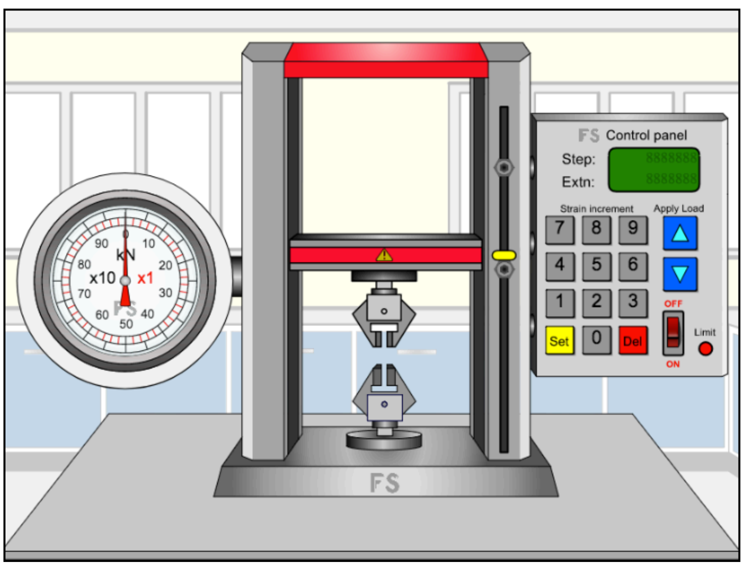
Tensile testing experiment

Background



Where do tensile properties come from?

All materials are made of **atoms** that are **bonded** together. Under light loading, materials stretch and then return to their original length when the load is removed. This **elastic** stretching is due to the **atomic bonds** stretching, all through the material. These stretched bonds create a force that pulls the atoms towards each other, which is why the material goes back to its original length.

Under larger loads (stresses), materials stretch permanently due to '**plastic**' deformation and don't return to their original length. This is because materials contain '**defects**' where atoms don't line up perfectly. During plastic deformation atoms jump position so that the defects move too. When the load is removed, the defects remain in their new positions, so the change in length of the material due to this remains.

When a large enough load is placed on a material, it **fractures**. This involves severing the atomic bonds across a plane in the component and overcoming the energy associated with each bond. For a completely brittle material that shows no plastic deformation, the **fracture energy** measured by breaking a component is equal to the sum of all the atomic bond energies where it has fractured.

Different materials have different atoms with different bond strengths and with different arrangements of defects. This is why materials have so many different tensile properties.

And so?

Tensile properties of materials are incredibly important to us. Strong materials may be used to create huge structures but the strength comes from the way its atoms are arranged and bind to each other. If we create **stronger**, **tougher**, **harder** or **stiffer** materials then we can develop new applications or reduce how much material is required for existing applications. Achieving this may involve changing the blend of atoms in a material (its composition) and how the atoms are arranged by changing the manufacturing and processing method. The Tensile Test is the principal way in which these properties are measured and is applied to all types of material.

Structural materials are required to withstand a variety of applied loads in use. Understanding how these materials respond to the applied loads is vital for informed materials selection. Here we investigate how materials behave under *tensile loading* (loads applied along the length of a material to cause stretching).

Stress and strain

Materials respond to tensile loading by elongating. The applied stress σ to the material is defined as:

$$\sigma = \frac{F}{A} \qquad (1)$$

where *F* is the loading force and *A* is the cross-sectional area of the sample.

The strain response ε that describes the elongation is defined as:

$$\varepsilon = \frac{\Delta l}{l} \qquad (2)$$

where l is the original sample length and Δl the change in length.

A tensile test measurement may be considered as measuring the strain response of a material to progressively larger stress. In practise, analysis is often performed by specifying a strain and measuring the stress required to achieve this. These measurements usually calculate the stress in terms of the original sample area, A_0, giving what is known as *engineering stress* σ_e:

$$\sigma_e = \frac{F}{A_0} \qquad (3)$$

Similarly, tensile test measurements usually provide the *engineering strain*, which is referenced to the original length l_0 of a sample:

$$\varepsilon_e = \frac{\Delta l}{l_0} \qquad (4)$$

Plotting stress against strain reveals a material's tensile behaviour (Figure 1).

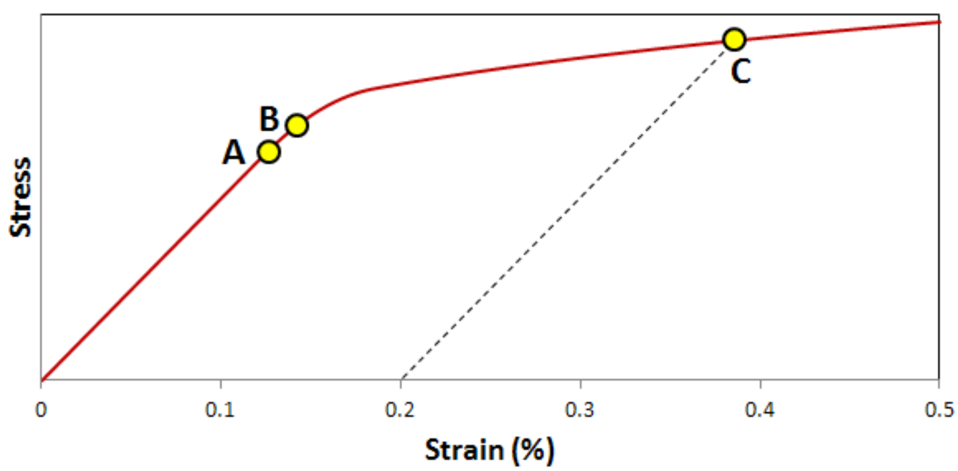


Figure 1. Stress-strain curve of a material under low stress and key points labelled.

At low stresses, materials respond in an elastic manner, so that removal of the stress results in a sample returning to its initial length (Fig. 1). This elastic region is almost wholly linear, with the constant of proportionality, the Young's modulus or elastic modulus, E, given by:

$$E = \frac{\sigma}{\varepsilon} \qquad (5)$$

Engineering stress and strain can be used in Eq 5 with a good degree of accuracy.

The limit of the **linear** response is termed the ‘proportionality limit’ (point A in Fig. 1) while the limit of the elastic region is termed the ‘elastic limit’ (point B in Fig. 1). The stress corresponding to the elastic limit is termed the ‘yield strength’, σ_Y. Elongation in the elastic region at the atomic scale is due to lengthening of bonds. This is completely reproducible, so that when the stress is removed, the sample returns to its original length and no work is done. Beyond the elastic limit, however, non-reproducible processes such as movement of dislocations start to occur that gives a non-linear stress-strain response (Fig. 1). When a material is taken into the this ‘plastic region’ of deformation, removal of stress sees a reduction in strain along a path in a stress-strain plot that has a gradient equal to that of the elastic region, i.e. the Young’s modulus E. Since determining the elastic limit can sometimes be difficult, an alternative approach is to define the ‘0.2 % offset yield strength’ as the stress required to increase the relaxed strain of a sample by 0.2 % (shown as the stress corresponding to position C in Fig. 1).

Under greater stress, materials eventually exhibit a maximum in σ_e, corresponding to the ‘ultimate tensile strength’ or ‘UTS’ (Fig. 2). Beyond this, the sample tends to undergo runaway elongation to fracture (Fig. 2).

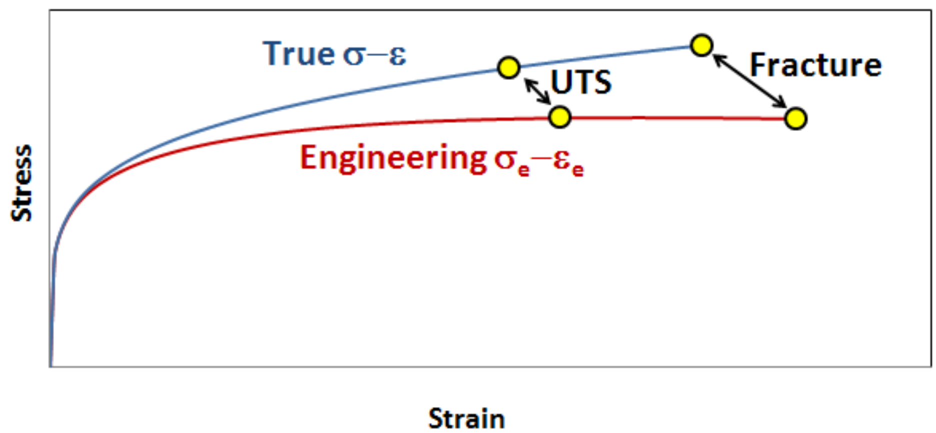


Figure 2. True and engineering stress-strain curves for a material under tensile loading.

Engineering stress and strain are referred to sample dimensions before the start of loading. These are approximations (usually given by a tensile test) to the ‘true’ stress and strain in a sample, for which dynamic (changing) sample dimensions are appropriate. For example, the cross-sectional area of a sample usually narrows during tensile loading, causing A to reduce during a measurement. The ‘true stress’ σ_T and ‘true strain’ ε_T can be calculated using the following relations:

$$\sigma_T = \sigma_e \ln(1+\varepsilon_e) \qquad (6)$$

$$\varepsilon_T = \ln(1+\varepsilon_e) \qquad (7)$$

The true stress becomes larger than the corresponding engineering stress, while the true strain becomes smaller than the corresponding engineering strain. A comparison of true and engineering stress-strain curves is shown in Fig. 2.

The strain energy E_{st} at any point in a stress-strain plot is determined by taking the area beneath the curve (Fig. 3), i.e.:

$$E_{st} = \int \sigma \, d\varepsilon \qquad (8)$$

In the elastic region, this gives (with appropriate substitutions of Eq. 1):

$$E_{st} = \tfrac{1}{2}\sigma\varepsilon = \tfrac{1}{2}E\varepsilon^2 = \tfrac{1}{2}\frac{\sigma^2}{E} \qquad (9)$$

It should be noted that the units of E_{st} are in J.m^{-3}, so E_{st} is an **energy density** term. True stress and strain are required for an exact value of E_{st}, although this can be approximated with the engineering stress and strain in the elastic region with a high degree of accuracy.

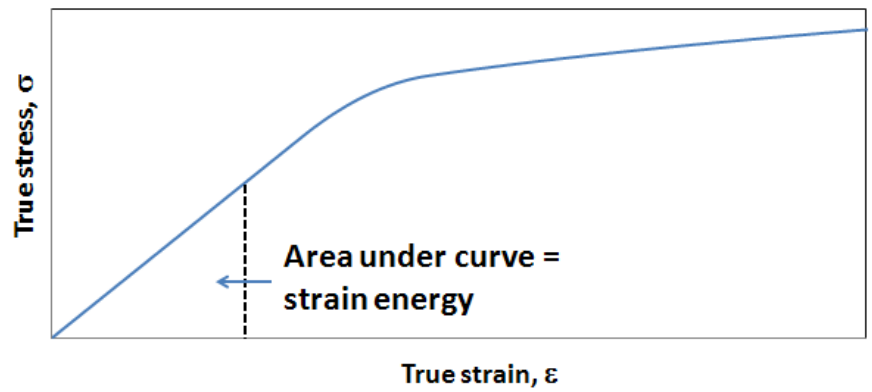


Figure 3. Calculation of strain energy from stress-strain plot.

Using Eq. 8 at the elastic limit (Fig. 4) gives the 'modulus of resilience' while using Eq. 8 at the point of fracture (Fig. 5) gives the 'modulus of toughness'. Again, these are energy density terms and can be useful for describing the energy performance of materials under tension.

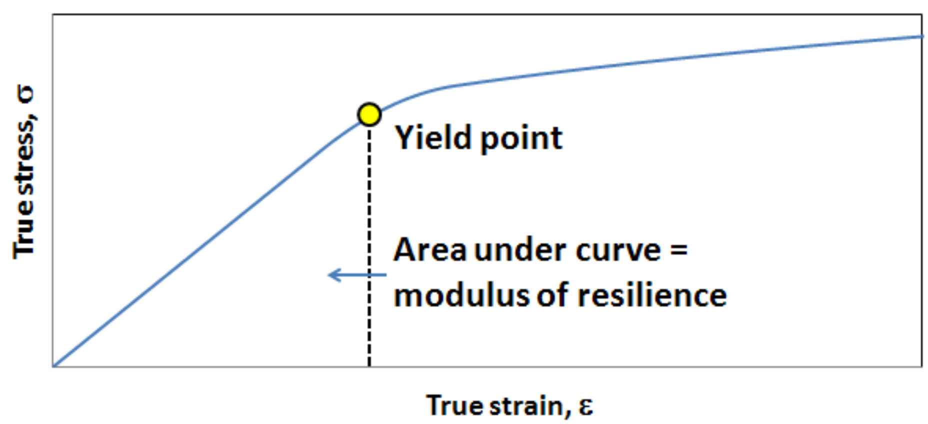


Figure 4. Calculation of modulus of resilience.

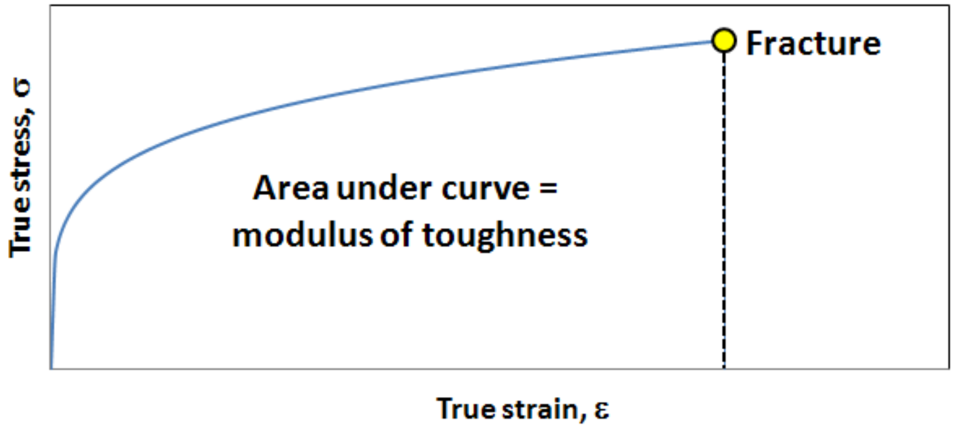


Figure 5. Calculation of modulus of toughness.

Reducing the loading to zero relaxes a material and releases any elastic (reproducible) strain energy. The area of the stress-strain plot enclosed by the curve then provides the **work done** in deforming the sample (Fig. 6). Clearly, if confined to the elastic region, there is no deformation and no net work done. Once in the plastic region, the work done (per unit volume) increases with the applied stress.

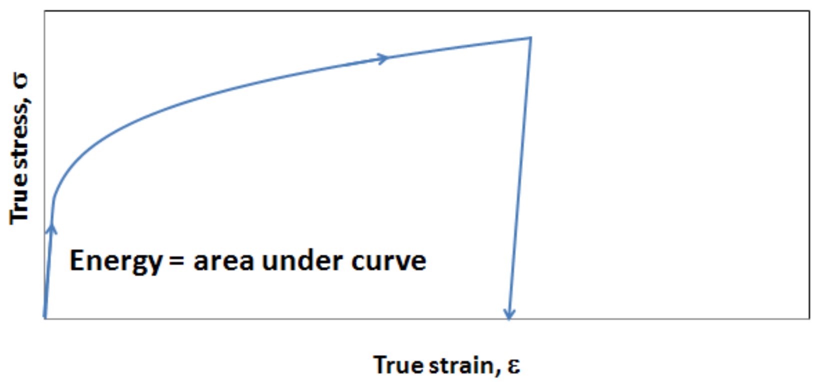


Figure 6. Calculation of work done (energy density) in tensile deformation.

A material can be **work hardened** (or 'strain hardened') by deformation up to the UTS (Fig. 7). Upon relaxation (removal of the load stress), large stress must be applied to create any appreciable elongation. Work hardening is usually achieved through taking a material through successive cycles of plastic deformation (Fig. 7). The work done in each of these cycles can be calculated independently as the area enclosed by the stress-strain curve and the strain axis.

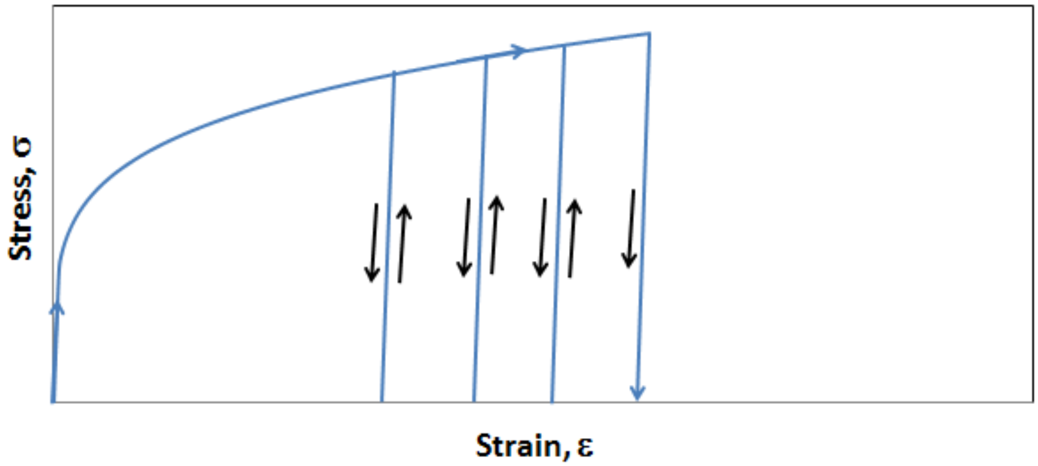


Figure 7. Strain cycling to work harden a sample.