ECOLE DES MINES DE NANCY

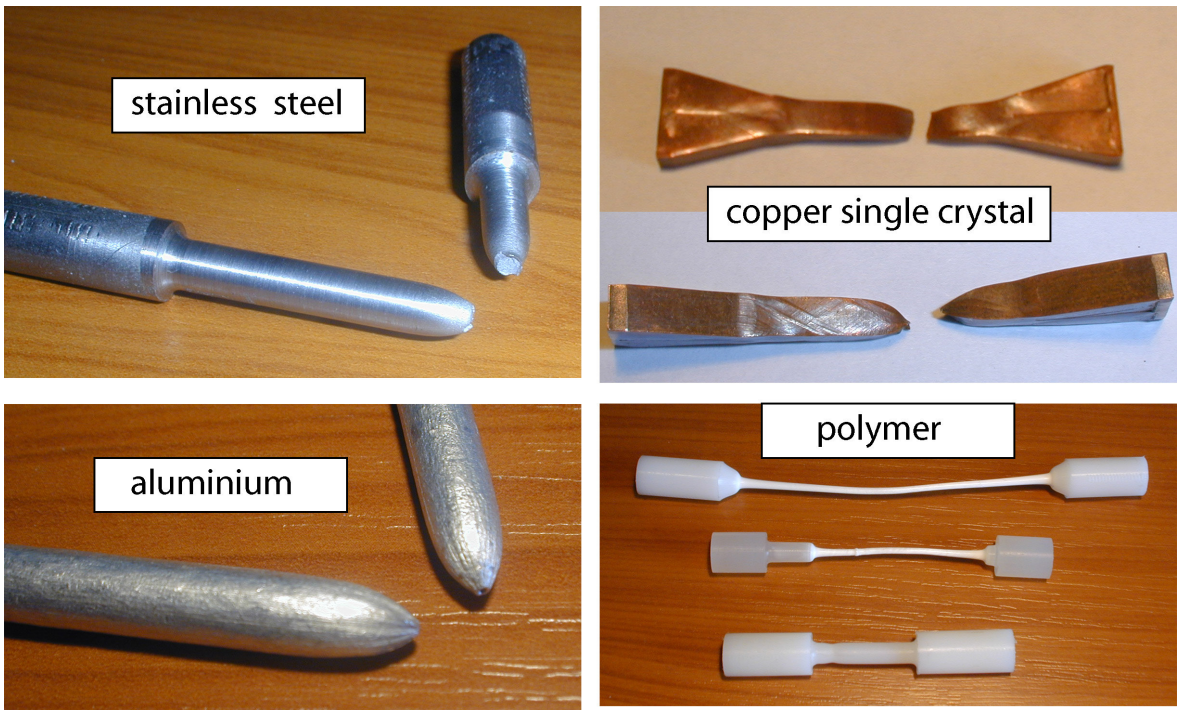
MECHANICAL TESTING OF MATERIALS

Tomáš Kruml

Jean-Pierre Michel

with the participation of John Robinson

version 2005



CONTENTS

1. INTRODUCTION

This note describes the most important and most frequent *mechanical tests*. It contains many technical terms which a future engineer should master in English as well as in French. This is the reason why the text is written in English and completed by a short English-French dictionary (the words in the dictionary are written in *italics* in the text). Moreover, some differences between British (UK) and American (USA) terminology are given.

The *mechanical properties* reflect the response of a material subjected to actions of external forces. Important mechanical properties are, for example, *Young's modulus, yield stress*, *ultimate tensile stress*, *ductility*, *hardness*, *resilience*, *toughness*, etc. In order to measure these properties, it is necessary to perform precise laboratory tests. The tests are *standardised* so that the results can be used by materials and metallurgical engineers and researchers all over the world.

The *stress state* which develops in the *specimen* due to the external *loading* during a mechanical test can be divided into 4 categories, as shown by Mohr's diagram:

- tensile (the case of the *tensile test*)
- compressive (*compression test*)
- pure shear (torsion test)
- complex stress state. In the *bending test*, stress is uniaxial (compressive in one half of the specimen and tensile in the other part) but heterogeneously distributed. In the case of multi-axial tensile tests, two or three normal components of the stress tensor are equal and positive, the stress being homogeneous in the specimen. *Shears* and inhomogeneous stresses develop in a body deformed in the torsion test. *The hardness* test and the Charpy *impact* test lead to complex and unexploitable stress state.

The load applied to the specimen varies with time in a defined way. The tensile test is performed at a constant *strain rate*. During the *creep* test, the stress is kept constant. The term *fatigue* is used if the specimen is damaged by *cyclic deformation*.

The main part of this note is focused on the uniaxial tensile test, which is surely the most important of all mechanical tests. It has been already partially described in sections 4.2.2, note "Elasticité" and 5.2, note "Notions complémentaires...". Other mechanical tests (the compression test, the multiaxial tensile test, the bending test, the torsion test, the impact test and the hardness test) are commented only very briefly. The specific testing conditions of uniaxial fatigue test and creep test are described in more details, because both tests have quite important applications in the industry.

This note describes the behaviour of polycrystalline materials. Specificities of deformation and data treatment in the case of single crystals will be discussed in further notes.

2. TENSILE TEST

2.1 Description of the test

The tensile test machine applies a gradually increasing uniaxial tensile load on the specimen, usually until *fracture* (fig. 2.1).

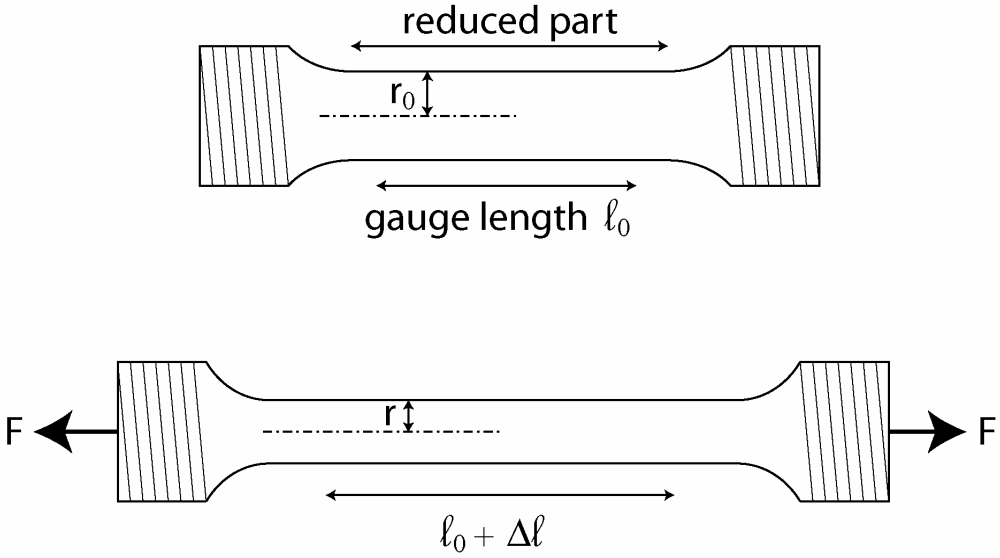


Figure 2.1 Schematics of the tensile test.

The *specimen's heads* are fixed in the holding *grips*. The reduced part of the specimen has a uniform cross section, most often circular but rectangular specimens are also used. The reduced part has to be long enough (at least 4 times its diameter; international standards impose $\ell_0 = 5.65\sqrt{S_0}$, where $S_0 = \pi r_0^2$) in order that the stress tensor $\overline{\overline{\sigma}}$ in the central part of the specimen, of *gauge length* ℓ_0, is purely uniaxial:

$$\overline{\overline{\sigma}} = \begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The strain tensor $\overline{\overline{\varepsilon}}$ is less simple: in the case of an isotropic material deformed elastically, $\overline{\overline{\varepsilon}}$ is diagonal but in strongly anisotropic materials *shear strains* may develop so that the tensile axis is no longer the principal strain axis.

Exercise: Find $\overline{\overline{\varepsilon}}$ for an isotropic material, characterized by Young's modulus E and *Poisson ratio* ν, in the elastic domain ($\sigma_{11} = \sigma$).

Solution:
$$\varepsilon = \begin{bmatrix} \sigma/E & 0 & 0 \\ 0 & -\nu\sigma/E & 0 \\ 0 & 0 & -\nu\sigma/E \end{bmatrix}$$

Usually, the function $\sigma_{11}(\varepsilon_{11})$ is plotted and a notation without indices ($\sigma \equiv \sigma_{11}$ and $\varepsilon \equiv \varepsilon_{11}$) is used.

2.2 Data treatment

2.2.1 Force – elongation curve

Two parameters are recorded during the test: the applied force F and the corresponding *elongation* of the specimen $\Delta\ell$. The *raw data curve* F ($\Delta\ell$) is never used in practice. The reason is visible in fig. 2.2 – one could obtain a false impression that the *strength* of Cu *single crystal* is comparable with that of high Mn *steel*, but of course the difference in the initial *cross-sectional area* S_0 has to be taken into account.

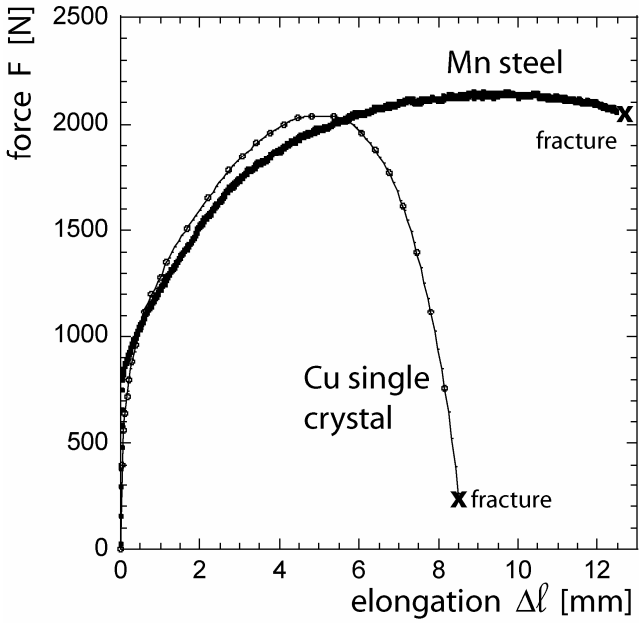


Figure 2.2 Comparison of two tensile raw data curves for a Cu single crystal (S_0 = 16 mm², ℓ_0 = 15 mm, room temperature) and high Mn steel (S_0 = 4.4 mm², ℓ_0 = 24.3 mm, 400° C). The elastic part at the onset of the curves is almost vertical.

Remark: As force is applied and $\Delta\ell$ is measured, the $\Delta\ell$ (F) graphic seems to be more appropriate than F ($\Delta\ell$). However, since F can both increase and decrease, $\Delta\ell$ (F) is not always an *invertible function*. This is the reason why F ($\Delta\ell$) graphics are preferred.

2.2.2 Engineering stress-strain curve

The easiest normalization of F and $\Delta\ell$ is the definition of *engineering stress* s and *engineering strain* e (see the note "Notions complémentaires...", section 3.2.1):

$$s = \frac{F}{S_0} \qquad e = \frac{\Delta\ell}{\ell_0}$$

where S_0 is the initial cross-sectional area and ℓ_0 the initial gauge length. The usual unit of the engineering stress is MPa. The engineering strain is either unitless or expressed as a percentage.

This approach does not consider the variations of the cross-section and gauge length during the test; nevertheless, it is the most often used data treatment for engineering applications. It gives a more realistic comparison of the tensile properties of materials than the raw data curve, see fig. 2.3.

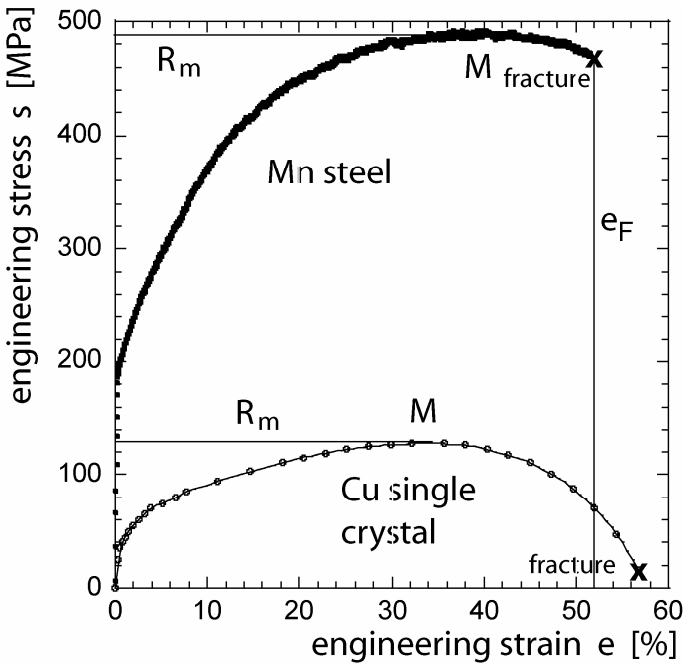


Figure 2.3 Engineering tensile stress-strain curves, the same specimens as in fig. 2.2.

Several important material characteristic are determined from the engineering stress-strain curve and from the measurement of the specimen's geometry before and after the test: Young's modulus, yield stress, ultimate tensile stress, elongation and area reduction.

a) Young's modulus E

Young's modulus is a slope of the $\sigma(\varepsilon)$ curve in the elastic domain. Since s and e are not too different from the *true stress* σ and *true strain* ε (defined in the next chapter) for small strains, it is possible to measure E as the slope of

the s (e) curve. The elongation must be measured directly on the specimen (see chapter 2.4.2). Unfortunately, due to *anelastic* effects, the value of E is always underestimated and an experimental error of at least 5-10% has to be expected. More precise assessments of E are made by the measurement of the elastic wave propagation velocity.

b) Yield stress $R_{0.2}$

In general, most structures are not supposed to change their dimensions permanently when a load is applied. It means that all parts of the structures must deform only elastically. The stress level at which plastic deformation begins (or where the phenomenon of *yielding* occurs) – the yield stress - is therefore of primary importance.

For some materials, the departure from the linear part of the curve is smooth and not easily detectable. Therefore, to avoid any subjectivity, the stress $R_{0.2}$ at 0.2% of plastic strain is measured as shown in fig. 2.4. This is taken to be the yield stress.

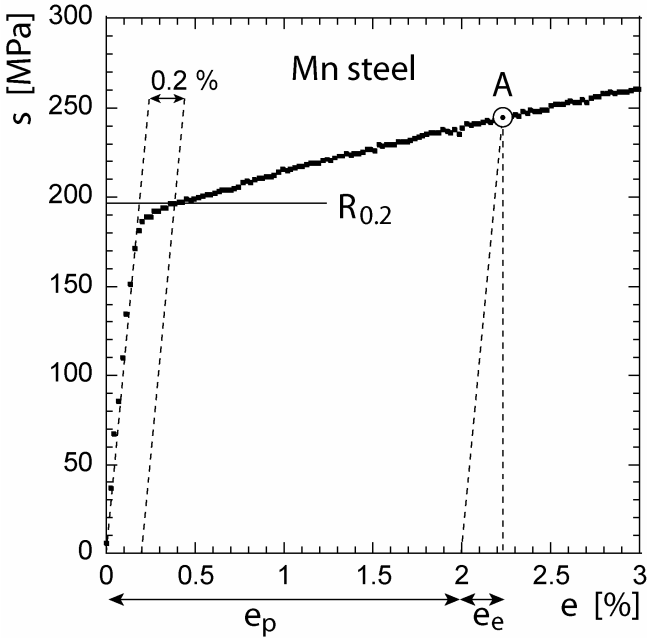


Figure 2.4 Beginning of the curve from figure 2.3 and the definition of $R_{0.2}$.

c) Ultimate tensile stress R_m

Most materials *harden* during plastic deformation. This means that it is necessary to continuously increase the stress in order to continue the plastic deformation. The engineering stress – strain curves show in general a maximum and then decrease until the fracture appears.

If the applied stress overcomes the $R_{0.2}$ value, the structure will deform permanently but it will not fracture immediately. Therefore it is interesting to know the maximum stress level which the material can support before the fracture. This stress is called the ultimate tensile stress, R_m (see fig. 2.3).

d) Fracture elongation e_F

Another measured parameter is the permanent (= plastic) elongation at the fracture e_F (see figure 2.3), expressed most often in percent. It can be measured from the stress-strain curve or by the measurement of the difference in length between the broken specimen and its initial length.

e) Area reduction Z

This parameter is defined by:

$$Z = \frac{S_0 - S_F}{S_0} \times 100$$

where S_F is the cross-sectional area at the point of fracture. S_F has to be measured after the test. The unit of Z is percent.

Remarks:

1. The term "*proportional limit*" is used for the point of departure from the linear part of the curve and is almost a synonym for the yield stress. In fig. 2.4, the proportional limit is about 180 MPa, while $R_{0.2}$ is 197 MPa.

2. At any point of the curve,

$$e = e_e + e_p = \frac{s}{E} + e_p$$

with e the total strain, e_e the elastic strain and e_p the plastic strain. If s increases after the yield point, both e_p and e_e increase, i.e. elastic strain of the specimen is larger at point M than at the yield point.

3. The term *strength* is sometimes used instead of stress (i.e. yield strength, ultimate tensile strength). While "stress" is related to external loading, "strength" is understood as a material property.

4. The Poisson ratio ν can only be calculated if the reduction of the cross-sectional area is independently measured in the elastic part of the curve.

5. Contrary to the fracture elongation, the fracture stress is not interesting (fragile materials are an exception).

2.2.3. Anelasticity

Anelasticity is a special type of plastic deformation. It appears above a certain stress level which can be regarded as a true elastic limit (σ_{et}). This limit is not well defined; it decreases when the precision of the stress measurement increases. For stresses between σ_{et} and σ_a, anelasticity is superposed to the elastic deformation, with the irreversible plastic deformation appearing above σ_a. Anelastic deformation disappears (but not immediately) if the external force is removed. From the thermodynamic point of view, anelasticity is an irreversible transformation since it is accompanied by the degradation of mechanical energy into heat but it is reversible in the mechanical sense since it disappears if stress turns down to zero.

Anelastic deformation is always retarded compared to stress, while elastic deformation is in phase with stress; anelasticity is therefore a phenomenon of mechanical *hysteresis*. This is clearly shown by a *loop* shape of *loading – unloading cycles*. Anelasticity is often small, but it cannot be neglected if precise values of elastic deformation are needed, e.g. for the determination of Young's modulus. It is especially important in certain classes of polymers, where it plays a role of mechanical amortisation of vibrations by transforming mechanical energy into heat.

Figure 2.5 shows real tensile curves measured in a steel with several loading – unloading cycles which makes the anelastic part of deformation visible. The loop width characterise the phase shift between anelastic deformation and stress. The loop surface is proportional to the dissipated energy.

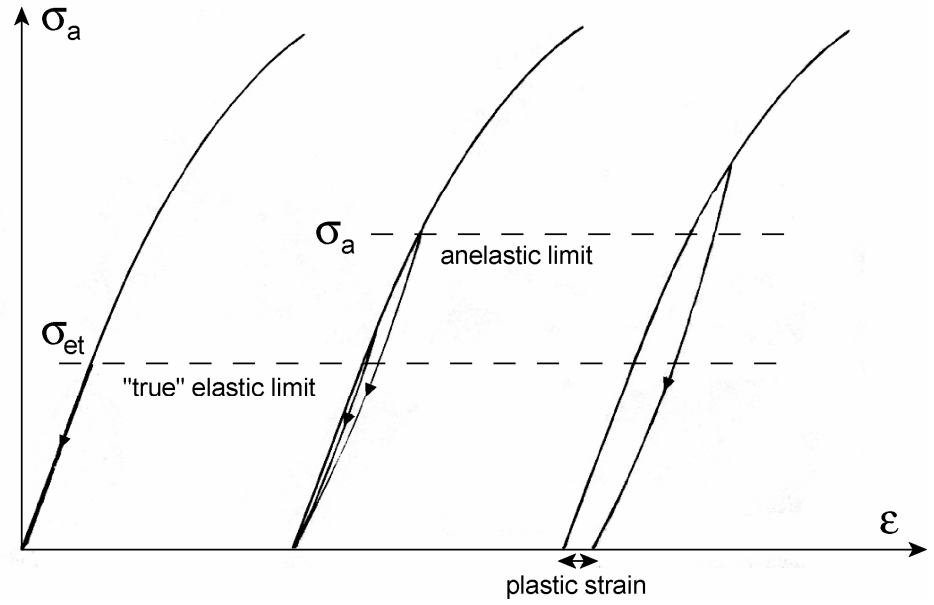


Figure 2.5 Real tensile curves measured in a steel, showing important anelastic deformation.

Remark: Many *pen recorders* exhibit their own hysteresis, therefore measurements of anelastic strain have to be done only with a good quality equipment.

2.2.4 Fragility and ductility

Fragility (or brittleness) is an opposite of ductility. A material is called fragile if it fractures either in the elastic part of the tensile curve, or after a "small" plastic deformation. Contrary, a material able to deform plastically is called ductile. The transition between fragility and ductility is chosen arbitrary, usually around 5% of strain. The quantities Z and e_f are also used for the definition of ductility.

Temperature and strain rate are two very important parameters which influence fragility, especially in the cases of polymers and *bcc metals* at low temperatures.

Remark: *Ferritic steels* show so called ductile – fragile (or ductile – brittle) transition if temperature decreases. The steel of which the Titanic's corpse was built becomes fragile at T ~ 10°C.

2.2.5 Examples of typical tensile curves

Every material has its own tensile curve, which reflects its chemical composition, its microstructure and the conditions of the tensile test (temperature and strain rate). Four typical shapes of tensile stress – strain curves are shown in fig. 2.6:

- Fig. 2.6 a). The typical curve for a fragile material - the fracture occurs in the elastic domain. It is the case of e.g. glasses, ceramics, semiconductors or *quenched* (but not *tempered* afterwards) steels at ambient temperature. Generally, the fracture stress σ_F does not characterise the material itself but depends on the *defects* properties (geometry and length of *cracks* or *cavities*, always present in those materials, or the surface imperfections due to *machining*). Because spatial distribution, shape and orientations of the defects are random, the dispersion of the measured σ_F could be quite large. It is necessary to perform several tests and to treat the results statistically, most often with the WEIBULL statistics.

  However, it is not possible to predict σ_F for a new specimen. We can only say that e.g. σ_F will be higher than 150 MPa with a probability of 60%. It means that if we would make tests with 10 new specimens, 6 of them would fracture at stress higher than 150 MPa.
- Figs 2.6 b) and 2.3. These two figures show the behaviour of ductile materials. The fracture happens at large plastic strain, after the *neck* appears (at the maximum of the curve) and develops. The yield stress is defined either as $R_{0.2}$ or, as in fig. 2.6 b), the *upper yield point* R_{eH} and the *lower yield point* R_{eL} are identified. Such curves are typical for e.g. pure or low alloyed metals. For very pure metals, Z can be near to 100% (see Al and Cu in fig. 2.12) and the fracture force can be close to zero.
- Fig. 2.6 c). In some cases (e.g. *annealed* Cu), no appreciable elastic deformation can be observed at the onset of the stress – strain curve. Nevertheless, some definition of the yield stress has to be applied (e.g.

$R_{0.2}$) since we cannot consider that the mechanical strength of such a material is equal to zero.

- Fig. 2.6 d). This is a typical curve for elastomers (= *rubbers*) which exhibit an entropic elasticity. The behaviour of the material is elastic (and anelastic) even if the deformation can be as large as 1000%; after the unloading, the specimen retrieves its initial length ℓ_0. It is not possible to define one value of the Young's modulus E. It is worth to note that E increases with the temperature, contrary to the behaviour of all others materials.

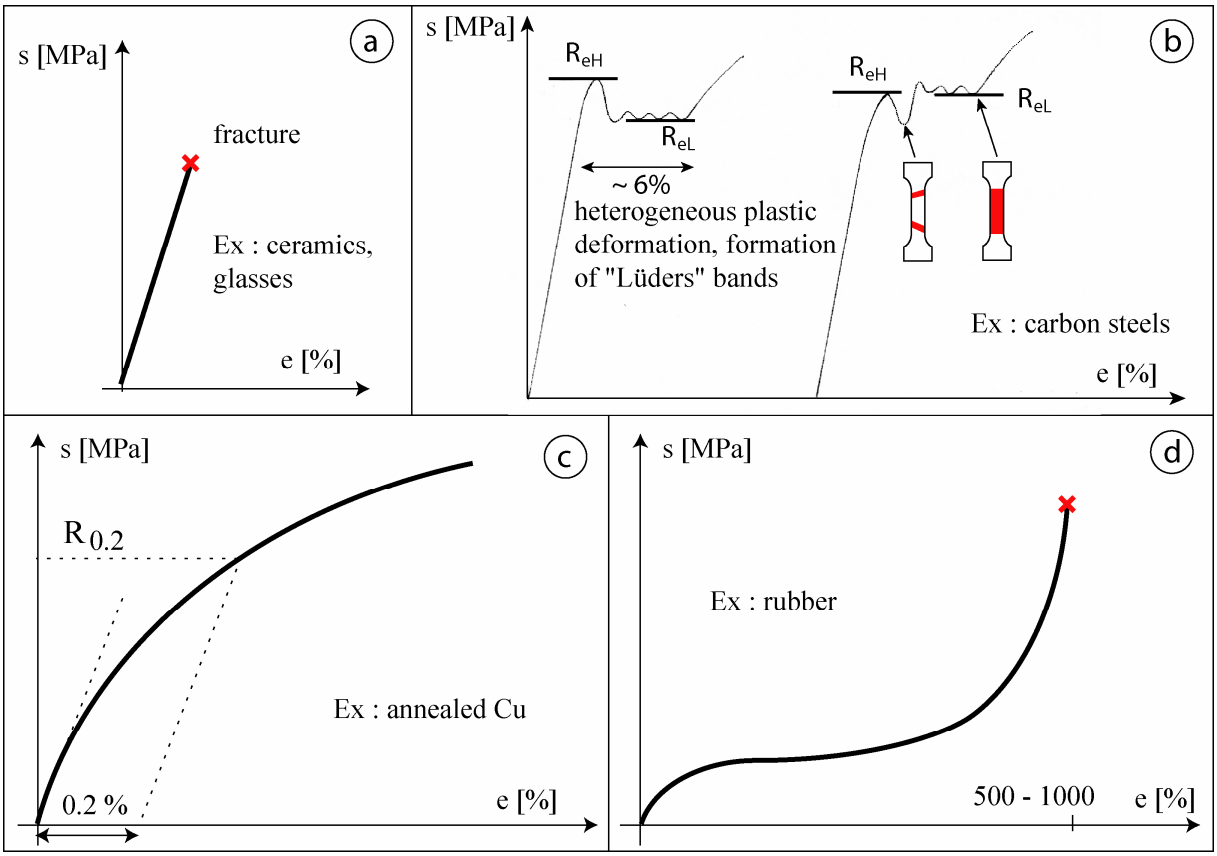


Figure 2.6 Examples of stress – strain curves. a), c) and d) are schematics, the real curves of a carbon steel are shown in b).

2.2.6 Transition between the elastic and plastic parts of the tensile stress – strain curves

This paragraph concerns mostly polycrystalline materials. Three typical transitions from elastic to plastic part of the curve are often observed:

- Sharp change of the slope between the elastic and the plastic parts of the curve. The yield stress is evident in this case. When used in calculations, such curves are often idealised as shown in fig. 2.7. If the work hardening is neglected, the behaviour is called "*perfectly plastic*". If the elastic deformation is neglected, the behaviour is called "*rigid*".

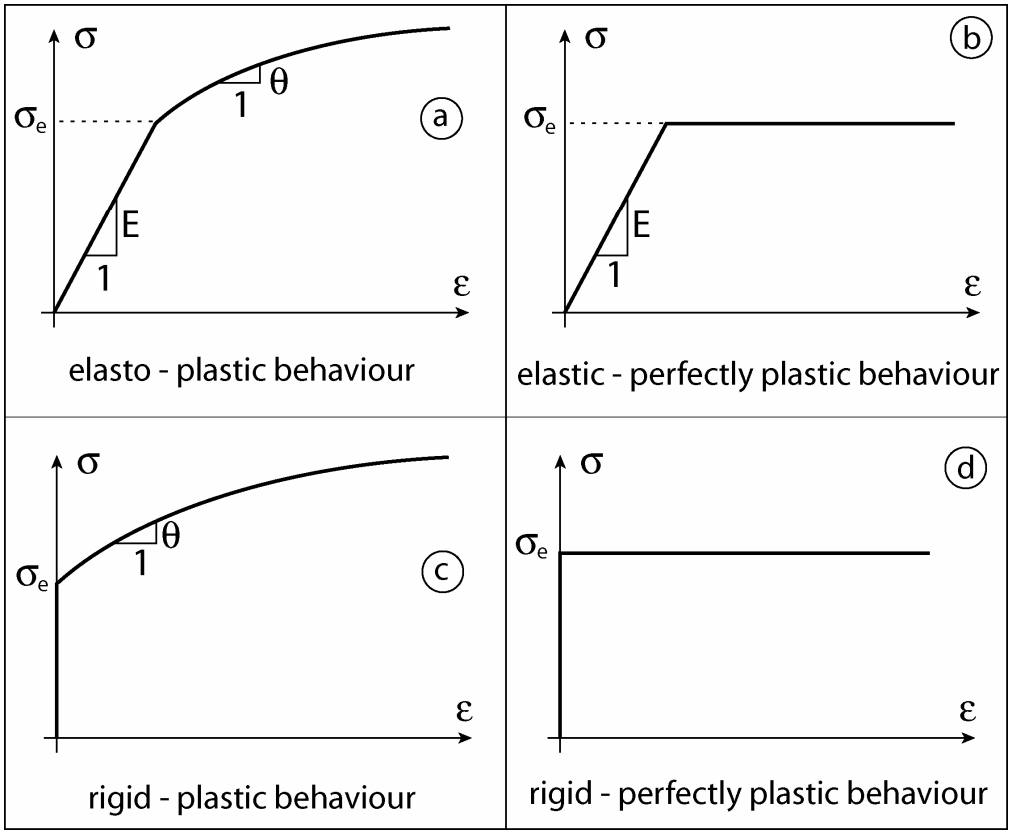


Figure 2.7 Idealised shapes of the tensile stress – strain curve.

- Continuous change of the slope. This is the case of figs. 2.3 and 2.6 c). The slope of the curve at the beginning is close to E. It is often possible to model the curve by the equation:

$$\sigma = k\varepsilon^n$$

where k and n are material parameters.

- Yield point and plateau (fig 2.6 c). After the initial linear stage, a rapid decrease of stress is observed. An unstable behaviour follows: a succession of erratic variation of stress around a certain constant level. The initial maximum is called the upper yield stress R_{eH}. This stress value is not used as a stress limit in the industrial designs for security reasons – R_{eH} is not an intrinsic characteristic of materials. The level of the first minimum is neither very representative. In agreement with the standards, the values R_{eL} defined in fig. 2.6 b) are considered as the yield stress. Such type of behaviour is often observed in hypoeutectic ferritic steels.
  The deformation of the specimen between R_{eH} and the end of the plateau is heterogeneous. Plastic deformation spreads in bands called "PIOBERT – LUDERS bands", inclined to the stress axis. The formation of a new band causes a drop of stress on the stress – strain curve. The bands are visible by a naked eye (especially if the specimen is flat, *polished* and covered by a varnish - see fig. 2.8). The plastic strain inside the bands ε_{pL} (in the region of 4 – 8 %) remains constant while the band widens. Other new bands appear in the specimen with the same ε_{pL}. At the end

of the plateau, the entire gauge length of the specimen is filled with bands and the macroscopic plastic deformation of the specimen is ε_{pL}. From this moment, the stress increases regularly and homogeneous plastic deformation is produced.

Remark: A decrease of the applied force is always caused by a plastic instability (= heterogeneous deformation). One such instability appears during necking, multiple instabilities can be observed in Piobert - Lüders bands formation.

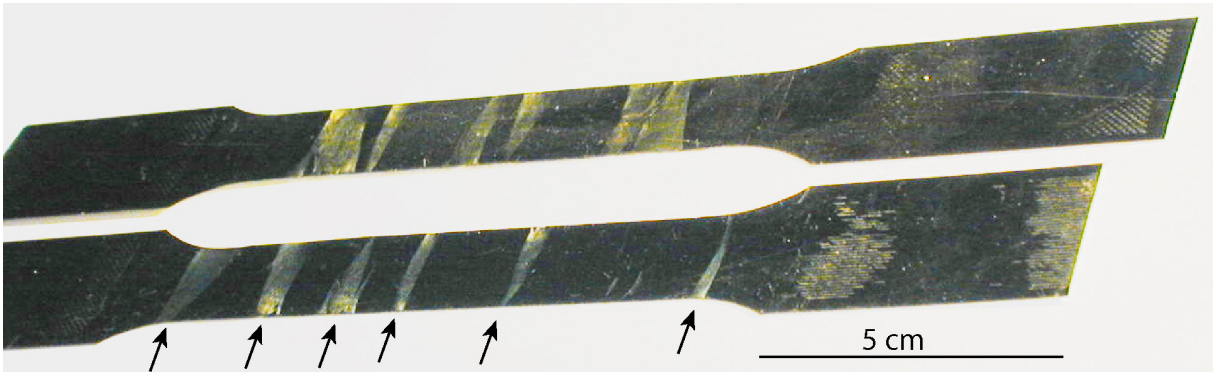


Figure 2.8 Piobert – Lüders bands. Thin sheet specimens of a very low carbon steel, deformed by a small amount of plastic strain.

2.2.7 True stress-strain curve

As the specimen is strained, its length ℓ increases and the cross-sectional area S decreases. Therefore, s becomes more and more different from the real $\sigma_{11} = \frac{F}{S}$ stress. Because the independent measurement of S is not generally performed, it is necessary to use an hypothesis which enables S to be calculated from the known ℓ value. It will be shown in the following notes that the plastic deformation of a crystal occurs often by *dislocation slip* and, in this case, the volume of the material remains constant.

The instantaneous cross-sectional area S can be therefore calculated using the constant volume hypothesis:

$$S_0 \ell_0 = S\ell$$

In the elastic domain, the above relation would be fulfilled only if $\nu = 0.5$, which is almost never the case. Nevertheless, when the elastic strain is small in comparison with the plastic strain (as in fig. 2.3), the constant volume approximation is rather good.

The so-called *true stress* σ is defined using this approximation:

$$\sigma = \frac{F}{S} = \frac{F}{S_0}\frac{\ell}{\ell_0} = s\,\frac{\ell_0 + \Delta\ell}{\ell_0} = s(1+e)$$

The *true strain* has already been defined in section 3.2.2, note "Notions complémentaires…". Since the gauge length ℓ increases continuously, the strain increase $d\varepsilon$ should be calculated using the instantaneous ℓ value and the true strain is obtained by integration:

$$d\varepsilon = \frac{d\ell}{\ell} \qquad \varepsilon = \int_{\ell_0}^{\ell} \frac{d\ell}{\ell} = \ln\frac{\ell}{\ell_0} = \ln(1+e)$$

The relations show that s and e are not too different from σ and ε if e is small. Because the elastic strain of metals is never larger than 1%, it is not important if the yield stress or E are measured on the s (e) or $\sigma(\varepsilon)$ curve. On the contrary, the 2 curves differ substantially once e increases (fig. 2.9). Note that the apparent softening of the material after the point M in the case of engineering curve is only an artifact due to the improper data treatment.

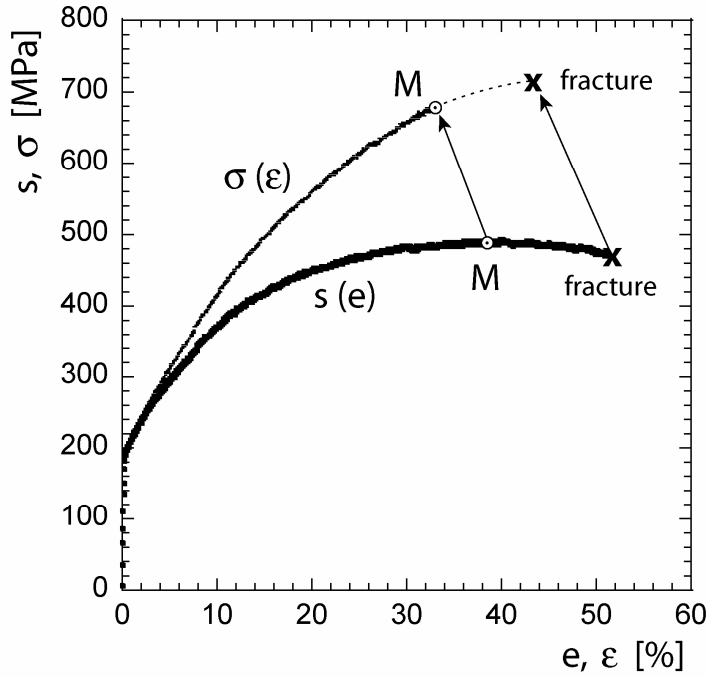


Figure 2.9 Comparison of the engineering and true tensile stress-strain curves

2.2.8 Necking

Above, we implicitly considered that the cross-section is uniform along the gauge length or, in other words, that the deformation is homogeneously distributed. This is often correct (but not guaranteed) before the maximum point M on the engineering curve but it is certainly false for $e > e_M$. When the

engineering stress reaches its maximum, the phenomenon of *necking* appears. One part of the specimen deforms more quickly than the rest and the shape of the specimen is no longer uniform (fig. 2.10). The stress in the neck is no longer uniaxial. The $\sigma(\varepsilon)$ curve after the M point has to be modelized, taking into the account the complex stress state in the neck.

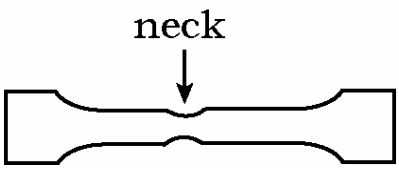


Figure 2.10 Shape of a specimen with a neck.

2.2.8.1 Why necking? Material elastic - perfectly plastic

Let's assume that the $\sigma(\varepsilon)$ curve has a shape like that in fig. 2.11 (such a material is called elastic-perfectly plastic) and that the A part of the specimen deforms a little bit more quickly than the B part. The cross-sectional area S_A is smaller than S_B and σ_A is consequently higher than σ_B. When σ_A reaches the level of yield stress σ_y, the A part begins to deform plastically while the rest of the specimen is still elastically strained. In the consequent deformation, σ_A will always be equal to σ_y but as S_A decreases, the external force necessary to deform the specimen with a constant strain rate $\dot{\varepsilon}$ will decrease too, i.e. σ_B decreases. The B part will never be plastically deformed with all the plastic deformation being localised in the neck A.

A neck is developed in elastic-perfectly plastic materials immediately after the yield stress is reached.

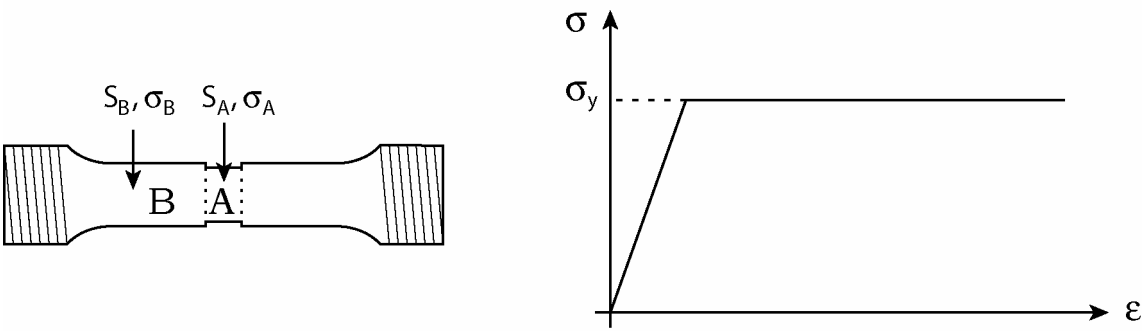


Figure 2.11 True stress-strain curve for a elastic-perfectly plastic material.

2.2.8.2 Why necking? Elasto-plastic material

Most materials exhibits a positive *work hardening rate* (WHR or θ), defined as the slope of the $\sigma(\varepsilon)$ curve in the plastic domain (in the elastic domain, this slope is E, see fig. 2.12):

$$\theta = \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon}\Big|_{\text{plastic}}$$

In this case, two mechanisms compete: i) because $S_A < S_B$, deformation in the A part is savoured, ii) since the material strengthens with deformation, the more deformed material in the A part is more resistant to deformation with respect to the material in the B part.

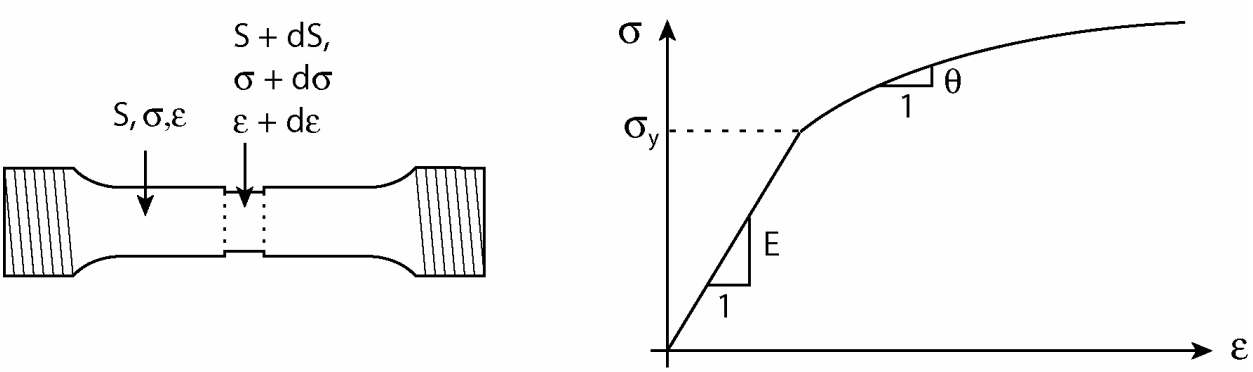


Figure 2.12 True stress-strain curve for an elasto-plastic material.

In the early stages of plastic strain, θ is high and the second mechanism prevents the neck form developing. The specimen is mechanically stable. θ decreases with ε and when the CONSIDERE criterion is fulfilled, the necking appears. The *Considère criterion* has a simple form (see *appendix*):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \sigma$$

It can be shown that this condition is satisfied exactly at the maximum point of the engineering stress-strain curve (fig. 2.13).

Remarks:

1) For the $\mathrm{d}\sigma/\mathrm{d}\varepsilon$ parameter, two equivalent terms are used: work hardening rate (WHR) or work hardening.

2) Just as *buckling* is an instability which appears in compression, necking is an instability which appears in tensile test. It limits the possibility of studying the $\sigma(\varepsilon)$ dependence at high ε during the tensile test.

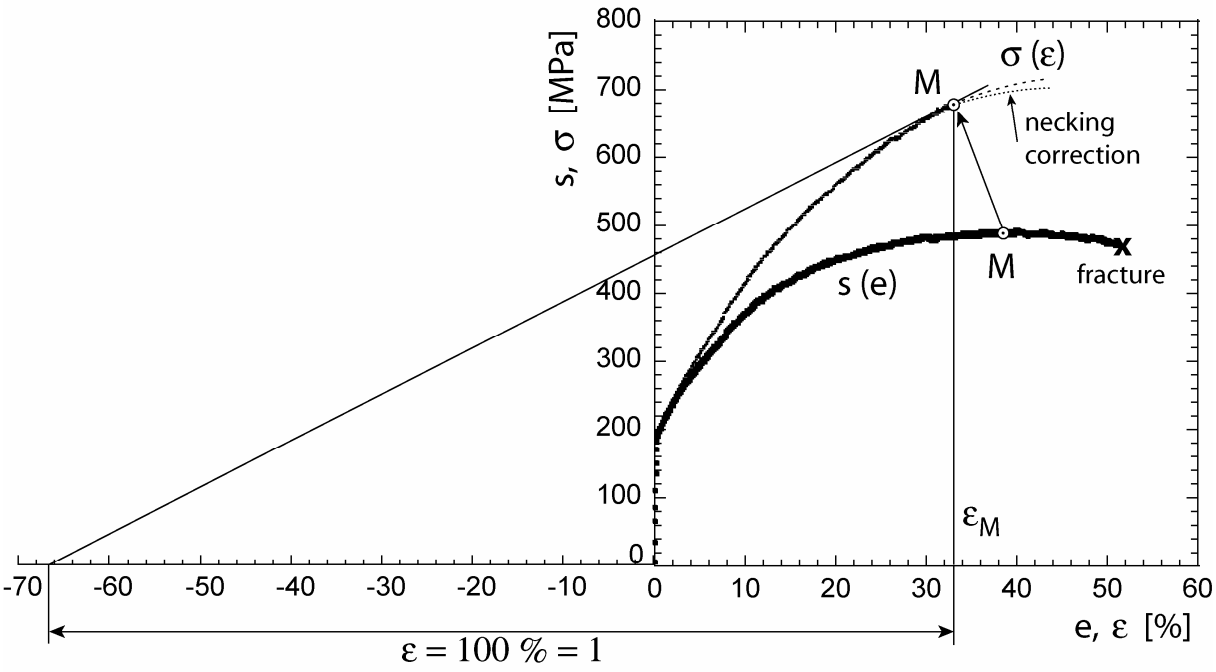


Figure 2.13 Graphic determination of the Considère criterion (the point of the onset of necking instability) on the true stress-strain curve. After this point, the $\sigma(\varepsilon)$ curve is no longer realistic. As already explained, in an attempt to "correct" this curve, complex stress-state in the neck region has to be taken into account.

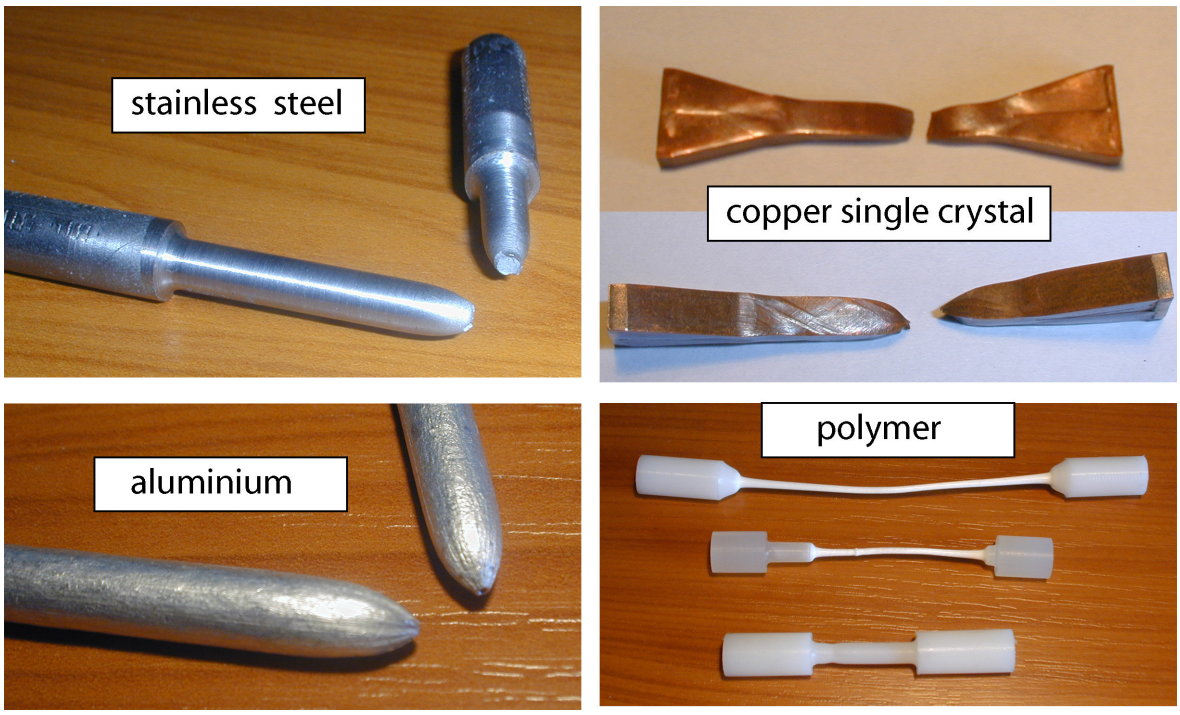


Figure 2.14 Examples of necking for various materials. Al and Cu are very ductile, Z is not far from 100%. A neck develops rapidly in polymers but then the material strengthens and fracture does not easily occur.

Exercise: Lets assume that the material obeys the *constitutive law* $\sigma = k\varepsilon^n$. This is often the case for materials with low yield stress (see section 5.2, note "Notions complémentaires..."). Find the true strain at which the necking appears.

Solution: $\varepsilon_M = n$ (use the Considère criterion)

2.3 Tensile test machines

Tensile test machines generally consist of a *frame* capable of supporting high forces, of a stable or moving traverse and of the system which applies the force. There are two main types of tensile test machines: servohydraulic and electromechanical (fig. 2.15).

a) Servohydraulic machines use the pressure of a hydraulic fluid. The pump maintains the high pressure of the fluid and the servo valve controls the pressure applied on the *piston*. The servo valve is controlled by an electric signal generated in the electronic part of the machine.
b) Electromechanical machines are equipped with an electromotor which turns the driving *screws* and move the traverse in a desired way.

Remark: One can often read that tensile tests are performed at a constant strain rate (either $\dot{e} = \text{const}.$ or $\dot{\varepsilon} = \text{const}.$). In fact, tensile machines often work under condition of constant traverse (or piston) velocity. Let's consider an elastic-perfectly plastic material. At first, both the specimen and the machine deforms elastically, due to the increasing stress. Once the specimen starts to deform plastically, the force in the deformation system is approximately constant, the machine does not deform anymore and all traverse displacement results in gauge length elongation. It means that the specimen strain rate is not exactly constant during the test. Since metals are generally not very sensitive to strain rate changes, the approximation of $\dot{e} = \text{const}.$ is quite acceptable in this case.

Nevertheless, mechanical properties of some materials (e.g. semiconductors) depend strongly on the strain rate. In order to keep a constant strain rate during the test, the traverse velocity has to be controlled by the signal from an extensometer attached to the specimen.

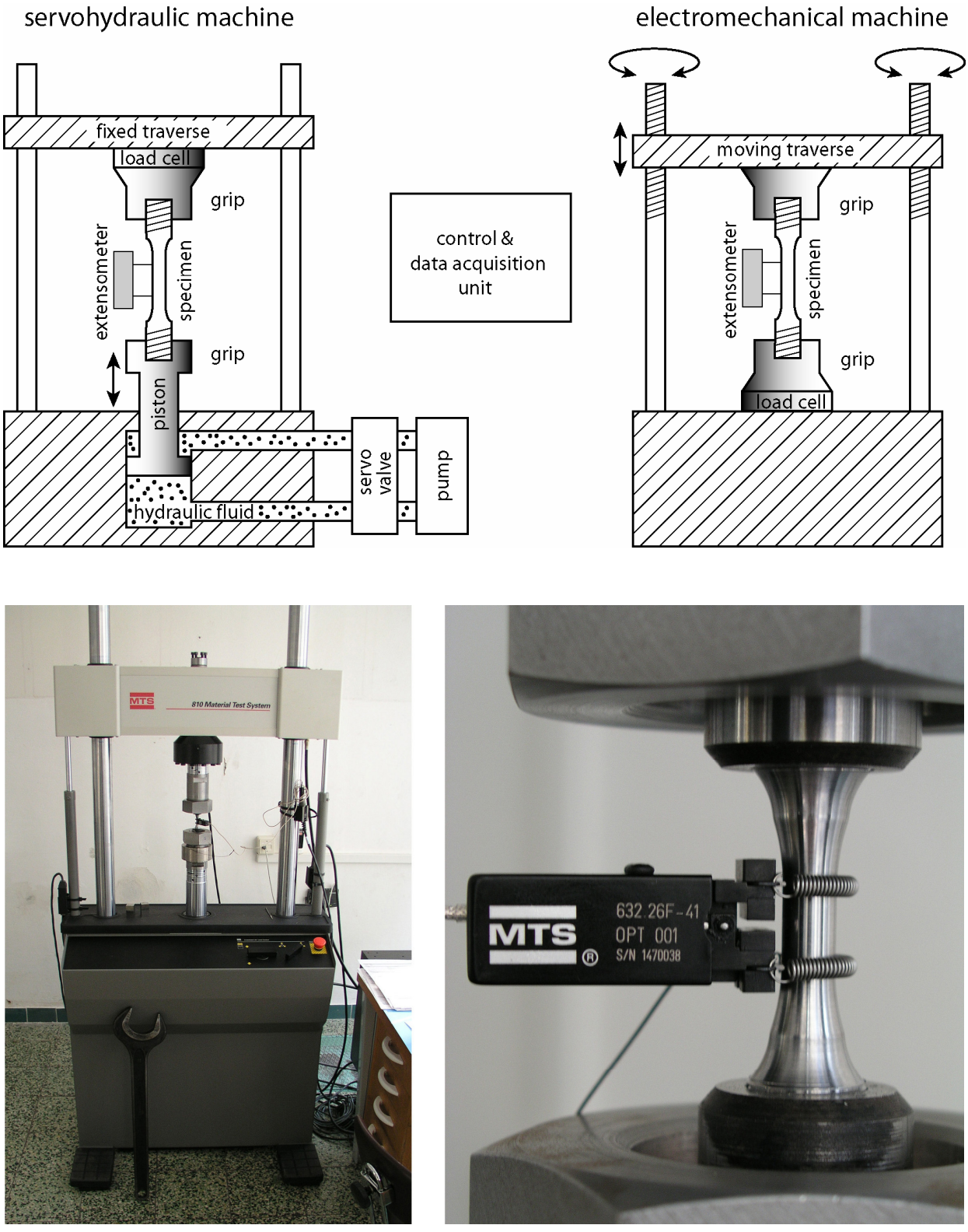


Figure 2.15 a), b) Schematics of tensile test machines. c) Servohydraulic machine, d) specimen for the fatigue test with attached extensometer.

There are several types of holding grips: screw grips as in fig. 2.15, self tightening grips or hydraulic grips. The grips and the specimen have to be well aligned because any bending of the specimen may influence significantly the results.

2.4.1 The force measurement

The apparatus which measures the force is called a *load cell*. It is in fact a calibrated elastic body which deforms as the force is applied. Its deformation is measured and the corresponding force is obtained from the known elastic modulus. The load cells have as a rule an excellent resolution, better than 10^{-6}.

According to the action - reaction Newton law, the force between the traverse and lower part of the machine (piston, fixed plate) is constant. The load cell can be therefore placed anywhere in series with the specimen. Often it is between the grips and the immobile part of the machine (fig. 2.15 a, b).

2.4.2 The elongation measurement

While the force measurement is precise and easy, the elongation measurement is not so straightforward.

a) Elongation is not measured at all or the traverse displacement is measured

One possibility is to measure only the force and time. The *displacement* of the traverse can be calculated from the known (and constant) velocity of the traverse. Alternatively, the traverse velocity is measured by a simple method. The question is how to extract the elongation of the specimen gauge length from the known position of the traverse. For such an analysis, it is necessary to take into account that:

- no tensile machine is "infinitely" rigid, i.e. the elastic elongation of the assembly of load cell, grips, heads of the specimen etc. is non negligible; in fact it can be higher than the elastic elongation of the specimen gauge length itself,
- good machines are purely elastic, so any detected plasticity comes from the specimen.

Therefore

$$\Delta\ell_{\text{traverse}} = \Delta\ell_{\text{elastic,machine}} + \Delta\ell_{\text{elastic,specimen}} + \Delta\ell_{\text{plastic,specimen}}$$

The apparent engineering strain e' is calculated using the initial specimen gauge length ℓ_0 :

$$e' = \frac{\Delta\ell_{\text{traverse}}}{\ell_0} = e_{\text{elastic,machine+specimen}} + e_{\text{plastic,specimen}} = \frac{1}{M}s + e_p$$

where M is the elastic modulus of the specimen – machine assembly (equal to Young's modulus of the specimen for an infinitely rigid machine).

The slope M of the elastic part of such a tensile stress-strain curve is smaller than E, but the $R_{0.2}$, R_m and e_F parameters are not influenced (see fig.

2.16). Also, the plastic deformation at any point of the curve is measured correctly.

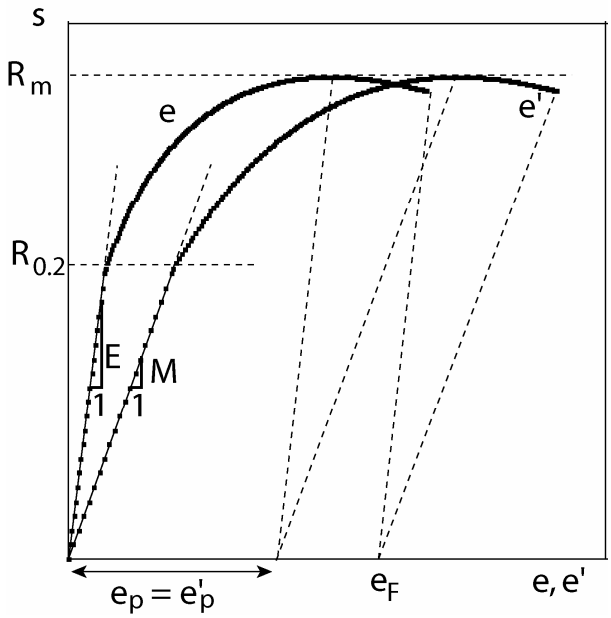


Figure 2.16 Comparison of stress-strain curves.

b) Extensometer between the grips

A second possibility is to measure the distance between two points close to the specimen, for example between the grips, using an extensometer. This results in the same analysis as above, because the deformation of grips, specimen's heads and specimen's gauge are present. Nevertheless, M is in this case closer to E and some undesirable anelastic effects due to the machine are eliminated.

c) Direct measurement of the gauge length

Direct measurements of the elongation of the specimen gauge length is the best method.

In the past, *resistive strain gauges* were used (fig. 2.17b). The gauges are glued to the specimen whose deformation induces changes in their resistance due to the i) increase of the length ℓ of the conductive wire between the two contacts, ii) reduction of its cross-section S and iii) the increase of its resistivity ρ.

Optical extensometry measures a difference between two marks at the specimen surface using a *laser beam*. Such non contact measurement is elegant but sometimes not as accurate as desired. It is the only method which can be used at very high temperatures ($T \geq 2000°$ C).

Today, the most common way is to attach a commercially made extensometer directly to the specimen by a spring or elastic (fig. 2-17a, see also 2.15 d). These extensometers give a distance between two sharp blades which are in contact with the specimen. Some practical problems arise:

- the extensometer's blades can slip on the specimen surface;

- the blades can initiate crack formation if the extensometer is fixed too tightly;
- extensometers do not support high or low temperatures (tensile tests at high or low temperatures are often demanded). The extensometer has to be placed outside of the furnace (or cryostat) and connected with the specimen by special *rods*.

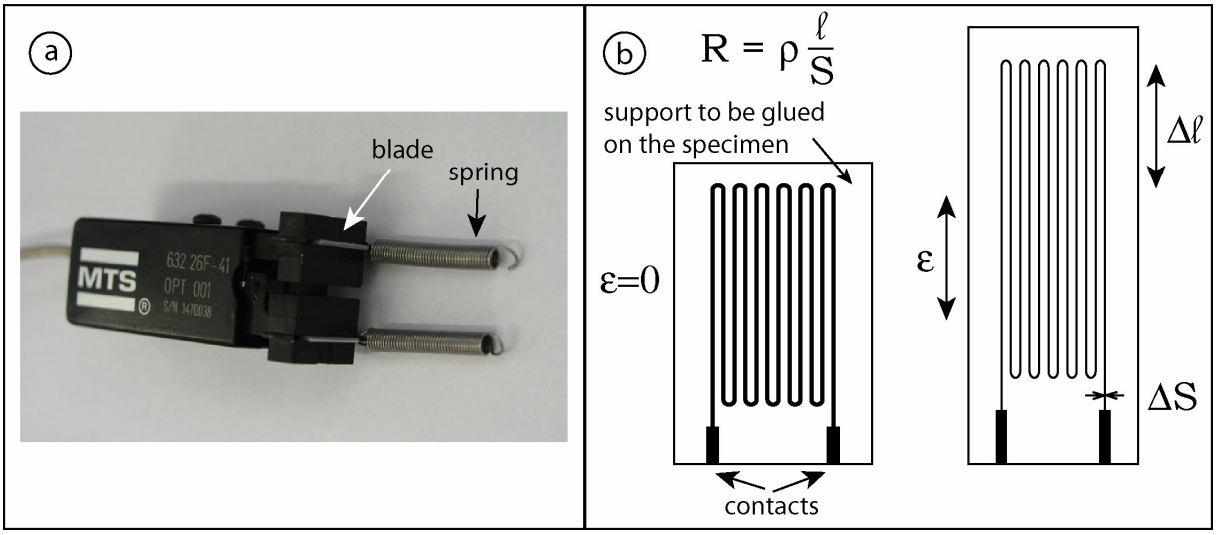


Figure 2.17 a) A commercial extensometer. b) A resistive strain gage. R is the resistivity of the wire between the two contacts. The winding shape enables to have a very long wire on a small surface – the precision of the measurement is enhanced.

Exercise: Which method was used to measure the data of fig. 2.4?

Solution: The slope of the elastic part of the curve of the figure is about 100 GPa. Knowing that E for steels is around 210GPa (room temperature) and about 190 GPa (400° C), the strain was very probably measured by method b).

2.4.3 Standards

The results of mechanical test should be understandable, reproducible and usable by engineers and researches all over the world. Therefore, some precise and easily realisable test conditions must be respected. These conditions are described by standards, which define testing machines, specimen shapes, experimental procedures and data interpretations. In the past, standards were defined at a national level, but today there is an effort to unify the standards at European and world scale.

One standard usually describes only one category of materials and one part of a mechanical test.

Exemples of standards:

- "Metallic materials; tensile testing; part 1: method of test". European standard EN 10002-1.
- "Metallic materials; tensile testing; part 2: verification of the force measuring system of the tensile testing machines". European standard EN 10002-2.
- "Steel and steel products -- Location and preparation of samples and test pieces for mechanical testing". European standard EN ISO 377.

2.4.4 Specimens

a) Industrial materials

A specimen has to be chosen with care that the results are representative for the material. Therefore, to characterise a material in form of a *sheet*, flat specimens are cut with the same thickness as the sheet. Cylindrical specimens are preferred in the case of *bulk materials*. During *casting*, *moulds* in shape of tensile specimens are filled at the same moment as the object is cast. Again, standards concerning the geometry and fabrication procedure of specimens have to be taken into account.

Remark: Sheet metals produced by *cold rolling* are strongly anisotropic and it is necessary to choose properly the orientation of specimens in the sheet. Notation: RD - the rolling direction, TD – traverse direction (in the sheet, perpendicular to RD), ND – normal direction (normal to the sheet). Usually, a set of specimens is used, with the axis orientation changing gradually from RD to TD.

b) Exotic materials

If the preparation of specimens and test conditions are unusual (rare, expensive, difficult to manipulate etc. materials), the results must be accompanied by their detailed description. Such a description could serve later as a basis for a new standard if the material overcomes the gap between a laboratory curiosity to industrial applications.

c) Objects

Sometimes entire object are tested in tensile test: *elevator ropes*, climbing ropes, long bones etc., mainly in order to measure the maximum force before rupture. Because these objects are often composed of several materials (multimaterial object) it is not possible to fabricate specimens of them; the entire objects must be tested.

3. OTHER MECHANICAL TESTS

Other important mechanical tests are described here only very briefly. We will focus on their characteristics, their domain of utilization, their advantages and drawbacks. Complementary sources (standards at the first place) are necessary to perform these tests.

3.1 The compression test

Tensile machines can be used for the compression test if the direction of the traverse motion is inversed. Specimen's shapes are mostly cylinders or parallelepipeds. The *compression fronts* have to be mutually parallel and perpendicular to the compression axis; precise *manufacturing* of specimens is therefore important. The length of the specimen must be i) large enough so that the test is close to the uniaxial one and not to the *crunch test*, but ii) small enough to prevent the appearance of buckling. As the best compromise, the length of specimens is about 3 times bigger than its diameter. The compression fronts must be lubrified, because they should be able to glide freely – a difficult task considering the magnitude of acting forces. The friction between the specimen and machine induce a *barelling* of the specimen. In this case, areas close to the machine are less stressed than the rest of the specimen and the stress state is no longer uniaxial (fig. 3.1). Artificially made *scratches* on the compression fronts can serve as reservoirs for lubricant. At high temperatures, *glass powder* is a very good lubricant, stable and chemically intact.

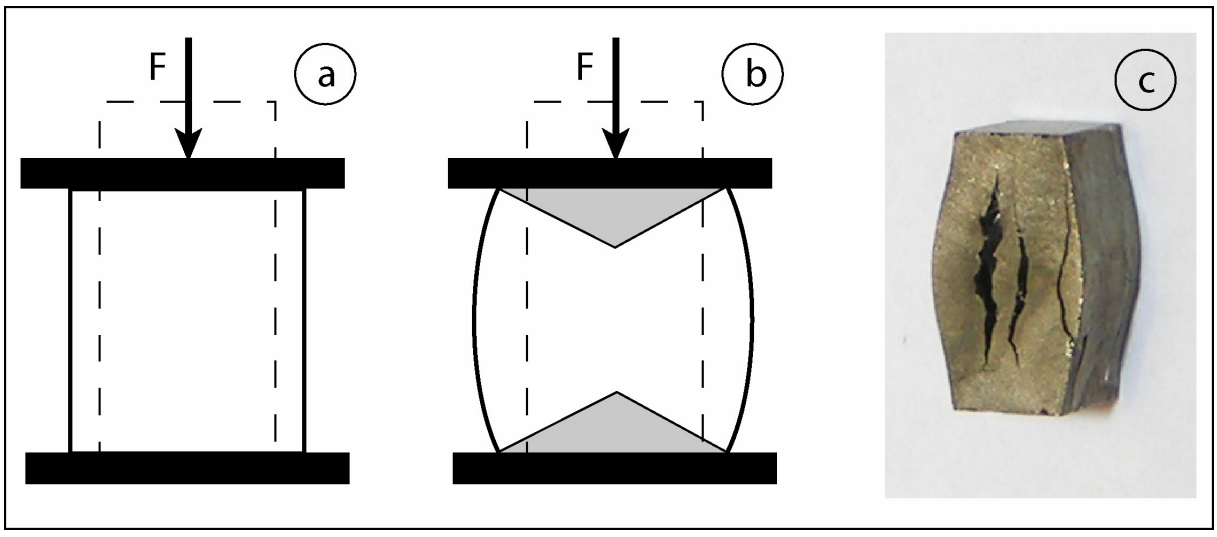


Figure 3.1 a) Correctly deformed specimen, stress is compressive, uniaxial and homogeneous in entire specimen. b) In the barrelled specimen, stress is no longer uniaxial and homogeneous - the grey parts are less charged than the rest of the specimen. c) Vertical cracks in barrelled Ge prove the existence of tensile stresses perpendicular to the specimen axis.

Advantages of the compression test are given in the following:

- specimens have a simple form and can be rather small which helps in the case of rare and expensive materials or materials which are difficult to machine;
- specimens can be deformed more than in the tensile test. Cracks in fragile materials are closed and necking of ductile materials does not occur, so e.g. cold rolling can be partially simulated.

3.2 The multiaxial tensile test

Uniaxial tensile test cannot furnish the constitutive laws for multiaxial loading (e.g. *stamping* of a sheet, a *vessel under pressure* etc.). Multiaxial tensile tests have been therefore performed.

- A specimen for biaxial tensile test is shown in fig. 3.2 a). Every specimen's head is made of several perforated slices. This special shape enables to load the specimen while its central part is free to deform along the second axis. Triaxial stress state can be reached by applying a compression force along the third direction.
- Triaxial tensile test can be performed too. The specimen shape is rather complex, its central part is cubic (fig. 3.2 b). Of course, a special testing machine is needed.

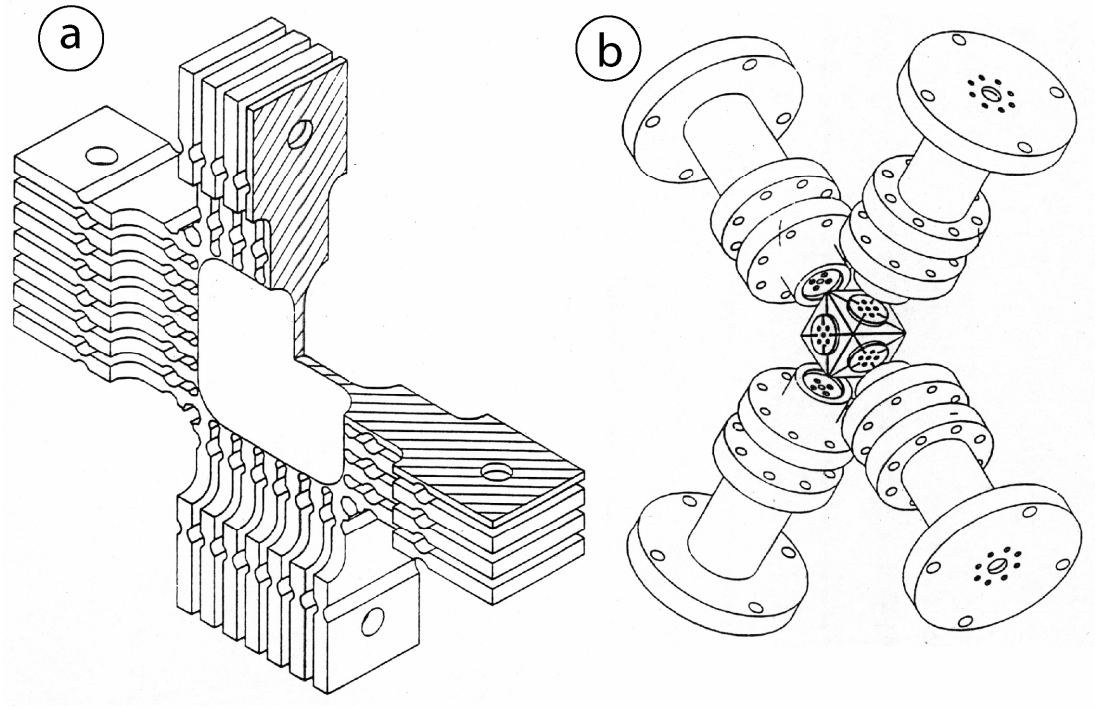


Figure 3.2 a) Specimen for biaxial tensile test, b) specimen and two sets of grips for triaxial tensile test (figures from LMT Cachan).

3.3 The bending test

In the bending test, a specimen of parallelepipedic shape lies on two supports. In *3-point bending test* (3PB, fig. 3.3 a), one force is applied in the centre of the specimen. 2 equal forces, symmetric in respect to the centre, are used in *4-point bending test* (4PB, fig. 3.3 b). In both cases, every fibre parallel to the surface is subjected to uniaxial loading: compressive above the neutral axis (fibre in the centre of the specimen which does not change its length), tensile below the neutral axis. The absolute value of the uniaxial stress increases with distance to the neutral axis and is maximum at the two external surfaces.

In 3PB, the stress is heterogeneous even along every fibre. In the elastic domain, maximum stress σ_{max} is reached in the centres of the two extern fibres:

$$\sigma_{max} = 3FL / 2bt^2$$

where b is the width of the specimen.

An advantage of 4PB is that the stress is constant along one fibre between the two load points. Its maximum value in the elastic case is

$$\sigma_{max} = 3Fa / bt^2$$

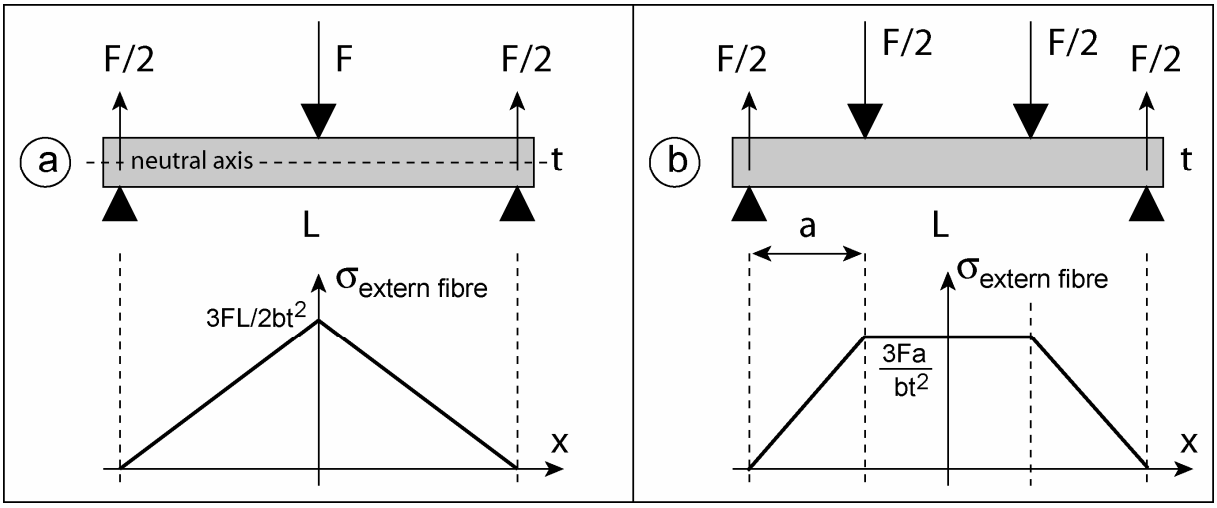


Figure 3.3 Schemes and stresses in the elastic domain of a) 3 – point bending test, b) 4 – point bending test.

The bending test is used mainly for fragile materials and for materials difficult to machine. Its main drawback is the heterogeneity of the stress. Once a part of the specimen is deformed plastically, there is no simple way to calculate the stress in every point of the specimen. The constitutive law

$$\sigma_p = f(\varepsilon_p)$$

is needed for this calculation, but this law is what we are searching for.

3.4 The torsion test

The specimen must be cylindrical in order to keep stress in the pure shear state. In the elastic case, there is only one stress component - $\sigma_{\theta z}$ – which is not equal to zero:

$$\sigma_{\theta z} = \mu \, r \frac{\varphi}{L}$$

L is the specimen length, φ is the applied rotation angle. Stress is not homogeneous, it increases with the distance to the centre and reaches the maximum value on the surface (r = R). Once the specimen is deformed plastically, the problem of the determination of the stress state arises, as well as in the bending test. The interesting feature of the torsion test is that there is a possibility to reach large deformations, since the necking phenomenon does not appear.

3.5 The impact test

This test measures the resistance of a material to the impact. The most common machine is the *CHARPY hammer*. It is in fact a heavy pendulum with a sharp edge. It is placed in an initial position A and released. At the lowest position, the pendulum hits the specimen with a *notch*, fractures it (it must be fractured into two pieced for a valid test) and rises up to a certain final position B (fig. 3.4). The absorbed energy ΔE is normalised to 1 cm^2 of the specimen cross-section. This value is not an intrinsic material parameter, since it includes the energy absorbed i) during the elastic deformation, ii) during the plastic deformation, iii) energy of creation of two free fracture surfaces and iv) non negligible kinetic energy of the two pieces of the specimen, ejected after the impact. It depends also on the notch geometry (V shape, U shape,..).

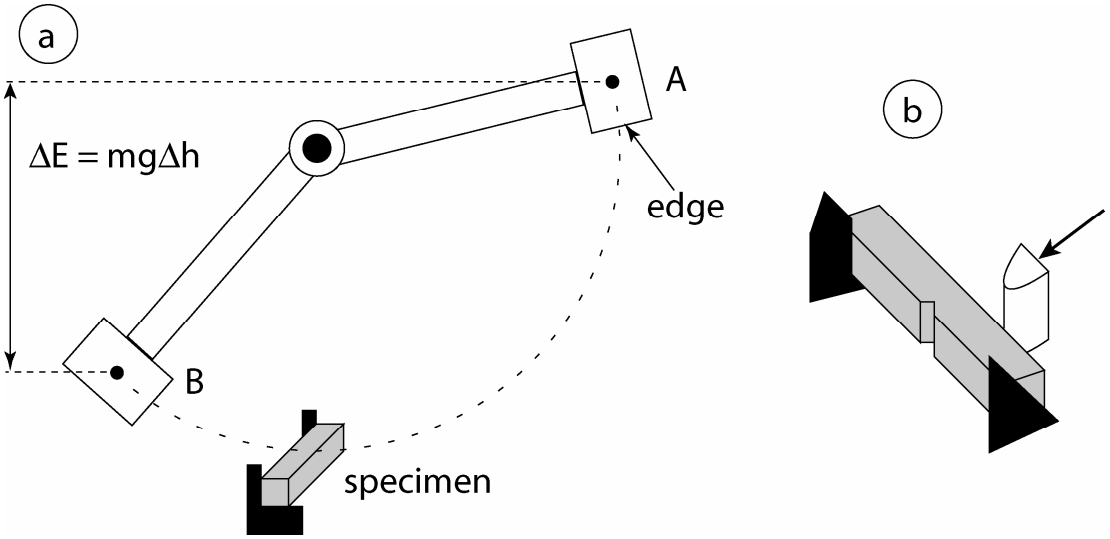


Figure 3.4 a) Charpy hammer and the impact test, b) the specimen with a V notch.

This comparative test can be easily accomplished at various temperatures. The positioning of the specimen takes only a few seconds so it is possible to take out the specimen from a *furnace* or cryostat and execute the test before the specimen temperature substantially changes.

3.6 The hardness test

The hardness test is appreciated and often used due to the simplicity of both the test procedure and the specimen preparation. Unfortunately its results are only comparatives. A tip called *indentor* is pressed into a flat specimen by a force; hardness is then defined as e.g. a ratio of the applied force and the surface of the imprint of the indentor. A large set of indentors exist, each of them appropriate for a certain class of materials, and also several different testing procedures (Brinell, Vickers, Rockwell, Knoop, microindentation, nanoindentation…) which differ by the magnitude of used forces (10 000 N for the Brinell test, microNewtons in the nanoindentation apparatus) and also by the details of hardness calculation. There is no reliable correspondence between the different hardness scales and the attempts to connect the hardness with e.g. R_m lead only to a rough estimation in a limited domain of applications.

Example: The hardness values are given in a form like "200 HB" or "200/1000/30 HB" which means that the hardness 200 was obtained by the Brinell test executed with a force of 1000 kg (i.e. ~ 10 000 N), applied during 30 seconds. Recently, there has been a tendency, mostly in scientific papers dealing with micro and nanoindentation, to use MPa as a hardness unit (N/mm^2 = MPa) which can lead to a confusion.

Remarks:
1) One important material parameter is the *critical stress intensity factor* K_{IC}, a characteristic influencing mostly the crack propagation – a very important problem. In fact, its definition and the measuring procedure necessitate certain knowledge of the fracture mechanics so it cannot be treated here.
2) A machine performing simultaneously tension or compression together with torsion is commercially available. The test is referred as multiaxial loading.

4. FATIGUE

The term *fatigue* is used for a process of *damage* evolution of a material due to cyclic loading. It is a dangerous phenomenon, because no obvious signs of the damage process can be observed throughout the majority of the loading cycles. Moreover, the magnitude of an external cyclic force which leads to fatigue fracture may be so small that its steady application – i.e. in the creep test – would not fracture the specimen. Another unpleasant feature of fatigue is a phenomenon of plastic strain localization. During cycling, the plastic deformation is concentrated in the weakest parts of the specimen, especially close to *notches*, and the fatigue *cracks* quickly nucleate in these regions.

Fatigue has been implicated in many failures of components and structures. In fact, all parts of machines which move, rotate or are subjected to vibrations are in danger of fatigue fracture. Fatigue is of a primary importance especially in the aeronautic industry.

In the following, only uniaxial cyclic loading will be considered. Of course, fatigue due to cyclic deformation in torsion, flexion, combined loading etc. appears in real life too. *Thermal fatigue* is the damage due to repeated thermal stresses, which originate from the temperature gradient in a specimen.

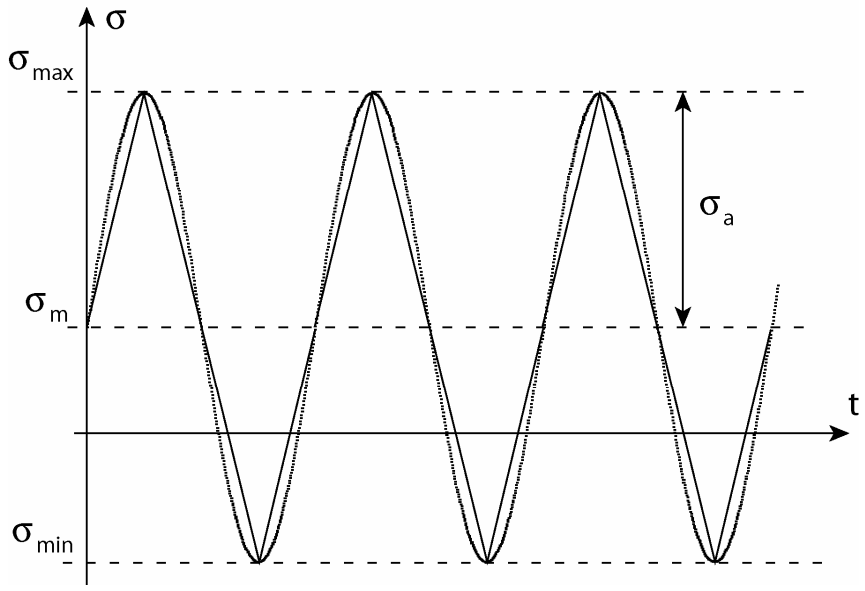


Figure 4.1 Uniaxial tension – compression cyclic loading with sinusoidal and triangular cycles.

In the fatigue test, sinusoidal or triangular cycles are usually applied (fig. 4.1). The cycle is characterized by the stress amplitude σ_a and the mean stress σ_m, or by σ_a and the stress asymmetry parameter R:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

Most often, symmetric cycles with R = -1 (or $\sigma_m = 0$, see fig. 4.2) are used. Tests with $\sigma_m \neq 0$ are sometimes called "creep – fatigue" tests.

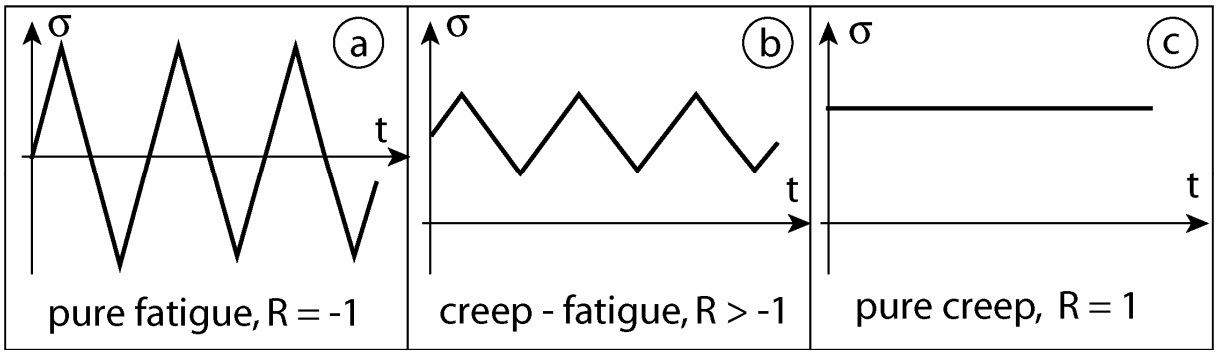


Figure 4.2 Tests with different R factors.

Three types of tests with non constant stress amplitude are performed (fig. 4.3):

- in the multiple step test, σ_a changes few times during cycling;
- in the incremental step test, σ_a increases and decreases gradually through each bloc of cycles;
- in the random loading test, σ_a varies in every half cycle.

The random loading tests are used for simulating real processes i.e. as in the landing of a plane. The stress evolution is measured in the real process and reproduced in the laboratory test, so it is not at all "random".

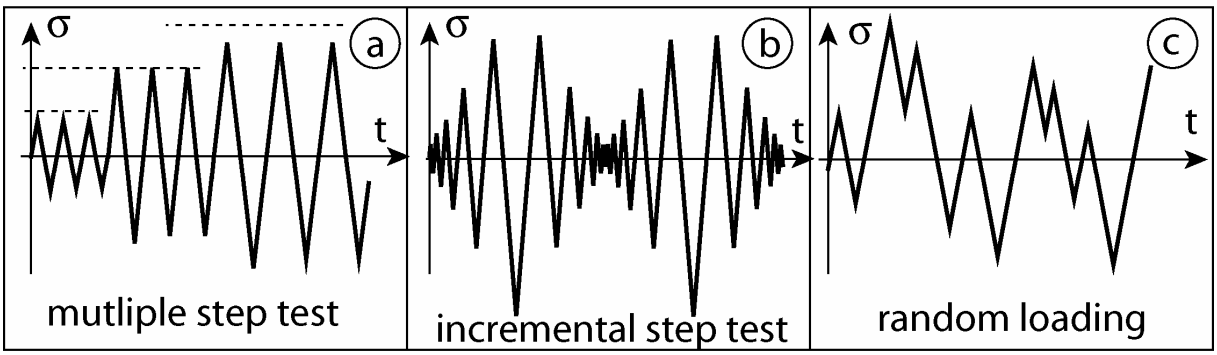


Figure 4.3 Other fatigue tests.

In the following, we will only consider uniaxial symmetric fatigue tests, i.e. the test as in figure 4.2a). The stress - strain dependence during cyclic loading is in the form of a *hysteresis loop*. Definitions of stress amplitude σ_a, strain amplitude ε_a and plastic strain amplitude ε_{ap} are clear from figure 4.4 a). As in the tensile test, the notation σ and ε mean respectively the normal stress and strain, parallel to the loading axis ($\sigma \equiv \sigma_{11}$, $\varepsilon \equiv \varepsilon_{11}$ if the loading axis is parallel to the x axis).

The fatigue test can be controlled in three ways. Up to now, the figures showed testing in which the stress amplitude is controlled but it is also possible to make tests with constant strain amplitude ε_a or constant plastic strain amplitude ε_{ap} (fig. 4.4 b).

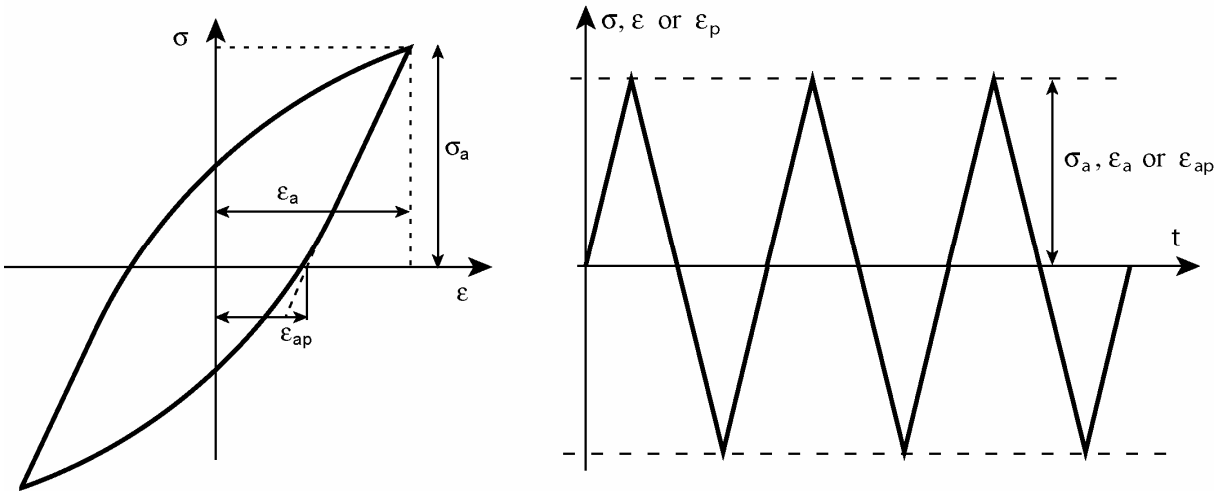


Figure 4.4 The stress-strain hysteresis loop and the three possibilities of fatigue test control.

4.1 Fatigue tests at constant stress amplitude

The first systematic fatigue experiments were performed by August WOEHLER around 1850. He used the fatigue in bending with constant force amplitude.

If σ_a is kept constant, the evolution of ε_a with cycle number N can be observed. If the material *cyclically hardens*, the same level of stress causes less deformation and ε_a as well as ε_{ap} decrease with N. It is observed that after some time, ε_{ap} becomes quite stable – the shape of the hysteresis loop does not change appreciably (fig. 4.5 a). This moment is called the saturation.

Industrial alloys with high initial dislocation density often show cyclic softening, as schematized in fig. 4.5 b).

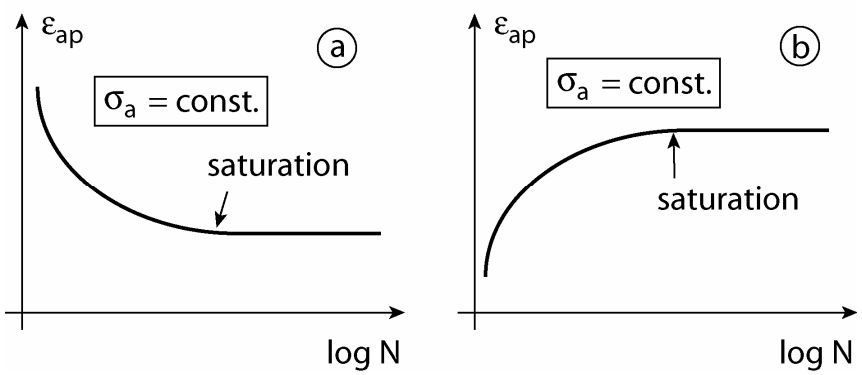


Figure 4.5 Evolution of material response with cycling with a constant stress amplitude. a) Material which cyclically hardens, b) cyclic softening.

The *fatigue life* is characterized by the number of cycles up to the fracture N_F. WOHLER observed an asymptotic behaviour of the N_F if plotted as a function of σ_a – this graphic is called the Wöhler curve (fig. 4.6). The asymptote is called the *fatigue limit*. This is an important parameter for the industrial design - if the expected cyclic stresses are under the fatigue limit, then fatigue fracture should never occur.

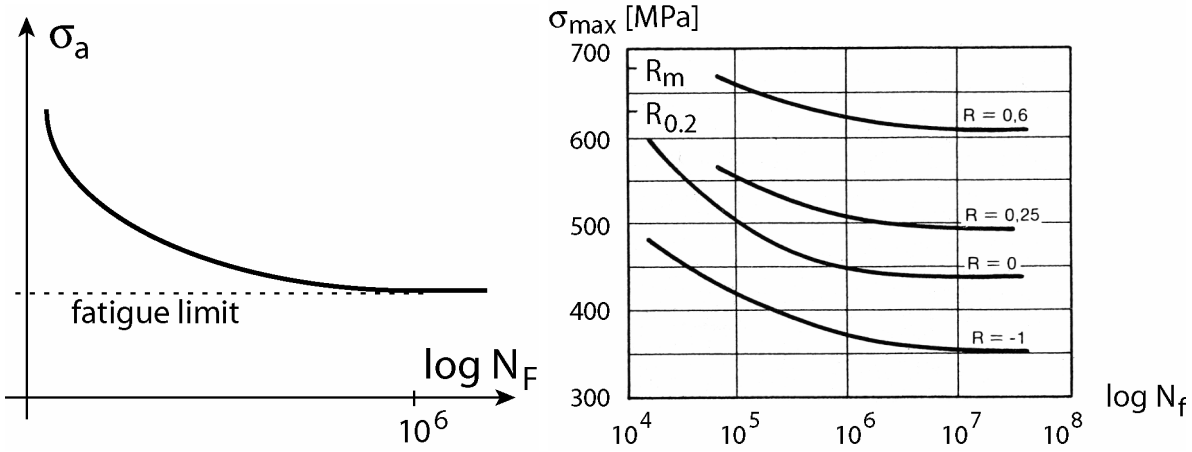


Figure 4.6 a) The basic Wöhler curve, b) dependence of the Wöhler curve on R.

Remarks:

1) A loading regime in which fatigue fracture occurs at $N_F < \sim 10^5$ cycles is called *low cycle fatigue*; above this value a high cycle fatigue domain exists. The terms "very high cycle fatigue" or "ultra high cycle fatigue" refer to tests in which more than ~ 10^7 cycles are reached.

2) The asymptotic behaviour is observed generally at $N_F \sim 10^6$ cycles. The fatigue limit is therefore sometimes defined as the maximum σ_a which does not lead to fracture after 10^6 (or 10^7) cycles.

3) The most dramatic changes in the material behaviour are observed at the beginning of cycling. To enlarge the first cycles on the graph, the axis along which the number of cycles is plotted always has a logarithmic scale.

4) Many materials do not show a clear saturation and figures 4.5a) and 4.5b) should only be considered as rough schematics.

4.2 Fatigue tests at constant plastic strain amplitude

The damage of the specimen is caused by plastic deformation. In the case of fig. 4.5a), the specimen is damaged more by the first cycles than by cycling in the saturation regime. This is a disadvantage of the fatigue tests at constant σ_a : the results are substantially affected by the first cycles. To avoid the early damage and consequently a life reduction, precycling is often used: the test begins with a small σ_a which is gradually increased up to the desired value (such precycling is called a loading ramp).

Another possibility is to cycle with a constant ε_{ap} during the test. From the scientific point of view, this is the most appropriate test if the mechanisms of fatigue process are to be studied. The dependence ε_{ap} (N_F) is called the MANSON - COFFIN curve (fig. 4.7). No asymptotic behaviour is observed on such curves.

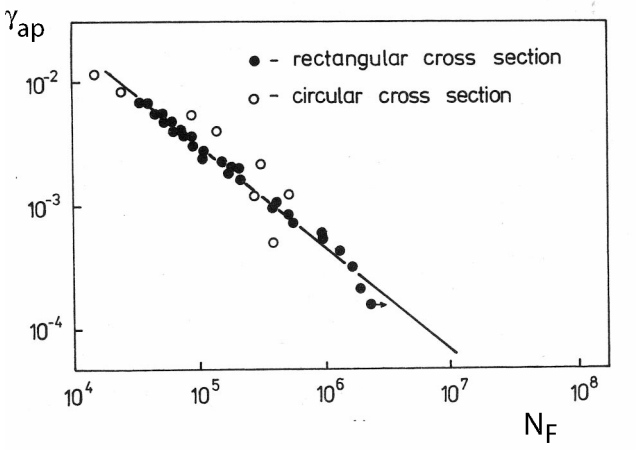


Figure 4.7 The Manson – Coffin curve for Cu single crystals oriented for single slip.

4.3 Fatigue tests at constant total strain amplitude

However, experimental measurement of plastic deformation in every cycle is a little bit complicated and time consuming. A reasonable compromise is to keep the amplitude of total deformation ε_a constant, which leads to comparable results with the case of constant ε_{ap}.

4.4 Fatigue machines

Electrohydraulic machines are used most often since they enable full control of the stress or strain as a function of time. The maximum frequency of cycling using these machines is up to 50 Hz, i.e. 10^7 cycles can be reached in about two days.

In resonant fatigue testing machines, the dynamic force is generated by an oscillating system (resonator) which runs at its natural frequency. The

oscillating system consists of the tested specimen and masses and springs. Resonant type machines most often use the full resonance, i.e. the operating point is situated at the top of the resonance curve. The resonator is excited by an electromagnetic system. These machines can only produce sinusoidal cycles with control of the force amplitude or displacement amplitude. The maximum frequency of cycling is up to 1000 Hz.

Ultrasonic fatigue testing consists in producing stresses and strains in a specimen by ultrasonic waves. As a consequence, the stress pulses can be repeated with a frequency of the order of 10 kHz. The stresses in the specimen can be estimated, but strains are difficult to measure. The stress amplitude is limited to the nearly elastic range since, in the presence of small plastic strain, the specimens heat very rapidly. Such type of testing remains rare.

5. CREEP

The creep test refers to tests at constant force or constant true stress (i.e. the force changes as the specimen cross – section changes). Once more, only uniaxial loading is considered here.

If the applied stress is relatively high and the testing temperature is not too high, the mechanisms of plastic deformation operating during a creep test are the same as in the case of the tensile test. On the contrary, at temperatures high enough for diffusion processes to be enabled, the specimens can, slowly but steadily, plastically deform even for stresses well below the yield point. Creep testing is therefore often focused on the behaviour of materials at high temperatures and low plastic strain rates. The temperature above which continuing slow deformation can be observed differs in different materials, but often it is not far from 50% of the melting temperature T_M (the ratio of actual temperature T and T_M is called the *homologous temperature*).

Low temperature plasticity is most often governed by dislocation slip. On the contrary, a large variety of mechanisms of plastic deformation have been identified at high temperatures.

One practical problem lies in the test duration. Structures like *pressure vessels* in *power plants* should be able to resist high temperatures and stresses for many years, but laboratory tests rarely take longer than few months. It is known that an extrapolation of laboratory data to real conditions is a difficult problem.

5.1 The creep curve

Since either s or σ is kept constant, strain is the only measured parameter. The dependence ε (t) is known as the creep curve. Alternatively, strain rate as a function of time is often used (fig. 5.1).

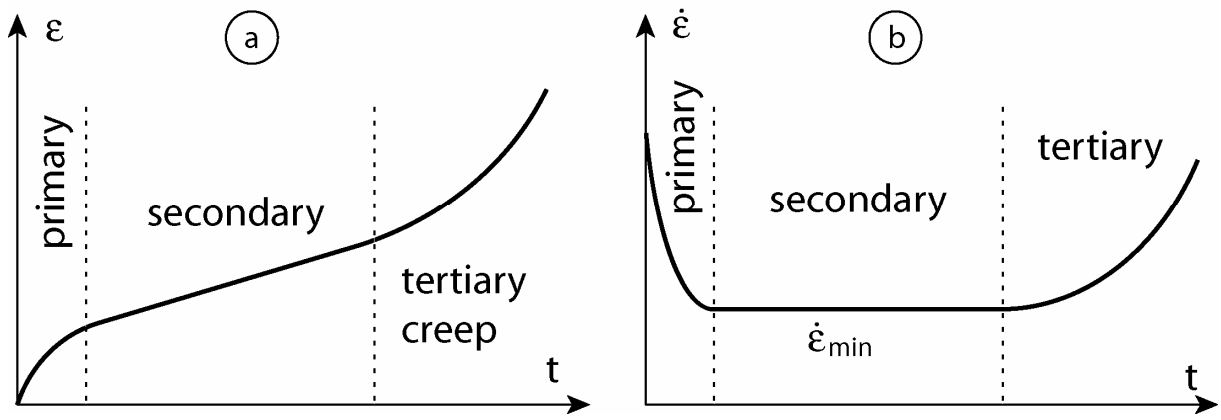


Figure 5.1 a) Schematic of a creep curve, b) strain rate as a function of time.

The creep curves quite often exhibit 3 regimes:

- at the onset of the curve, the strain rate decreases rapidly – primary creep;
- the secondary creep regime (or steady state creep) is characterized by a constant strain rate, called $\dot{\varepsilon}_{ss}$ or $\dot{\varepsilon}_{min}$;
- accelerating creep in the tertiary regime precedes creep fracture.

The minimal creep rate $\dot{\varepsilon}_{min}$ and the time to fracture t_f are two interesting parameters. If several creep tests at the same temperature and different stresses are carried out, a power law dependence between $\dot{\varepsilon}_{min}$ and σ is found:

$$\dot{\varepsilon}_{min} = B\sigma^n$$

where n is the stress exponent and B depends mostly on temperature. According to the stress exponent n, metallic materials are empirically divided into 2 classes:

- class I alloys with n ≈ 3 are typically solid solutions;
- class II alloys with n ≈ 4-5 are typically pure metals (see fig. 5.2).

Remark: The term "creep" is used for 1) a mechanical test at constant load or force and 2) the phenomenon of slow plastic flow under a stress which is lower than the yield point.

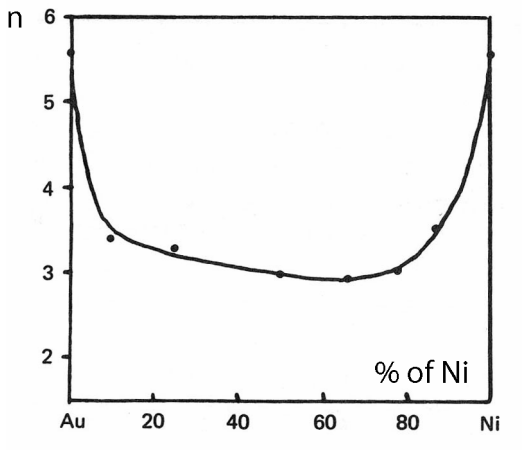


Figure 5.2 The stress exponent for Au – Ni solid solutions.

5.2 Creep machines

Creep machines can be very simple – the dead weight acts on the specimen, directly or through a lever. As a consequence, both constant force and constant true stress tests can be carried out.

One possibility of how to keep constant stress is schematized in fig. 5.3. The force acts on the specimen using a special lever. The curvatures at the ends of the lever are made in such a way that the distance a is constant (circular curvature with the centre at 0) but r decreases as the specimen elongates. The initial stress σ is:

$$\sigma = \frac{mg}{S_0}\frac{r_0}{a}$$

A constant volume of the gauge is assumed:

$$S = S_0\frac{\ell_0}{\ell} = S_0\frac{\ell_0}{(\ell_0 + \alpha a)}$$

r_0, S_0, and ℓ_0 are initial values at $t_0 = 0$ s, the initial position of the lever is horizontal ($\alpha_0 = 0$). In order that the true stress remains constant:

$$\frac{mgr_0}{S_0 a} = \frac{mgr}{Sa} = \frac{mgr(\ell_0 + \alpha a)}{S_0 \ell_0 a}$$

and the profile of the lever has to be constructed with:

$$r = \frac{r_0 \ell_0}{(\ell_0 + \alpha a)}$$

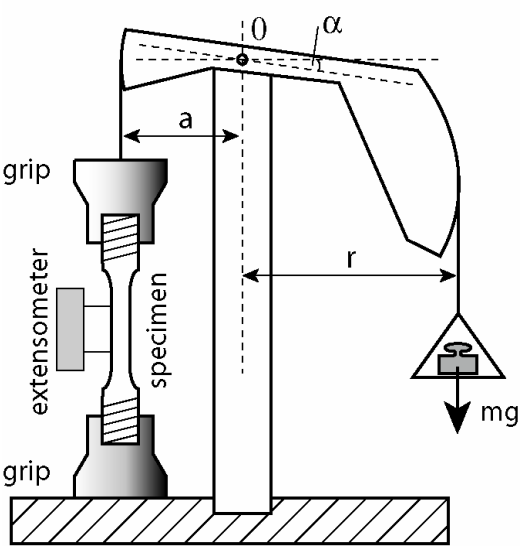


Figure 5.3 Creep machine working at constant true stress.

S U M M A R Y

The tensile test is relatively simple to perform and it supplies well defined and important material characteristics: the yield stress, the ultimate tensile stress and, with less precision, the Young modulus. For the data analysis, it is important that the stress state in the specimen is homogeneous and simple. The instability called necking prohibits to achieve large deformations. Stress and strain are calculated using two widely used definitions:
1) Engineering strain e, engineering stress s:

$$e = \Delta\ell / \ell_0 \qquad\qquad s = F / S_0$$

2) True strain ε, true stress σ (calculated from the constant volume hypothesis):

$$\varepsilon = \ln(\ell / \ell_0) \qquad\qquad \sigma = F / S = s(1 + e)$$

The compression test is used instead of the tensile test if the tested material is brittle, difficult to machine, rare or too expensive. The main problems are i) the possibility of buckling and ii) the friction between the specimen and the machine, which results in barrelling.

The bending test is another simple test used for the characterisation of brittle specimens. The stress state is heterogeneous, it varies along the specimen from compression to tension.

The torsion test enables to achieve large deformations without limitations of necking.

The hardness test is among the most popular tests due to its simplicity. Nevertheless, it is not a proper test from the physical point of view – the results are influenced by several different mechanisms and it is not possible to extract easily intrinsic material parameters.

The (Charpy) impact test is designed for estimation of brittleness of the material. The specimen is broken by an impact of a heavy object called Charpy hammer and the energy absorbed in the specimen during the fracture is measured.

Fatigue is involved in about 70% of industrial accidents. It is especially dangerous if notches are present.

Creep means a slow plastic flow at very low stresses, which appears at high temperatures.

APPENDIX
THE CONSIDERE CRITERION

We will try to calculate the work hardening θ necessary to prevent a neck formation for an elasto-plastic material.

Let's assume that one region is deformed more than the rest of the specimen, the local deformation is $\varepsilon + d\varepsilon$ (fig. 2.12). The local cross-section is therefore reduced by dS and σ increases of dσ, in comparison with the rest of the specimen.

The applied force F is constant in the specimen (Newton's law of action and reaction):

$$F = \sigma S = \text{const} \Rightarrow \frac{dS}{S} = -\frac{d\sigma}{\sigma}$$

We assume that the volume of the material does not change with deformation:

$$V = SL = \text{const} \Rightarrow \quad \frac{dS}{S} = -\frac{dL}{L} = -d\varepsilon$$

The local increase of stress dσ due to the reduction of the cross-section is therefore :

$$\boxed{d\sigma = \sigma\, d\varepsilon}$$

If the work hardening $\theta = d\sigma/d\varepsilon$ is larger than σ, material strengthens more rapidly with deformation than is the stress increase in the neck due to the cross section reduction. It is more difficult to deform the material in the neck than in the rest of the specimen – the specimen is mechanically stable.

Once θ becomes smaller than the applied stress σ, the specimen is mechanically instable and the neck formation is favorized.

REFERENCES

Generalities:

W. D. Callister : Science et génie des matériaux, Dunod Editeur, 2001

Techniques of Metals Research, vol. 5 : "Measurement of Mechanical Properties" (Part 1 and 2), **R.F. Bunshah** ed., John Wiley & Sons - Interscience, 1971.

Techniques de l'ingénieur, volumes MB1 et MB 2 (periodically actualised)

H.W. Hayden, W.G. Moffatt, J Wulff : The Structure and Properties of Materials, Vol. III, John Wiley & Sons, 1966

A. Mortensen : Déformation et rupture (3 tomes), polycopié de l'Ecole Polytechnique Fédérale de Lausanne, 2002

Fatigue :

S. Suresh : Fatigue of materials, Cambridge University Press, 1998

J. Polak : Cyclic plasticity and low cycle fatigue life if metals, Elsevier, 1991

M. Klesnil, P. Lukas : Fatigue of metallic materials, Elsevier, 1992

Creep :

F.R.N. Nabarro, H.L. de Villiers : The physics of creep, Taylor & Francis, 1995

J.-P. Poirier : Creep of crystals, Cambridge University Press, 1985

R.W Evans, B. Wilshire : Creep of metals and alloys, The Institute of Metals, 1985

English – French dictionary

3 (4) point bending	flexion 3 (4) points
aluminium (UK) aluminum (USA)	Al
anelasticity	anélasticité
annealing	recuit
appendix	annexe
area reduction	réduction d'aire
barrelling	mise en tonneau
bcc metals	métaux c.c.
bending	flexion
blade	couteau
buckling	flambage
bulk materials	matériaux massives
casting	fonderie
cavities	cavités
Charpy hammer	mouton – pendule de Charpy
cold rolling	laminage à froid
compression test	essai de compression
compression front	face d'appui
Considère criterion	critère de Considère
constitutive law	loi de comportement
cracks	fissures
creep	fluage
critical stress intensity factor	facteur d'intensité de contrainte critique
cross-section	section droite
crunch test	essai d'écrasement
cyclic deformation	déformation cyclique
cyclic hardening	écrouissage cyclique
damage	endommagement
defects	défauts
dislocation slip or dislocation glide	glissement de dislocations
displacement	déplacement
ductility	ductilité
elevator rope	câble d'ascenseur
elongation	allongement
engineering curve	courbe conventionnelle
engineering strain	déformation conventionnelle
engineering stress	contrainte conventionnelle
fatigue life	durée de vie en fatigue
fatigue limit	limite de fatigue
fatigue	fatigue
ferritic steel	acier ferritique
fracture elongation	allongement à la rupture
fracture	rupture
fragile, brittle	fragile
frame	cadre
furnace	four
gauge (UK) or gage (USA) length	longueur utile
glass powder	poudre de verre
grips	mors
hardening or strengthening	durcissement
hardness	dureté
homologous temperature	temperature homologue
hysteresis loop	boucle d'hystérèse
hysteresis	hystérèse
impact test (or Charpy test)	essai d'impact de Charpy
indentor	indenteur
invertible function	fonction bijective
laser beam	faisceau laser
to load	charger
load axis	axe de traction
load cell	cellule de force
loading – unloading cycles	cycles charge – décharge
loop	boucle
low cycle fatigue	fatigue oligocyclique
lower yield point	limite d'élasticité inférieure
machining	usinage
to manufacture	usiner
mechanical properties	propriétés mécaniques
mechanical test	essai mécanique
mould	moules
necking	striction
notch	entaille
pen recorder	table traçante
perfectly plastic	parfaitement (ou idéalement) plastique
piston	vérin
Poisson ration	coef. de Poisson
polishing	polissage
power plant	centrale électrique
pressure vessel	récipient à pression
proportional limit	limite de proportionnalité
quenching	trempe
$R_{0.2}$	limite d'élasticité conventionnelle
raw data curve	courbe brute
resilience	résilience
resistive strain gauges	jauges de déformation
rigid	rigide
rod	tige
rolling direction RD	sens du laminage SL
rubber	caoutchouc
scratches	rainures
screw	vis

shear strain	déformation en cisaillement
shear stress	contrainte de cisaillement
sheet	tôle
single crystal	monocristal
softening	adoucissement
specimen	échantillon
specimen's head	tête d'échantillon
spring	ressort
stainless steel	acier inoxydable
stamping	emboutissage
standard	norme
steel	acier
strain rate	vitesse de déformation
strain, deformation	déformation
strength	résistance
stress state	état de contrainte
stress	contrainte
tempering, annealing	recuit
tensile test	essai de traction
thermal fatigue	fatigue thermique
toughness	ténacité
true strain	déformation vraie ou rationnelle
true stress	contrainte vraie ou rationnelle
true stress-strain curve	courbe rationnelle
ultimate tensile stress	résistance à la traction
upper yield point	limite d'élasticité supérieure
work hardening (rate)	durcissement par écrouissage
yield stress, yield point (UK), proof stress (USA)	limite d'élasticité
yielding or plasticity	plasticité
Young's modulus	module d'Young