

Lecture 2: APPLIED METALLURGY

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APPLIED METALLURGY

- [Lecture 2.1 : Characteristics of Iron-Carbon Alloys](#)
- [Lecture 2.2 : Manufacturing and Forming Processes](#)
- [Lecture 2.3.1 : Introduction to the Engineering Properties of Steels](#)
- [Lecture 2.3.2 : Advanced Engineering Properties of Steels](#)
- [Lecture 2.4 : Steel Grades and Qualities](#)
- [Lecture 2.5 : Selection of Steel Quality](#)
- [Lecture 2.6 : Weldability of Structural Steels](#)

Lecture 2.3.1 :

Introduction to the Engineering Properties of Steels

SUMMARY: This lecture provides a brief introduction to the crystalline nature of metals and the structure-sensitivity of the material properties. It explains the effect of dislocations on mechanical strength and demonstrates the use of the tensile stress/strain curve as the main means of characterizing strength. It introduces the concept of Poisson's ratio, multi-axial stress states, strain hardening and the influences of temperature and strain rate. It describes the metallurgical and mechanical means of improving strength. It introduces the concept of hardness.

1. INTRODUCTION

1.1 Nature of Metals

Metallic bonding is a consequence of the metal atoms giving up valence electrons to a 'free electron gas'. Metallic structures at the atomic level are then envisaged as almost close-packed arrays of metal ions surrounded by the electron gas. The bonding is, in most cases, non-directional. As a consequence the common metallic crystal structures are face-centred cubic, e.g. Cu, Al, Ni, or body-centred cubic, e.g. Fe. (Some metals exist with a hexagonal close-packed structure, e.g. Zn, Cd, but these are not commonly used for structural applications.)

Metals (and alloys) with cubic structures exhibit four characteristic metallic properties, namely:

- good ductility (or malleability).
- high thermal conductivity.
- high electrical conductivity.
- metallic lustre.

1. INTRODUCTION

1.1 Nature of Metals

Ductility is a consequence of the lack of directionality in the bonding of the atoms and the close-packed nature of the crystal structures which normally allows profuse crystallographic slip to occur under stress. The non-directionality in the bonding also allows thermal vibrations to be readily transmitted from one vibrating atom to its neighbours, hence the high thermal conductivity. The existence of free electrons provides for high electrical conductivity. These free electrons are also responsible for metallic lustre since incident light of a wide range of wavelengths can be readily absorbed and re-radiated.

1. INTRODUCTION

1.2 Structure-Sensitive and Structure-Insensitive Properties

Before embarking on an examination of the properties of interest, the meaning of structure-sensitivity and structure-insensitivity, in the context of material properties, must be clarified.

Structure-insensitive properties are those which are not influenced significantly by changes in microstructure or macrostructure. It is recognised that many of the physical properties of a material, e.g. elastic modulus, bulk density, specific heat, and coefficient of thermal expansion, do not vary other than by small amounts from specimen to specimen of a given material, even if the different specimens have been subjected to very different working and/or heat treatment processes. This insensitivity is present despite the fact that these processes may have produced quite substantial microstructural and macrostructural modifications. On the other hand most of the mechanical properties are very dependent on these modifications. Thus, for instance, the yield strength, ductility and fracture strength are seen to be structure-sensitive.

2. STRENGTH

2.1 Dislocations and Plastic Deformation

For an understanding of the mechanical behaviour of metals, it is necessary to consider both elastic and plastic deformation. Elastic deformation is reversible, i.e. deformation lasts only as long as load is applied. Hooke's laws connect elastic strain with stress as follows:

$$\sigma = E \cdot \varepsilon$$

$$\tau = G \cdot \gamma$$

where

σ and ε are the uniaxial stress and strain respectively

τ and γ are the shear stress and shear strain.

E is the Young's modulus (210000 N/mm²)

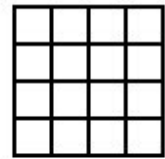
G is the shear modulus (80000 N/mm²)

Response of a simple lattice to shear loading is shown in Figure 1. Initially the response is elastic, Figure 1(b), i.e. when the load is removed all the deformation is recovered. Beyond a limiting stress known as the yield stress, the deformation becomes elastic-plastic, Figure 1(c); when the load is removed only the elastic deformation reverses and the plastic deformation remains, Figure 1(d). This figure shows that crystallographic planes have moved against each other. Simple equations for plastic deformation (corresponding to Hooke's law for elastic deformation) do not exist.

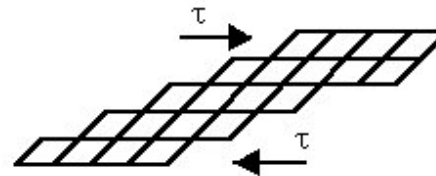
2. STRENGTH

2.1 Dislocations and Plastic Deformation

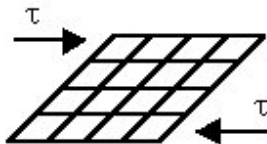
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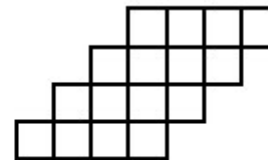
(a) Simple lattice



(c) Elastic plastic deformation



(b) Elastic deformation (reversible)



(d) Plastic deformation

Figure 1 Elastic and plastic deformation

2. STRENGTH

2.1 Dislocations and Plastic Deformation

Theoretical estimates of the critical shear stress required to move a crystallographic plane one slip unit give $\tau_{crit} \sim G/(2p)$. Measurements show that the highest strength steels attain approximately 10% of the theoretical strength. However structural steels have strengths which are two orders of magnitude less than the theoretical value. Therefore, there must be a mechanism which facilitates the slipping of crystallographic planes. This mechanism is the presence of lattice defects called dislocations. Figure 2 shows an example of a simple dislocation. During plastic deformation, a dislocation moves through the atomic lattice within the crystal, Figure 3.

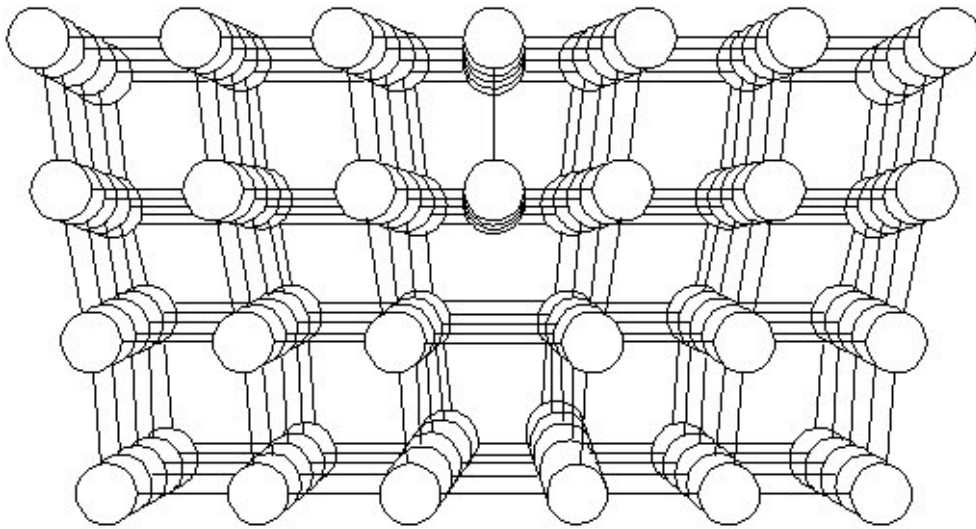


Figure 2 Dislocation in crystal lattice

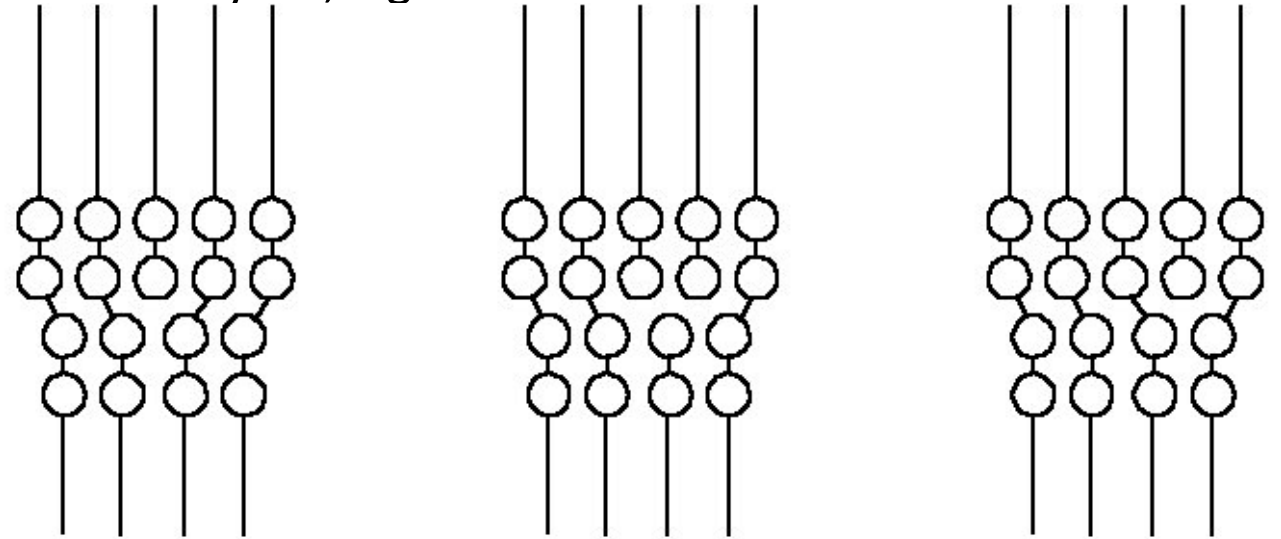


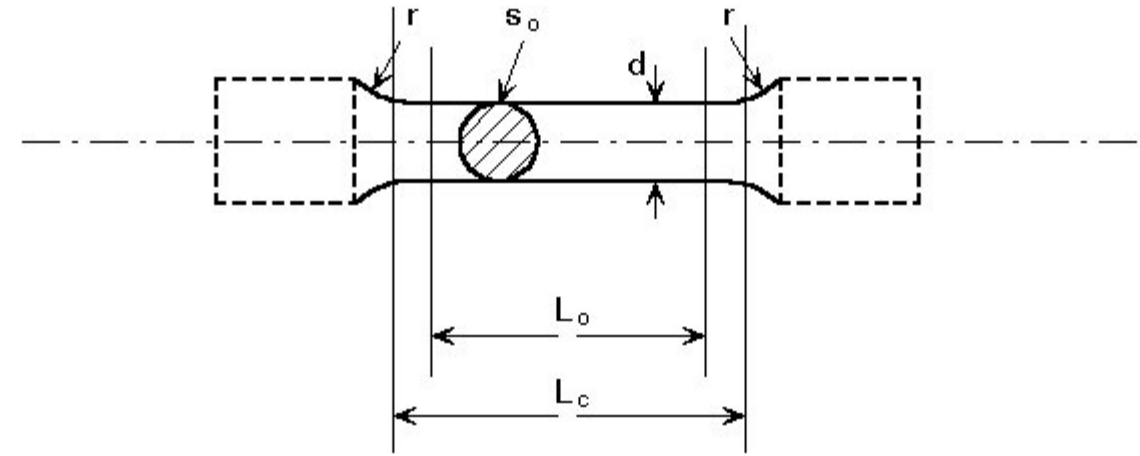
Figure 3 Movement of a dislocation through a crystal lattice

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

The mechanical properties of materials are determined using standardised test pieces and testing procedures. For ductile materials like most steels, tensile tests are the commonly applied testing method. Brittle materials are usually tested by bending or compression.

Tensile properties are usually measured using long and narrow specimens (Figure 4) which guarantee a uniaxial stress state. Round cross-sections are preferred, although rectangular specimens are employed for plate and strip and for the determination of deep drawing properties. Important parameters that have to be controlled during tensile tests are strain rate and testing temperature. The strain rate is controlled by the cross-head speed of the testing machine; the temperature can be regulated by a furnace or a cooling chamber.



L_o = Gauge length

L_c = Parallel length

r = Transition radius

s_o = Original cross-section area

d = Gauge length diameter

Note : For proportional test specimens, $L_o = 5,65 \sqrt{s_o}$

Figure 4 Geometry of standard test piece

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

Load (F) and elongation (ΔL) are measured during testing, from which the stress (σ)-strain (ε) curve can be obtained by taking the test piece dimensions into account. The nominal or engineering stress σ_n is the load F divided by the original cross-section area S_o :

$$\sigma_n = F/S_o \quad (1)$$

The nominal or engineering strain e_n is the ratio of the change in length ($L-L_o$) to the original length L_o :

$$\varepsilon_n = (L - L_o) / L_o = \Delta L / L_o \quad (2)$$

Figures 5 and 6 show the stress-strain curves obtained by Equations (1) and (2) for two types of steel.

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

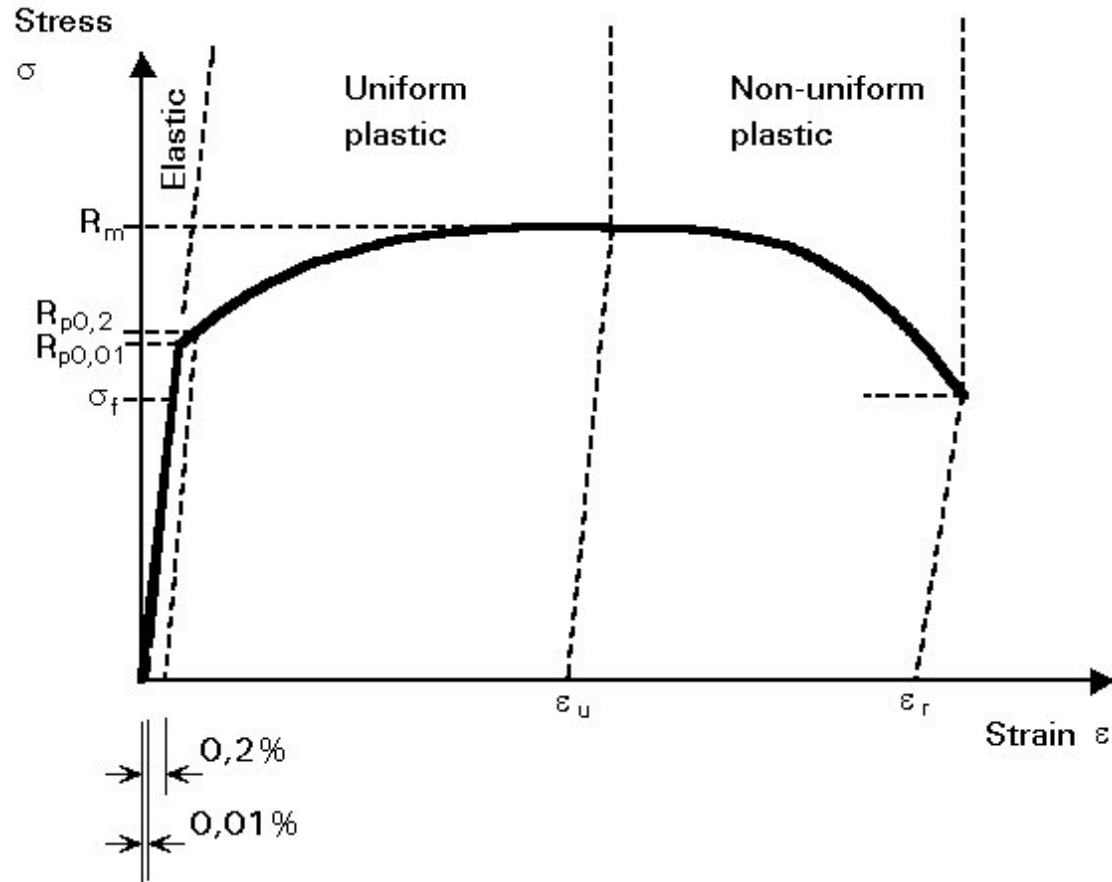


Figure 5 Engineering stress-strain curve of a metal, e.g. high strength steel, with continuous transition from elastic to plastic deformation

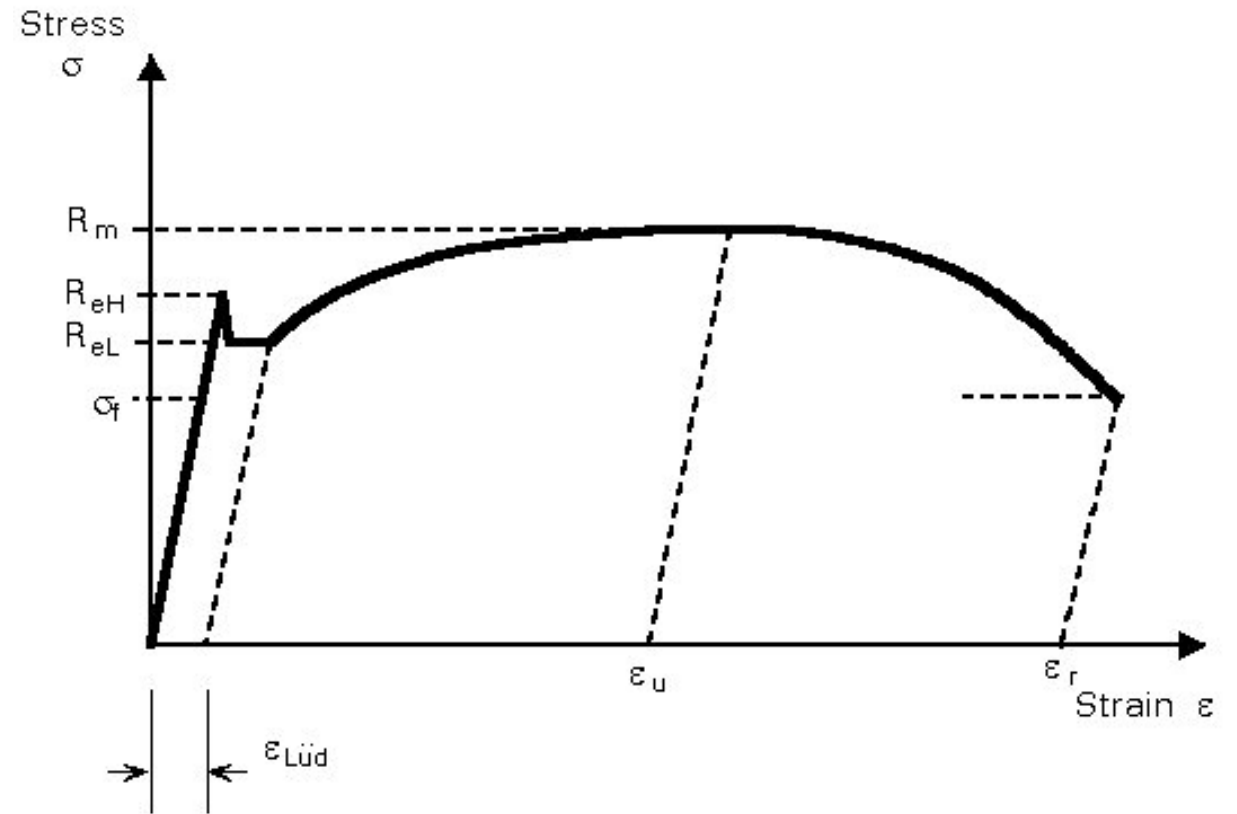


Figure 6 Engineering stress-strain curve of a metal, e.g. mild steel, with a yield point

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

The engineering stress-strain curve can be divided into three regions: elastic deformation, uniform plastic elongation with continuously increasing stress ($\varepsilon \leq \varepsilon_u$) and non-uniform plastic elongation ($\varepsilon > \varepsilon_u$).

In most metals there is a gradual transition from elastic to plastic behaviour and it is necessary to define a proof stress, usually $R_{p0,1}$ or $R_{p0,2}$ in order to characterise the onset of yielding. These are stresses at which a permanent elongation of 0,1 or 0,2% of the initial gauge length is obtained.

Some metals and especially mild steels show a discontinuity between the elastic and plastic regimes with a marked yield point followed by a short period of non-uniform plastic strain (Figure 6). This yielding phenomenon is described by:

- the upper yield stress R_{eH} at the initiation of yielding.
- the lower yield stress R_{eL} , which is the stress value during propagation of the Lüders bands.
- the Lüders strain $e_{Lüd}$ (about 1-2% for mild steels).

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

The reason for this behaviour is that the dislocations are pinned by interstitially dissolved Carbon and/or Nitrogen atoms. These dislocations have to be unpinned by the upper yield stress. Once the dislocations are released they can continue to move at the lower yield stress. This process does not take place homogeneously over the whole specimen. Markings, known as Lüder's bands indicating plastically deformed regions, appear at 45° to the direction of loading and expand across the whole gauge length of the specimen.

In the range of uniform elongation, further plastic deformation is only possible by a continuously increasing load. The dislocation density grows with increasing deformation, making further deformation more difficult due to the interaction between the dislocations. This effect is referred to as strain or work hardening. The rate of strain hardening (ds/de) is high initially but decreases as plastic deformation increases.

In the third region of deformation the specimen continues to become narrower, but this now takes place locally resulting in the necking shown in Figure 7.

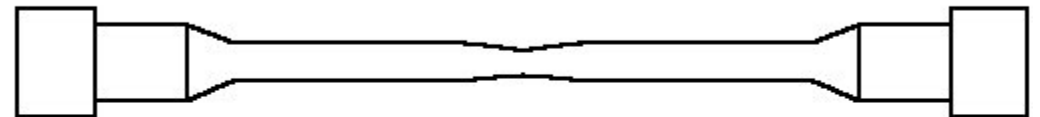


Figure 7 Tension coupon at point of failure

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

The stress at which necking begins is the ultimate tensile stress $R_m = F_{max}/S_0$, the corresponding strain is the ultimate strain e_u . Following the onset of necking, the load necessary to maintain elongation decreases although the local stress within the necking region continues to increase. Continued deformation leads to fracture, which is characterised by the fracture stress s_f and the fracture strain e_r . The percentage reduction of area at fracture

$$Z = 100 (S_0 - S_u)/S_0$$

is a measure of the material's ductility, where S_u is the minimum cross-section area at fracture in the necked region.

For the engineering stress-strain curve, both stress and strain are related to the initial specimen dimensions (S_0, L_0). Because the cross-section and length change continuously during deformation, these equations do not give a true indication of the stress and strain history. For a better description of the material properties, the change of the cross-section area must be taken into account. The true stress and the true strain are defined as follows:

$$\sigma_t = F/S \quad (4),$$

where S is the instantaneous cross-section area.

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

Considering that plasticity takes place under conditions of constant volume, the relation between true and engineering stress and strain in the region of uniform elongation can be derived:

$$\sigma_t = \sigma_n (1 + \varepsilon_n) \quad (6)$$

$$\varepsilon_t = \ln (1 + \varepsilon_n) \quad (7)$$

In the region of necking, the instantaneous cross-section of the specimen must be measured to obtain the true stress and the true strain. The true strain (Figure 8) is:

$$\varepsilon_t = \ln \frac{S_0}{S} \quad \text{for } 0 \leq \varepsilon \leq \varepsilon_r \quad (8)$$

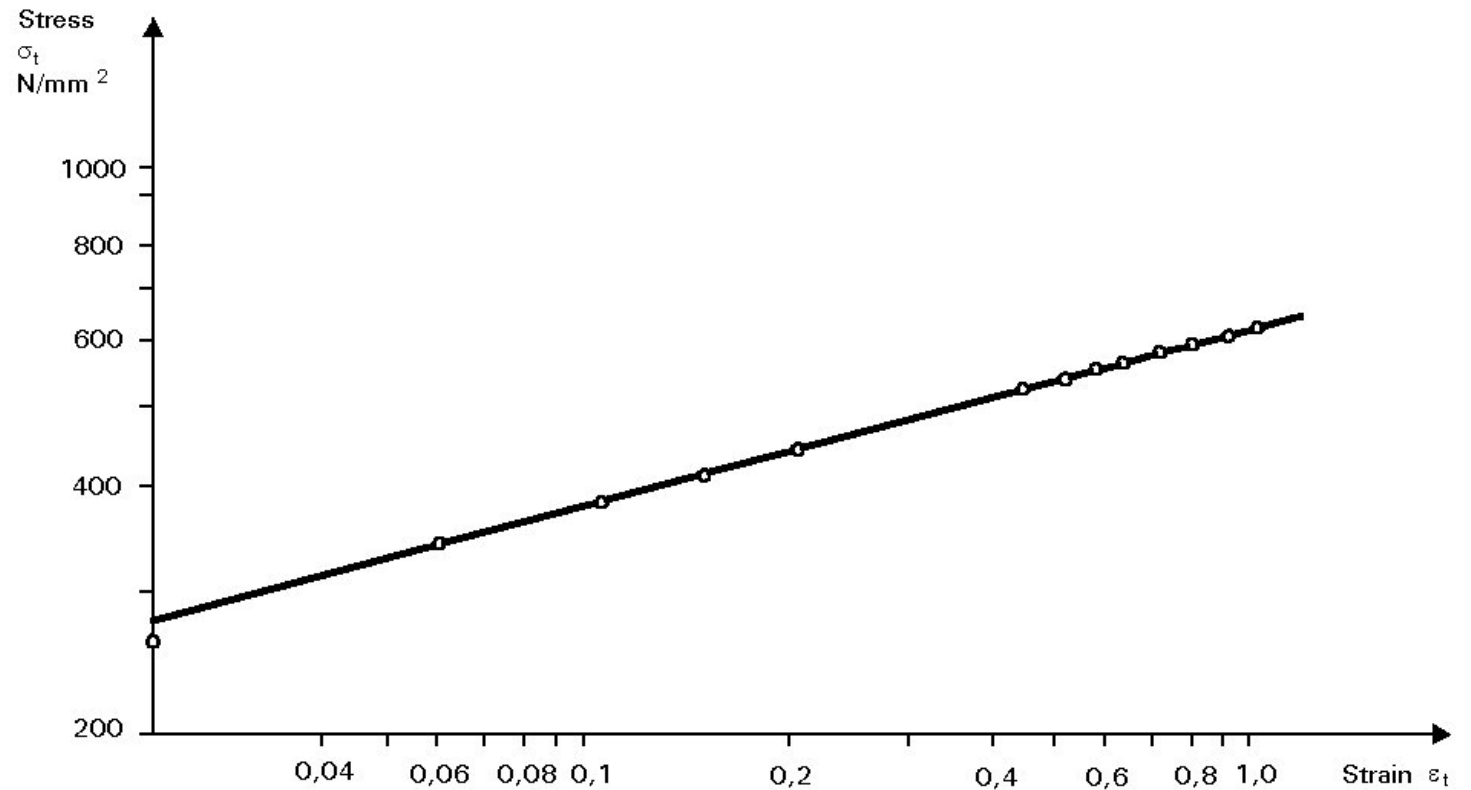


Figure 8 Double-logarithmic plot of true stress versus true strain

2. STRENGTH

2.2 Stress-Strain Curve for Simple Tension Specimen

- For the determination of the true stress, a correction factor k_m must be taken into account because of the multiaxial stress state resulting from necking.
- Figure 9 shows the engineering stress-strain curve (1) and the corresponding true stress-true strain curve without (2) and with (3) consideration of the multiaxial stress state. Note that the true strain becomes much larger than the engineering strain due to necking and that strain hardening is always positive.

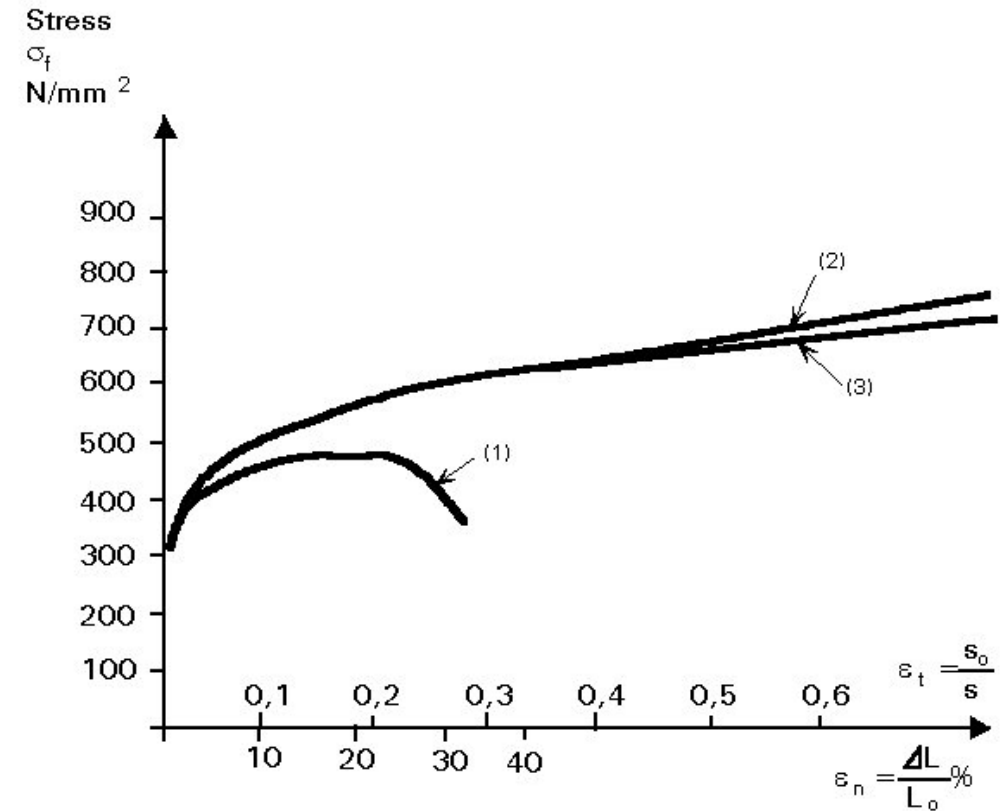


Figure 9 Engineering stress-strain curve (1) and corresponding true stress-strain curve without (2) and with (3) correction regarding the multiaxial stress state

2. STRENGTH

2.3 Multi-axial Response

2.3.1 Poisson's ratio

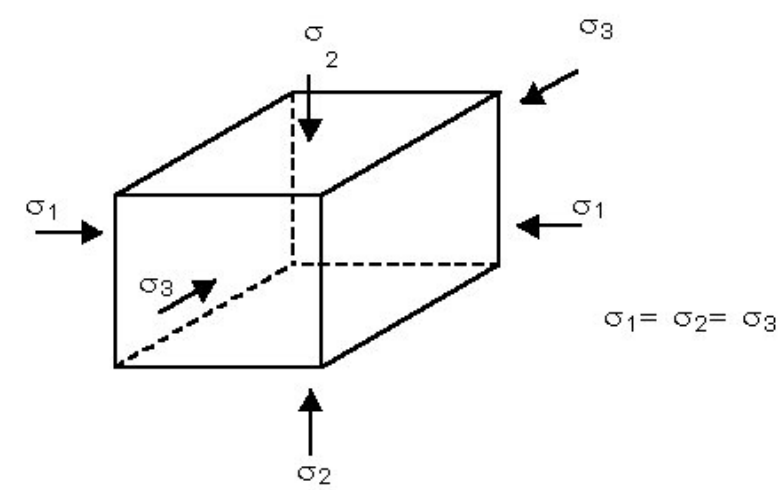
The previous section discussed the longitudinal response of a simple tensile specimen. If measurements of transverse strain (ϵ_{trans}) had also been taken it would have been found that the specimen became narrower as it extended. In the elastic region $\epsilon_{\text{trans}} = \nu\epsilon$, where ν , called Poisson's Ratio, has the value of about 0,3. This implies that the volume of the elastically deformed material is increasing. In the plastic region, with much higher strains, the volume of material does not change significantly and $\epsilon_{\text{trans}} \gg 0,5\epsilon$ which implies that Poisson's ratio has a value of 0,5. This constant volume condition is most clearly illustrated in the necked region as rupture approaches. The locally higher longitudinal strains, are accompanied by high transverse strains giving the local necking.

2. STRENGTH

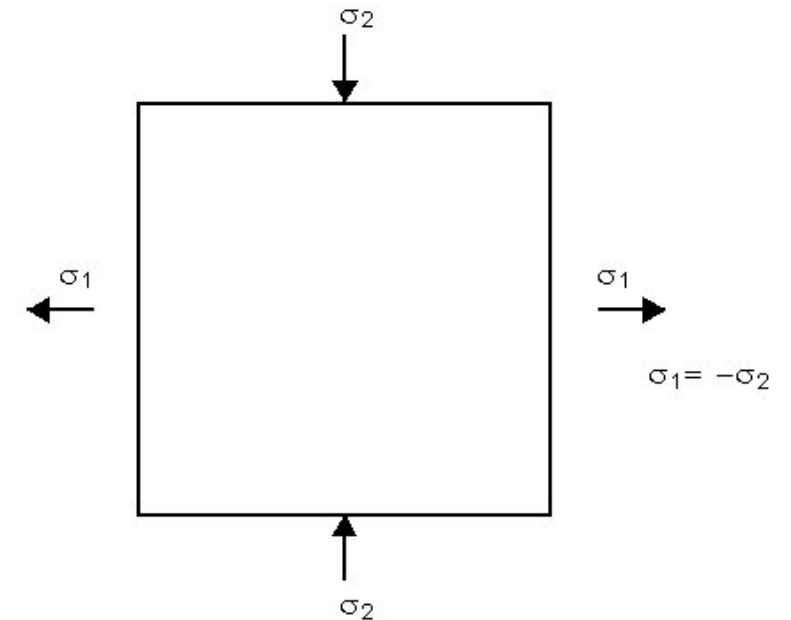
2.3 Multi-axial Response

2.3.2 Multi-axial stress states and their influence on yielding

In many engineering situations stresses exist in more than one direction. Examples are shown in Figure 10. The direction and magnitude of these stresses influence the onset of yielding. In the balanced triaxial compression shown in Figure 10a, the material cannot yield because it has "nowhere to go" until there is a breakdown in the atomic structure of the crystals at several orders of magnitude of stress greater than the uniaxial yield stress. In the two-dimensional pure shear case of Figure 10b the tendency to expand in the x-direction from the tensile stress σ_1 is "encouraged" by the y-direction compression stress σ_2 , and vice versa.



(a) Uniform tri-axial compression



(b) Pure shear in two dimensions

2. STRENGTH

2.3 Multi-axial Response

2.3.2 Multi-axial stress states and their influence on yielding

Different mathematical expressions have been developed to describe this interactive yield, and different formulations prove to be more accurate for different materials. Figure 11a illustrates the two most common criteria for metals under a two-dimensional stress state. The Hencky-von Mises expression which is usually used for steel and for three dimensional stresses, is given by:

$$\sigma_y = (1/\sqrt{2}) \{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2\}^{1/2}$$

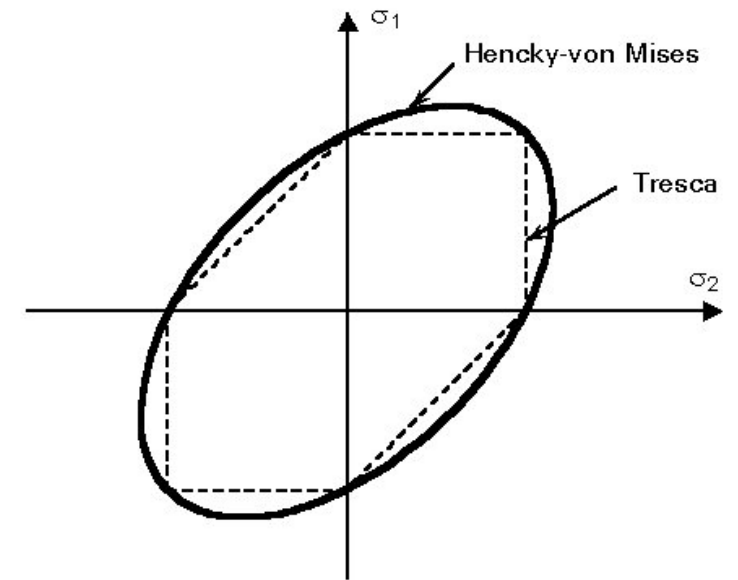
where σ_1 , σ_2 and σ_3 are the three principal stresses.

2. STRENGTH

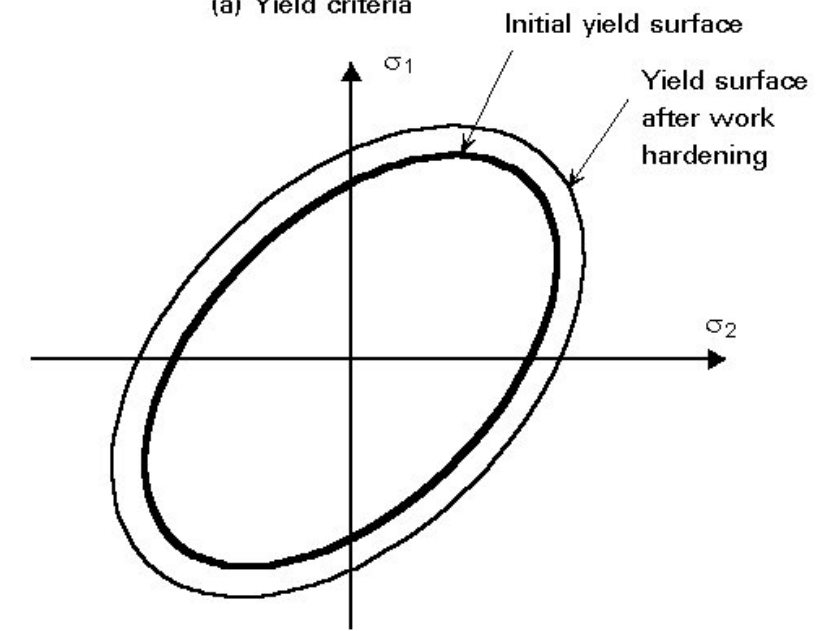
2.3 Multi-axial Response

2.3.3 Strain hardening under multi-axial stresses

Figure 11b shows the most common model for work hardening in the presence of multi-axial stresses. In *isotropic* work hardening the yield surface expands uniformly, as shown.



(a) Yield criteria



(b) Isotropic work hardening

2. STRENGTH

2.4 Influence of Temperature and Strain Rate

Most engineering structures operate at ambient temperatures and are subject to loading rates that are sufficiently slow not to influence response significantly. However, elevated temperatures can be encountered in service (boiler plant) or by accident (fire). Impact and other accidental loading can lead to strain rates whose influence cannot be ignored.

2. STRENGTH

2.4 Influence of Temperature and Strain Rate

2.4.1 Temperature

The movement of dislocations is facilitated by increasing temperature. Both yield and ultimate strengths are reduced as a result. In structural steels there is little loss of strength up to about 300°C. Thereafter there is a progressive loss of strength with increasing temperature. At 600°C the strength is typically 50% of that at ambient temperature.

Creep, i.e. increasing strain at constant stress, in structural steels can be discounted at ambient temperature. However at temperatures in excess of about 500°C creep deformation becomes significant. The influence of elevated temperatures on both stiffness and strength is illustrated in Figure 12.

2. STRENGTH

2.4 Influence of Temperature and Strain Rate

2.4.1 Temperature

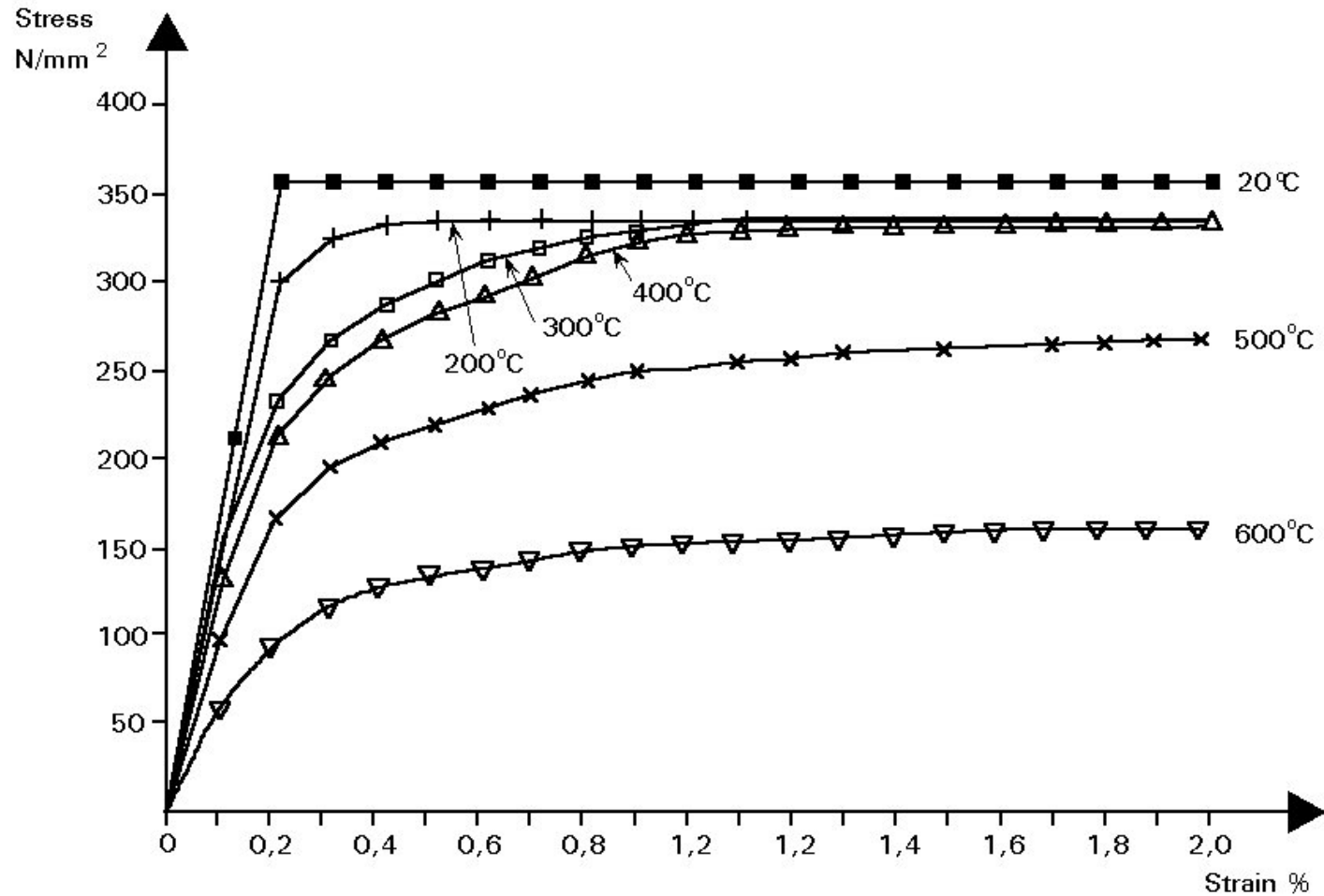


Figure 12 Influence of temperature on the mechanical properties of structural steel (Example shown is Fe490)

2. STRENGTH

2.4 Influence of Temperature and Strain Rate

2.4.2 Strain rate

Dislocation movement is a time-dependent process. It is therefore understandable that high strain rates make yielding more difficult which is reflected in increased yield stress. The most widely accepted model for strain rate effects is the Cowper-Symonds expression given below. The significance of this effect on the tensile stress/strain behaviour is illustrated in Figure 13.

$$\sigma/\sigma_s = 1 + \{\dot{\epsilon}/D\}^{1/q}$$

where:

$\dot{\epsilon}$ = strain rate

σ = dynamic yield stress

σ_s = static yield stress.

D and q are dimensionless curve fitting coefficients.

D = 40.4 s⁻¹ and

q = 5 for mild steel

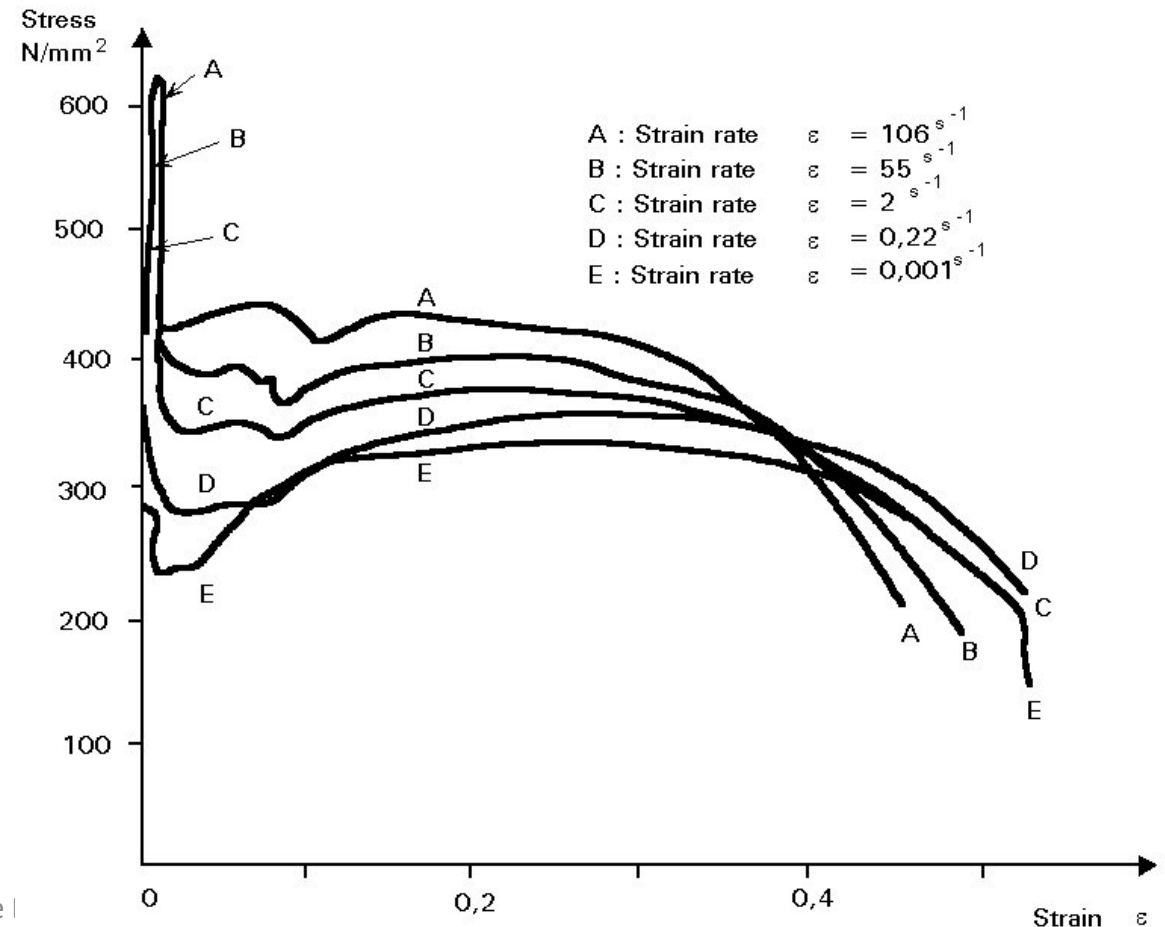


Figure 13 Influence of strain on mechanical properties of mild steel

2. STRENGTH

2.5 Means of Strengthening

The strength of a steel can be described as the resistance against the onset of plastic deformation under an external load. Plastic deformation occurs by the movement of dislocations through the metal lattice which enables single lattice planes to slip consecutively over one another. If this motion is hindered by lattice defects, a higher external load must be applied so that the dislocations can overcome the obstacles. It is for this reason that means of increasing the strength of steels always aim at hindering dislocation movement. Obstacles to dislocation motion can be classified according to Table 1.

TABLE 1

Dimension	Generator	Mechanism
0 (point)	solute atoms	solid solution hardening
1 (linear)	dislocations	strain hardening
2 (plane)	grain boundaries	grain refinement
3 (spatial)	particles	precipitation/dispersion hardening

Strengthening of Steels

2. STRENGTH

2.5 Means of Strengthening

- **Solid solution hardening**

The increase of strength is produced by foreign atoms which are dissolved in the metal matrix. Since foreign atoms differ in size, physical and electrical properties compared to the metal matrix, they cause a lattice distortion that hinders the movement of dislocations. The increase of yield stress depends on the kind, amount and distribution of the foreign atoms, Figure 14. It can be seen that the increase of strength caused by C and N is especially high. This is due to the fact that these atoms dissolve interstitially between the atoms of the matrix, which results in a high lattice distortion. The other elements shown in Figure 14 dissolve substitutionally and occupy regular lattice positions producing less distortion.

Increasing strength by solid solution hardening leads to a decrease in toughness. (Toughness is the ability of a material to avoid brittle fracture - see Lecture 2.3.2.) Therefore, the potential level of strength attainable by solid solution hardening is usually not sought because of the possibility of brittle fracture.

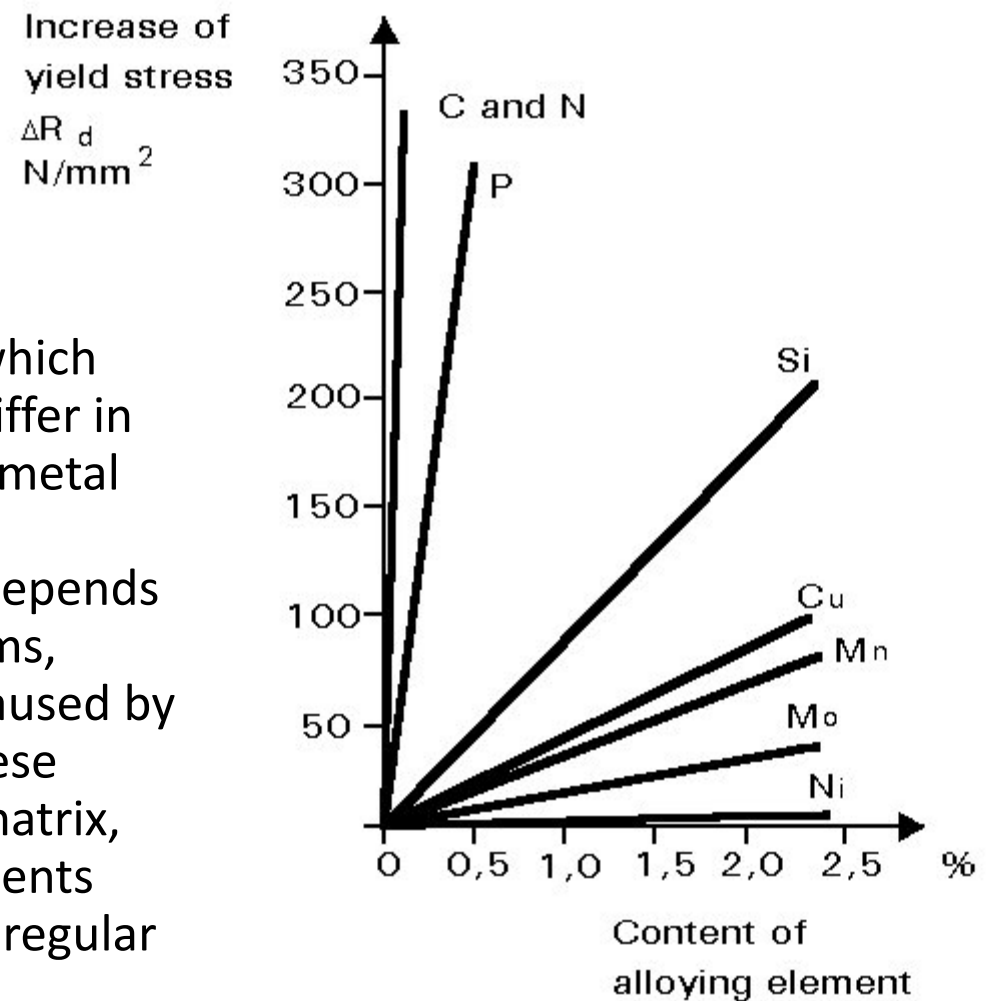


Figure 14 Influence of alloying content on the lower yield stress of ferrite at room temperature

2. STRENGTH

2.5 Means of Strengthening

- **Strain hardening**

Linear lattice defects are the dislocations themselves. The lattice distortion surrounding the dislocation disturbs the movement of other dislocations. This interaction increases with increasing dislocation density.

When cold forming steel, e.g. cold rolling, dislocations must continuously be produced because they permanently block each other. The dislocation density rises and increases the strength of the steel by strain hardening (Figure 15). Such hardening is accompanied by a pronounced reduction in toughness.

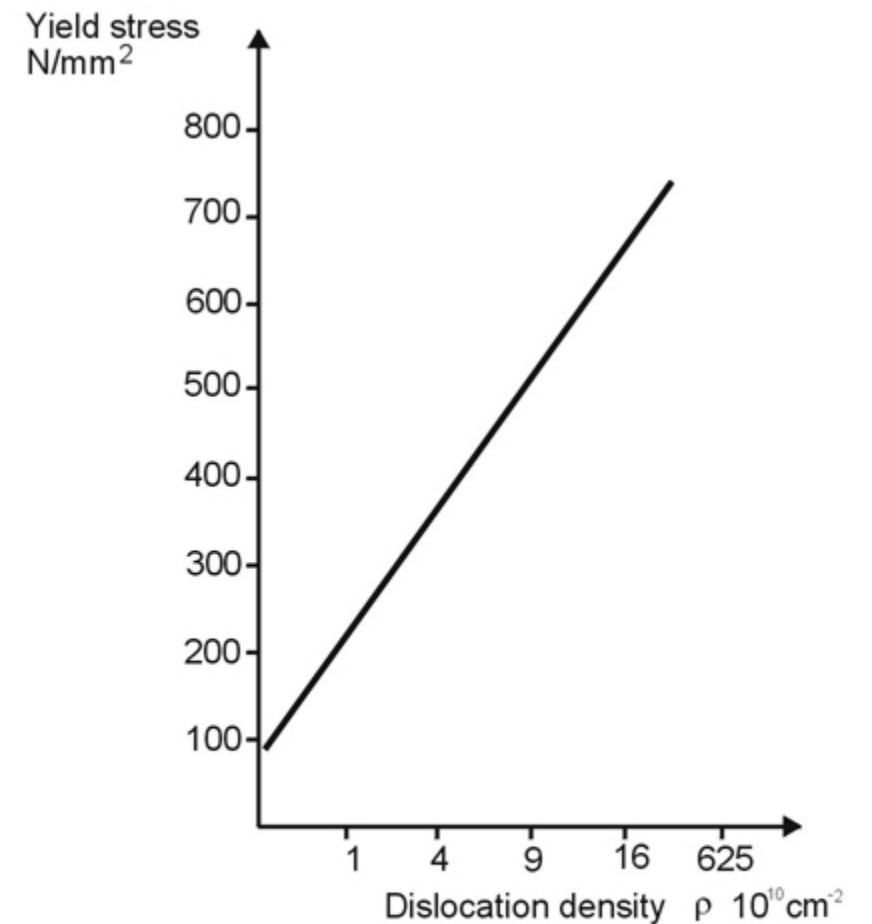


Figure 15 Dependence of lower yield stress of α -iron on the dislocation density

2. STRENGTH

2.5 Means of Strengthening

- **Grain refinement**

Grain refinement is the most important strengthening mechanism in structural steels because it is the only method of strengthening which is accompanied by an increase in resistance to brittle fracture.

The grain boundaries are barriers to dislocation motion. Consequently as the grain size is decreased, the number of barriers increases and this is reflected in increased yield strength. The effect of grain size on yield stress is described by the Hall-Petch equation:

$$R_{eL} = \sigma_{iy} + k_y \cdot d^{-1/2}$$

where

R_{eL} is the minimum yield strength

σ_{iy} is the friction stress; the stress at which yielding begins in a material with very large grains

k_y is the grain boundary resistance

d is the mean grain diameter.

2. STRENGTH

2.5 Means of Strengthening

- **Dispersion and precipitation hardening**

When a moving dislocation encounters a particle it can pass by only two mechanisms:

- cutting through the particle, or
- bowing between and around particles, leaving a section of the dislocation as a ring around the particle.

In steels, the dominant particle hardening mechanism is dislocation bowing. Strength is then inversely related to the interparticle spacing. Consequently strength increases as the particle size decreases and as the volume fraction of precipitates increases.

Strengthening particles are obtained most usually by the precipitation process in the matrix during heat treatment. In steel this is most familiar during tempering of quench hardened medium carbon steels, but it also occurs in structural steels during cooling after controlled rolling or during subsequent tempering treatments.

2. STRENGTH

2.6 Hardness

"Hardness" is a measure of resistance to deformation when a loaded indenter is forced to penetrate the surface of the metal under test. The penetration of the indenter into the specimen leads to a local deformation which is both elastic and plastic.

Testing methods can be either static or dynamic. Both elastic and plastic deformation are considered for the evaluation of dynamic hardness, expressed in terms of the absorbed energy. Dynamic testing methods include impact hardness testing and Shore hardness testing. Their advantage lies in the possibility of quick testing which can be performed at any location. Compared to static hardness testing methods, the dynamic methods are less precise.

The common static testing methods of indentation hardness differ in the type of indenter forced into the metal. The Brinell test uses a hardened steel ball (EN 3), the Vickers test (EN 5) a square-based diamond pyramid (included angle = 136°), and the Rockwell test (EN 10004) is performed with a diamond cone indenter (included angle = 120°).

2. STRENGTH

2.6 Hardness

The indenter is slowly (almost statically) pressed into the specimen. After removing the load, the size of the indentation is measured. Compared to dynamic testing, only the plastic deformation is taken into account. Static testing methods are favoured in industry and research because of the consistency of test results.

The different hardness measurements correlate quite closely, especially at lower values. The correlation of hardness values with other measures of resistance to deformation, such as tensile properties, is more complicated but a useful engineering rule of thumb is that the tensile strength in units of Nmm^{-2} is approximately 3 times the Vickers hardness.

3. CONCLUDING SUMMARY

- Most engineering properties of metals are structure sensitive.
- The principal quantities defining the mechanical properties of metals under non-repeating loading are:
 - Young's modulus.
 - Poisson's ratio.
 - Yield stress, or proof stress for metals without a defined yield point.
 - Ultimate strength.
 - Hardness.
- These properties may be influenced by:
 - temperature.
 - strain rate.
 - multi-axiality.
 - geometry.
- The optimal combination of strength and toughness may be achieved by controlling:
 - alloying content.
 - level of impurities.
 - physical treatment.

APPENDIX 1:

Typical mechanical property data for weldable structural steels

Steel (Grade according to EN10025)	Condition	Yield Stress (N/mm ²)	Ultimate Tensile Strength (N/mm ²)	% Elongation to Fracture (L _o = 5,65ÖS _o)
Grade Fe430B (0,25% carbon)	hot-rolled	275	470	22
Grade Fe430D (0,19% carbon)	normalised	275	470	22
Grade Fe510B (0,23% carbon)	hot-rolled	355	550	20
Grade Fe510D (0,18% carbon, 0,10% vanadium)	normalised	355	550	20

APPENDIX 1:

Typical mechanical property data for some common non-ferrous metals and alloys

Metal or alloy	0,2% Proof Stress (N/mm ²)	Ultimate Tensile Strength (N/mm ²)	% Elongation to fracture (L _o - 5,65ÖS _o)
Aluminium (annealed)	34	77	47
Aluminium (cold worked)	94	115	13
Duralumin (annealed)	123	231	15
Duralumin (age-hardened)	278	432	15
Cooper (annealed)	54	223	56
Copper (cold worked)	285	316	13
70-30 brass (annealed)	85	320	65
70-30 brass (cold worked)	378	463	20

APPENDIX 1:

Typical values of Young's modulus for metals

Metal	Al	Au	Ti	Cu	Fe	Ni
kN/mm ²	70	79	120	130	210	200