, so does the length of the specimen. For an increase dF, the length l increases by dl.

$$d\varepsilon = \frac{dl}{l} \quad \rightarrow \quad \varepsilon = \int_{l_o}^{l} \frac{dl}{l} = ln\frac{l}{l_o}$$ longitudinal true strain

However, the commonly called engineering or nominal strain is:

$$\varepsilon_n = \varepsilon_e = \frac{\Delta l}{l} = \frac{l}{l_o} - 1 \xrightarrow{yields} l = l_o(1 + \varepsilon_e)$$

The term "stretch" or "**stretch ratio**" (λ) is often used to express the deformation;

$$\lambda = 1 + \varepsilon_e$$

The subscripts t and e can be used for true and engineering values. Then we have

$$\varepsilon_t = \ln(1 + \varepsilon_e)$$

True Stress and Strain

- Nominal (or engineering) stress is defined as

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

where A_o is the original area of cross-section.

- The relationship between the true stress and the engineering stress is

$$\frac{\sigma_e}{\sigma_t} = \frac{A}{A_o} \quad \rightarrow \quad \sigma_t = \sigma_e \frac{A_o}{A}$$

$$A_o l_o = Al \quad \rightarrow \quad A_o = A \frac{l}{l_o} = A(1 + \varepsilon_e)$$

- therefore, we have.

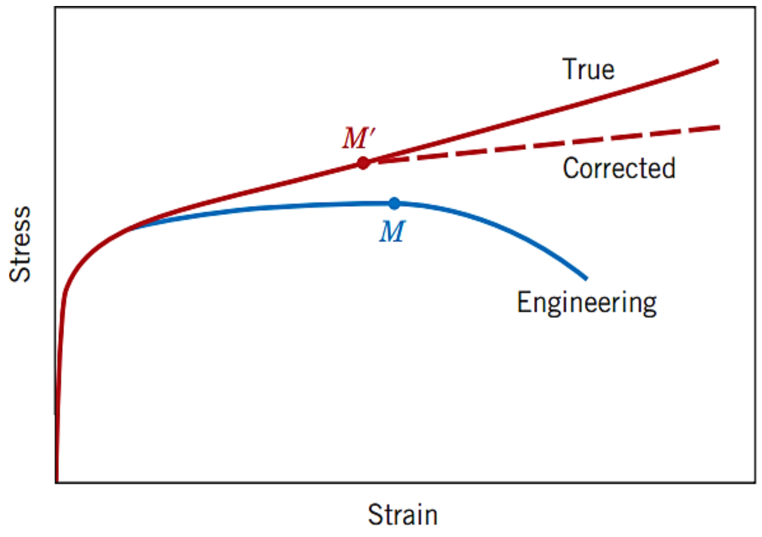
$$\sigma_t = \sigma_e(1 + \varepsilon_e)$$

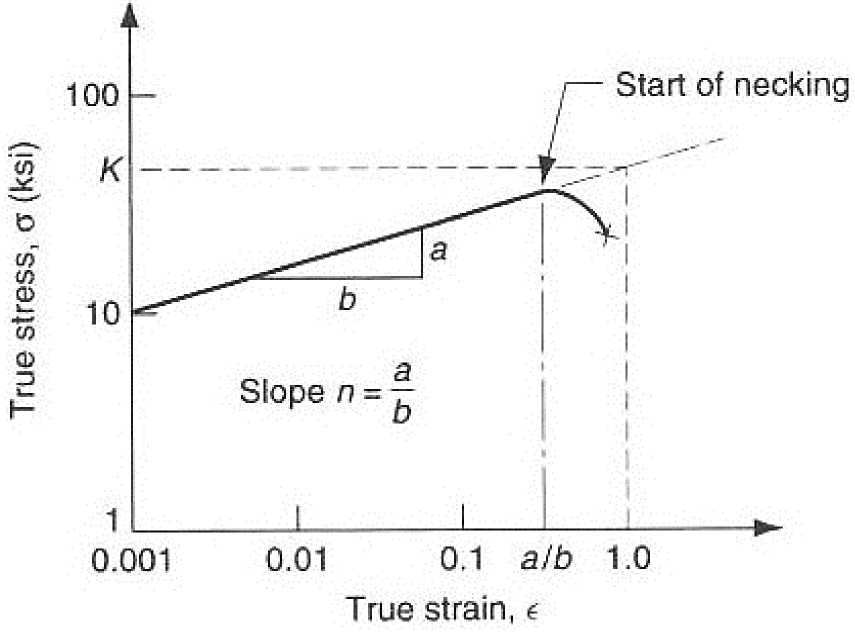
True Stress and Strain

- The true stress necessary to **sustain** increasing strain continues to rise past the tensile point M`.
- The formation of a neck is the introduction of a complex stress state within the neck region.
- As a consequence, the **correct** stress (**axial**) within the neck is **slightly lower** than the true stress.
- The **true strain** at fracture is much **higher** than the "**total strain**."
- For some metals and alloys the region of the true stress– strain curve from the onset of plastic deformation to the point at which **necking** begins may be approximated by

$$\sigma = K\varepsilon_p{}^n$$ (**Hollomon equation**)

This equation describes strain hardening as a power law function of stress and strain after yielding.





$$\sigma = \sigma_o + K\varepsilon_p{}^n$$ (Ludwik equation)

It is often preferred because it includes the stress up to the yield point, not just the stress produced by strain hardening.

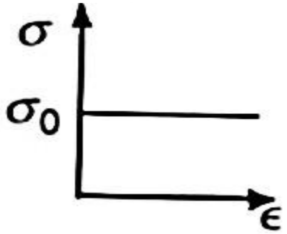
n=strain-hardening exponent *K*=strength coefficient

In cases where the material has already experienced some plastic deformation the following equation represents strain hardening.

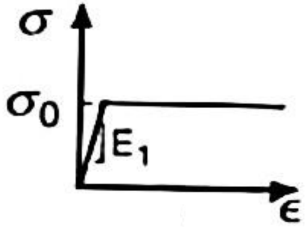
$$\sigma = K(\varepsilon_p + \varepsilon_0)^n$$ (Swift equation)

What is "flow stress"?

Shapes for stress-strain curves

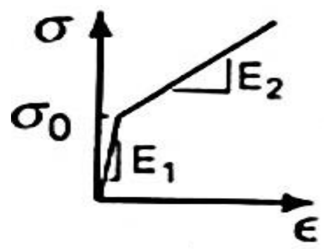


- If the material does **not work-harden**, the plastic curve is **horizontal**, and the idealized behaviour is called **perfectly plastic**.

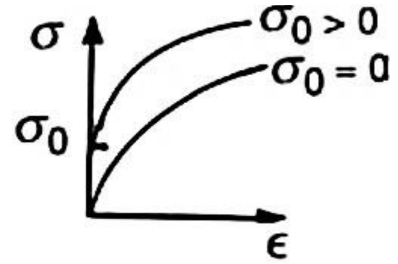


- If the plastic deformation is **not so large**, the portion of the curve cannot be neglected, and one has an ideal **elastoplastic** material.

- the ideal elastoplastic behaviour refers to a **linear curve** with two slopes E_1 and E_2 that represent the material's **elastic and plastic** behaviour, respectively.



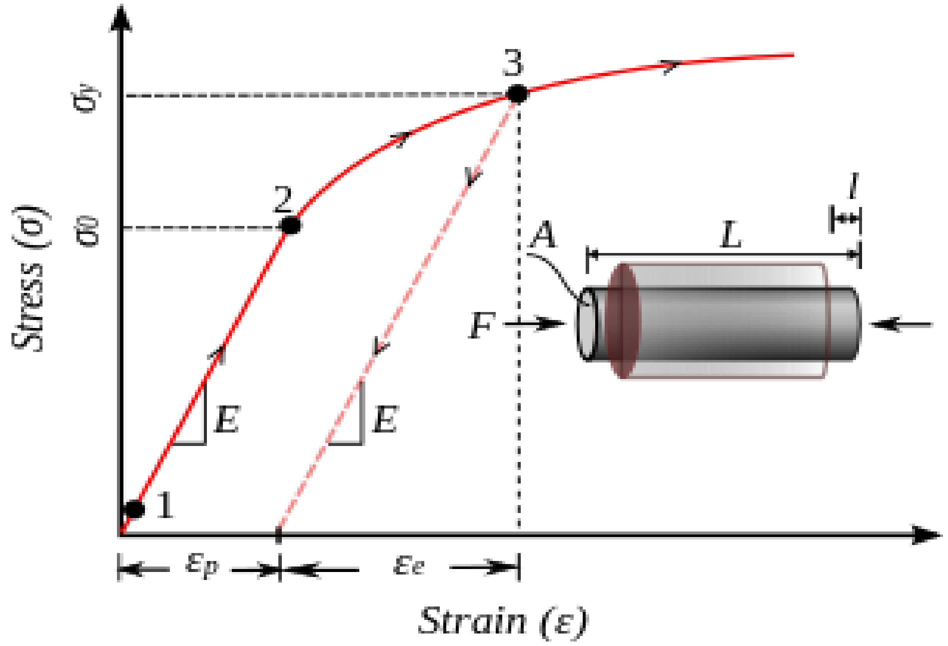
- A better representation of the **work-hardening** behaviour is obtained by assuming a **gradual decrease** in the slope of the curve as plastic deformation proceeds.



Plastic Strain

- The total strain ε_{total} at any point beyond the yielding point is equal to the elastic strain component ε_{el} plus the plastic strain component ε_{pl}.

$$\varepsilon_{total} = \varepsilon_{el} + \varepsilon_{pl}$$



- The strain hardening exponent depends on:
  - The Nature of the material
  - The temperature at which it is work-hardened
  - The strain

Necking Phenomenon

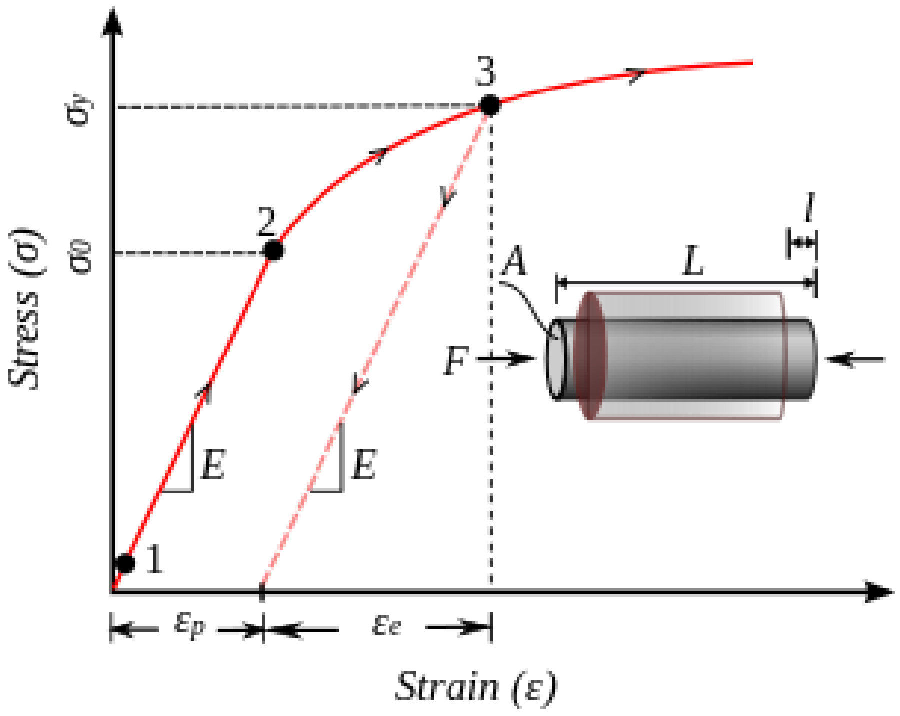
- Necking corresponds to the part of the tensile test in which **instability** exists.
- Necking starts when the **increase** in stress due to the reduction in cross-sectional area starts to **exceed** the **increase** in load-bearing ability because of work-hardening.
- For metals that **do not** exhibit any work hardening capability, necking should start **immediately** at the **onset of plastic flow**.
- The state of stress at the center of a neck is **not uniaxial tension**. (The external boundaries of the neck generate the **tensile components perpendicular to the axis** of the specimen. (**How**?)
- Bridgman showed that the **effective** part of the stress (the part of the axial stress causing yielding).

$$\bar{\sigma} = \frac{\sigma_{av}}{(1 + 2R/r_n) ln(1 + r_n/2R)}$$

σ_{av} is the measured stress (F/A), R is the radius of curvature of the neck and r_n is the radius of the cross section in the thinnest part of the neck

Strain Hardening or Work Hardening

When a material is permanently deformed, the **dislocations** move until they are **stopped** by something else in the crystalline lattice, like grain boundaries or alloying elements. However, one of the most effective dislocation-stoppers is another dislocation. When dislocations run on different planes and intersect, they cannot pass through each other. The dislocations pile up against each other and can become intertwined.



This dislocation **entanglement prevents any further permanent deformation** of that particular grain without the use of significantly greater energy. This increases the strength of the material under any subsequent loading.

Failure Theories

- *No universal theory of failure for the general case of material properties and stress state.*
- *Several hypotheses have been formulated which are characterized as theories.*

- Ductile materials ➡ $\varepsilon_f \geq 0.05$ and $S_{yt} = S_{yc} = S_y$

  Brittle materials ➡ $\varepsilon_f < 0.05$ and $S_{yt} \neq S_{yc\,y}$

- **Ductile materials (yield criteria)**
  I. Maximum shear stress (**MSS**).
  II. Distortion energy (**DE**).
  III. Ductile Coulomb-Mohr (**DCM**).

- **Brittle materials (fracture criteria)**
  I. Maximum normal stress (**MNS**).
  II. Brittle Coulomb-Mohr (**BCM**).
  III. Modified Mohr (**MM**).