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Foreword

This study support for the subject Technical Materials is primarily intended for students of the combined type of study. In the combined form of study there is a much smaller proportion of direct contact teaching and that makes it even more difficult for the students. Therefore, this study support is here to assist you and in some ways to eliminate the handicap. It is not a new study material; there are plenty of those already. This study material is, if possible, a specific form of compensation for the lack of direct instructions and a reference to subsequent literature, whether it will be textbooks or other publications.

When writing this study support, I have tried to maximize the readability of the text. That cannot be achieved, at least in my opinion, without certain simplifications, restrictions and sometimes even a lack of accuracy. If someone felt there is too many of those simplifications, I apologize in advance. But my pedagogical experience in teaching this subject has brought me to the point, where this text is the result.

Despite a careful checking of the text I am almost certain that I did not avoid all the errors, typos, etc., maybe even factual errors. I will be grateful, if you notify me about them, so that I can gradually correct the text. You can do it either directly during the lessons, or via the following e-mail address: jaroslav.sojka@vsb.cz.

I wish all of you, who will be using this study material, a lot of energy to study!

Author

Study guide

This study material is divided into four major sections - chapters. Most of them are further divided into smaller units - sub-chapters. Each sub-chapter has an indicative time for study. This is only an estimated time for managing the whole chapter. Do not take it as an indication of something set or done, and easily get down to it, even if you have less time at the moment.

How should you work with this study support?

The basic learning elements are sub-chapters numbered for example 2.1, 2.2, 3.1 etc.

- Try to read the entire sub-chapter.
- See if you can draw most of the images by hand, in particular the schemes or diagrams.
- If there are **any solved examples in the sub-chapter**, please write them over and solve them again yourself.
- Look at the **summary of terms** and try to answer yourself, whether these concepts make sense to you.
- As an indication, you can look at **the questions and** try to formulate answers to at least some of them.

If you could do it all the first time, it would be excellent, but we do not suppose it.

Read the text again and take notes on what you consider important. Draw the pictures, diagrams, etc. again, read the summary of terms and try to describe them in your own words. Then, go over the questions again. The questions are formulated simply, so that the answer can be found in the text. Answer the question briefly **in writing**!!! Answers to the questions are in the key, which is always at the end of the main chapter. Compare your answers with the key. Answers in the key and your answers may not match perfectly, but they should have the same meaning.

Then you can proceed to the tasks (if any are listed).

If you have problems you cannot cope with, please contact your teacher (whose name will be introduced in the introductory lecture) by e-mail, or directly in his/her office. You can always contact the subject guarantor, prof. Jaroslav Sojka, e-mail: jaroslav.sojka@vsb.cz, phone no. 596994245.

In this course you will process the semester program where detailed instructions on the processing, range etc. will be introduced very likely in the second lecture along with recommendations on literary sources which would be appropriate to refer to.

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1. Introduction.

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Time for study: not stated - this chapter has just a get-to-know or pick-up character



Objective After reading this chapter, you should:

• get tempted into a more detailed study of all other chapters.



Lecture - well, it is not meant in the truest sense of the word lecture, but hopefully you'll forgive me.

Technical Materials as a subject is included in the school curriculum of *master degree studies of Metallurgical Engineering.* Even though your specialty is in metallurgy and related areas, we think that you should be knowledgeable not only in various types of metal materials, but also in other technically significant groups of materials. The course will put emphasis on the relationship between the performance of materials and their inner structures - at different levels of the scale.

So in this subject, after more generally aimed chapters, we're going to pay attention to some metallic materials.

When using technical materials in practice, utility properties are very important, where mechanical properties are the most important. However it is true that almost all the utility properties, including mechanical ones, are very closely related to the structure of the material and a change in the structure, respectively the utility properties of materials can be controlled and changed. And that is desirable and valuable. Therefore, we will put (relatively) great emphasis on the internal structure of materials. You can get acquainted with the characteristics of different materials in detail, when you will work with them. But later in the job, the connection with internal structure will be difficult to search for and yet it is a key relationship.

The subject Technical Materials builds on the subjects that you have completed in the course of BSc studies, especially on the subjects: Basics of Progressive Structural Materials (newly under Introduction to the Study of Materials and Metallurgy) and Materials Science. I will draw your attention to those parts in the text, which you should refresh or review. In some cases, I will briefly explain the most important areas again. You know, they say: repetition is the mother of wisdom. At the beginning, you should revise especially:

- The bonds between atoms, i.e. strong bonds covalent, ionic, metallic and also weak bonds (molecular).
- In addition you should go over the defects of the crystal lattice, in particular dislocations. Dislocations are amazing defects which are often associated with a number of very useful properties of metal materials, as well as others, and we will meet them quite often.
- And finally, you should revise the metastable binary diagram iron carbon.

2. MECHANICAL PROPERTIES OF MATERIALS AND BASIC MECHANISMS OF THEIR FAILURE

2.1. Basic mechanical properties



Time for study: 2.5 hours



Objective After studying this section you will be able to:

- Define basic mechanical properties of the materials;
- Describe the tensile test;
- Characterize variables obtained by the tensile test and their importance;
- Describe the Charpy impact test;
- Characterize variables obtained by impact tests;
- Describe and explain the dependence of metallic materials toughness on temperature;
- Characterize the so-called transition temperature of brittleness and its determination.



Lecture

In many subjects we said that for the application of a certain material in the construction of a larger unit utility properties are very important. They represent a set of all properties that the material must comply with throughout the service life of the structure and must fulfil its function well in order to avoid malfunction, or e.g. an undesired reduction of service life. Among utility properties several groups may be included such as physical properties, chemical properties, etc. For most materials, at least in terms of mass production, the most important are mechanical properties, which are part of physical properties. However, for their exceptional importance, mechanical properties are very often described separately as an individual group of properties.

Which mechanical properties are the most relevant ones? Surely, you remember.

They are:

- strength of materials;
- toughness of materials.

The strength of materials can be simply defined as the maximum stress that a material can transmit without any violations, or defect formation, such as cracks. The strength of the materials is mostly determined by a tensile test, which is briefly described further. That is because it does not only detect the strength of a material, but also other very important characteristics.

We have simply defined the toughness of the material as the energy required for material failure. Sometimes it is characterized as material resistance against the formation and growth of defects, cracks in particular. The toughness of metallic materials is generally determined by an impact test (see below).

D Tensile test

The tensile test is one of the basic mechanical tests. It is a static test, in which the test specimen is loaded in the testing machine with a prescribed-power speed, usually up to failure. During the test, the dependence of the working force F (N) on absolute elongation is recorded ΔL (mm). This dependence is called a tensile or **working diagram**. This test is usually carried out at a certain loading rate (crosshead movement speed) at a temperature of 20°C, but also according to the requirements at higher or lower temperatures.

What does the **specimen** for a tensile test look like? It is a bar mostly with a circular or rectangular cross-section, where so-called *initial measured length* L_0 (Figure 2.1) is marked. Test bars can be either smooth, i.e. their cross-sectional area is the same along the entire length, or may be provided with heads, i.e. extended bar ends, which are clamped to the testing machine.

Note: The total length of a smooth bar also includes parts which are necessary for fastening to the test machine.

The initial measured length L_0 for flat bars with rectangular cross-section is determined either as an absolute length (50, 80 or 100 mm), or as the ratio between L_0 and initial cross-section S_0 ($L_0 = 5.65\sqrt{S_0}$ for the "short" bar, $L_0 = 11.3\sqrt{S_0}$ for the "long" bar). With bars of cylindrical cross-section L_0 it is set at five times or ten times the average diameter of the specimen.



Fig. 2.1. Test bar examples for tensile test (a) bar of circular cross-section, (b) flat bars of rectangular cross-section.

By the effect of the loading force F (N) on the tested bar, the initial measured length is extended from L_0 to L_1 with elongation ΔL , the so-called absolute extension (or elongation), and at the same time the original cross-section S_0 is reduced to immediate S'. There is a tensile stress σ formed in the tensile bar (equation/eq. 2.1).

$$\sigma = \frac{F}{S'},$$
 eq. 2.1.

which is referred to as **the true stress**. In practice, it is difficult to detect an immediate crosssection area; therefore the loading force refers to initial cross section S_0 . The resulting stress

$$\sigma = R = \frac{F}{S_0}$$
eq. 2.2

is referred to as **the contractual stress** R. Stress is expressed in units of MPa (megapascal); while 1 MPa = 1 N / mm².

As we have already said, the result of the tensile test is a working (tensile) diagram (Fig. 2.2 - valid for ductile metallic material). The working diagram can be divided into several areas.

The first one is an area of *elastic (flexible, reversible) deformation*. The tested rod in this section extends proportionally by increasing the loading force. If we relieve (unload) the bar in this section, it will return to its original length. The relation between the stress and the proportional extension ε ($\varepsilon = \Delta L/L_0$) is expressed by

$$\sigma = E \cdot \varepsilon$$
 eq. 2.3.

which we refer to as Hooke's law for uniaxial tension. What is important for us is the constant E, the tensile modulus (frequently GPa unit - gigapascals). It is a material constant.

Note: Elongation ε expresses the change length $\Delta L = L_1 - L_0$ related to the initial length L_0 of the tested bar.



Fig. 2.2. Working (tensile) diagram F- ΔL .

The second area is the area of *uniform plastic deformation*. Dislocations in metallic material will begin to move after exceeding a certain stress (the so-called yield strength - see below), there is also formation of new dislocations and the material begins to be permanently (plastically) deformed. There is a diversion from linear stress dependence on proportional extension and the increased stress on the proportional extension (deformation) declines gradually to zero.

Up to this point the measured part of the test bar is deformed uniformly, i.e. (it) narrows evenly over the entire length.

The third phase is the area of *non-uniform plastic deformation*. There is a fall in (contractual) stress and defects begin to appear in the tensile test bar - the material is either entirely or partially damaged and often creates a local necking, - the so-called neck. This stage

ends with fracture of the test bar. Fig. 2.3 shows how deformation occurs on a tensile test bar during loading.



Deformation

Fig. 2.3. The deformation of tensile test bar during loading.

To evaluate basic strength characteristics, working diagram $F-\Delta L$ is converted to the diagram $R -\varepsilon$ (contractual stress-elongation). When calculating the stress all measured forces will always relate to the area of the original cross-section S₀. Diagrams $R-\varepsilon$ differ for various materials in both the strength characteristics and the values of deformation (Fig. 2.4).



Fig. 2.4. Schematic comparison of tensile diagrams for various metallic materials(a) steel without significant yield point, (b) steel with significant yield point,(c) ductile cast iron, (d) grey cast iron, (e) aluminium alloy.

What characteristics can we read from the tensile tests and working diagram? Basic characteristics obtained when a tensile test is applied are the following:

- yield stress;
- ultimate tensile stress;
- elongation at fracture;
- reduction in area.

The yield stress can be simply defined as the maximum stress to which the material deforms elastically, i.e. reversibly. For metallic materials there applies no movement of dislocation until the yield point. The yield stress is contractual stress and may be either significant or insignificant, and corresponds to force F_e (N). In the tensile diagram there is a point (Figure 2.5), where there is a stop or even decrease of loading force at progressive permanent deformation. Significant yield stress is referred to as upper yield stress R_{eH} or lower yield stress R_{eL} (Fig. 2.5a). We determine insignificant yield stress for a certain plastic (permanent) deformation (e.g. $\varepsilon = 0.2$ %). It is called contractual yield stress $R_{p0.2}$ (Figure 2.6b).



Fig. 2.5. Determination of yield stress from tensile diagrams. (a) significant upper yield stress R_{eH} or lower yield stress R_{eL} (b) insignificant contractual yield stress $R_{p0,2}$

The yield stress is calculated by dividing the respective loading force and the initial crosssectional area. For example, to calculate lower yield stress we can calculate:

 $R_{eL} = \frac{F_{eL}}{S_0}$

eq. 2.4

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The ultimate tensile strength (stress) is also contractual stress and corresponds to a maximum load during the tensile test (Figure 2.3). It is referred to as R_m .

$$R_m = \frac{F_m}{S_0}$$
 eq. 2.5

It has already been stated that ultimate tensile strength can be defined as the maximum stress when the loading still does not involve material defects and there is no development of degradation.

Elongation at a fracture is the maximum proportional plastic (permanent) elongation ε_p in %. This is referred to as *A*, and further to the size of the initial measured length, e.g. A_5 (for "short" test bar), A_{10} (for "long" test bar), A_{50} ($L_0 = 50$ mm), etc. The elongation at a fracture shall be calculated in accordance with equation (eq. 2.6)

$$A = \frac{L_u - L_0}{L_0} \cdot 100$$
 eq. 2.6

where L_0 is the initial measured length, which we marked on the test bar and L_u is the ultimate length measured after the fracture. This can be measured by putting both parts of test bar together and measuring the originally indicated length L_0 . The shape and dimension of the test bar changes until the fracture, which can be seen in Figure 2.6. We then obtain different values of elongation at fracture for different initial (measured) lengths (e.g. $A_{10} < A_5$) and the resulting values may not be transferred or converted.



Fig. 2.6. The change of test bar dimensions under the loading force until the fracture.

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Reduction in area (Z) indicates maximum relative necking after the fracture of the test bar in %. The formula for calculation is shown below (Eq. 2.7):

$$Z = \frac{S_0 - S_u}{S_0} \cdot 100$$
 eq. 2.7

Where S_0 is the original cross-section of the test bar in mm² and S_u is the minimum (ultimate) cross-section of the test bar/rod in mm² in the place of fracture.

Note: The initial area of a round bar cross-section S_0 may be calculated as the area of a circle, i.e. $S_0 = \frac{\pi d_0^2}{4}$. Similarly, the circular cross-sectional area of the bar after fracture S_u shall be calculated as $S_u = \frac{\pi d_u^2}{4}$.

The yield stress and the tensile stress have therefore a character of stress, where elongation at a fracture and reduction in area are dimensionless quantities, i.e. they are given as a percentage. All four quantities obtained by the tensile test are very important. Regarding the comparison of the importance of the yield stress and the tensile strength, it is applicable to metallic materials, but the yield strength is still a bit more important. Why? This is because, in service, metallic materials may be loaded only with less stress than the yield stress, i.e. in the area of elastic deformation. Plastic deformation is not allowed during service. There are many reasons, but we will only need the two most important ones. Plastic deformation is not constant even at a constant loading stress over time, but gradually increases with time. And that is unacceptable. Imagine, for example, that a deflection of a steel ceiling would expand with time. This could have a number of consequences, such as cracking plaster, etc. The second reason is that although the dislocations are rather regarded as beneficial defects, nothing applies absolutely. Dislocations arising from plastic deformation, respectively, the accumulation of dislocations, may produce germs of defects (may be source of defects) and even cracks, which may cause material rupture. And that is what everyone is afraid of. The yield stress is therefore the stress, according to which the construction is dimensioned, i.e. the size determination. Elongation at fracture and reduction in area are also very important. They provide us with some information about the material toughness (ductility), even if detected by a static test. Put in a simplified way, the higher elongation at fracture and reduction in area, the more ductile a material is.

Charpy Impact Test

Among the dynamic tests the impact test is a basic test to determine the toughness of metallic materials. Determination of metallic material toughness is extremely important. Did you

know that the opposite of toughness is brittleness? And if we fear something about the engineering materials, then it is the brittleness of the material, or rather its brittle failure. Brittle failure can cause the sudden collapse of structures, e.g. bridges, pressure vessels, etc., with all its negative consequences. It is very important that the toughness of materials depends significantly on temperature since the toughness of materials decreases with decreasing temperature in general. This decrease in toughness with decreasing temperature, however, heavily depends on the type of crystal lattice. For metals with a face-centered cubic lattice (fcc: face centered cubic) the decrease in toughness with decreasing temperature is only moderate and materials with this crystal lattice remain ductile even at low temperatures. This is due to the fact that the fcc lattice has a higher degree of symmetry (coordination number 12 - do you remember?) and consequently, the dislocation movement in this lattice is easier. Dislocations can move even at low temperatures, when the energy of the vibrational motion of atoms is low. In contrast to bcc metal lattice (bcc: body centered cubic), when the temperature drops, a sudden drop in toughness at a given temperature interval occurs as well. The material behaves as considerably fragile at low temperatures than. This is because, in the case of bcc materials, the lattice dislocation movement is more difficult and it is helped by thermal activation, i.e. a. more intense vibrational movement of atoms. At low temperatures, when the intensity of the vibrational motion of atoms is low, dislocation movement is very difficult, therefore plastic deformation is not possible and material behaves as fragile. Therefore, metallic material with a bcc lattice can due to temperature change act as ductile- at "higher" temperatures, or as brittle - at "lower" temperatures. A comparison of toughness, expressed by the energy for fracture - called impact energy at an impact test - is shown in Fig. 2.7 (for different kinds of metallic materials).



Fig. 2.7 Dependence of impact energy on temperature for different materials 1 - with fcc lattice, 2, 3 - with bcc lattice, 4 - cast iron.

The impact test in bending is based on the findings, how much energy is consumed to break the test bar in bending. The Charpy impact test is the most commonly used test. The principle is to break the test bar with a one-side notch with one impact hit of a pendulum hammer. The test bar is placed on the supports with a notch on the opposite side to which the hammer strikes (Fig. 2.8). The result of this test is to determine the impact energy K (J), which expresses the energy consumed for body deformation and fracture propagation. This test was first introduced in the early 20th century by Georges Charpy. Unfortunately, as a standard test for toughness evaluation, it came into practice after the Second World War. The expression "unfortunately", is used here on purpose. If the materials were tested previously, it would have been possible to prevent many disasters which happened before the introduction of this type of test, including the sinking of the ship Titanic.

The impact test has two specific features:

First, it is an impact test, i.e. the load acts quickly. That is very important, because the toughness of materials decreases with increasing the strain rate. The faster the loading force works (with related stress), the more brittle the material is. It is due to the fact that the brittleness of materials relates to their inability of plastic deformation. Plastic deformation is possible under the condition of a dislocation movement and this movement requires certain time.

The second specific feature is that the tested bodies are provided with so-called notches (see below). Beyond other things, notches represent stress concentrators, which are often present in real structures. We can therefore say that the Charpy impact test takes into account the real situation in the loaded structures, especially the high loading rate and the presence of stress concentrators.

Test specimens for the Charpy impact test are standardized in a size $10 \times 10 \times 55$ mm. They are provided with a V-notch with a depth of 2 mm (notch angle is 45 °) or U-notch with a depth of 5 mm (respectively 2 or 3 mm) - Fig. 2.9. For samples with a V-notch the test bars may be even made of smaller dimensions with a width of 7.5 or 5 mm (the notch is on the narrower area). According to the notch type, the impact energy is indicated as *KV* for samples with a V-notch and *KU* for samples with a U-notch.



Fig. 2.8. Test bar placement on pendulum hammer supports.



Fig. 2.9. The shape and dimensions of the test bars with a V-notch and a U-notch.

Impact energy can be converted to notch toughness *KC* (indicated as *KCV* or *KCU* depending on the notch type) as in accordance to equation 2.8:

$$KC = \frac{K}{S_0},$$
 eq. 2.8

where *K* is impact energy in J, S_0 is area under notch in cm².

Notch toughness KC is stated in units J·cm⁻².

During the impact test the **proportion of brittle fracture** P_{KL} in % and the deformation characteristics Δb , the so-called **transverse extension** is also evaluated.

The proportion of brittle fracture is determined from the ratio of the brittle fracture area S_{kl} and the ratio of the area under the notch S_0 (eq. 2.9) – Fig. 2.10.



Fig. 2.10. The evaluation of a brittle fracture ratio P $_{\rm KL}$.

D Transition temperature

If we apply the Charpy impact test on a material with a bcc lattice at different temperatures and the resulting impact work values K or notch toughness KC are dependent on temperature T plotted in the graph, we obtain the so-called **transitional curve** (Fig. 2.11). From transitional curves we can determine transition temperatures, which help us to evaluate the resistance of a material to the brittle fracture. **Transition temperature** T_T may be determined from various criteria:

- For a certain value of notch toughness, e.g. for $KCV = 35 \text{ J} \cdot \text{cm}^{-2}$ for a weldable low-carbon steel,
- from the mean value of notch toughness KCV_{avg},
- for 50 % of brittle fracture P_{KL} .



Fig. 2.11. Transition curve during impact test.

The transition temperature for steel is an important characteristic of a material's ability to withstand impact loads and the ability of the material of cold forming at a given temperature. For technical practice it is important that the material should be loaded at temperatures above **transition areas.** The transitional area is influenced by metallurgical factors, heat treatment, chemical composition, grain size, welding, temperature, loading rate, etc. However, it is established for specific conditions of stress, which are used for testing, whereas in other circumstances, the material may behave differently.



After studying this section the following terms should be clear:

- Basic mechanical properties strength, toughness;
- Basic characteristics obtained in a tensile test yield stress, tensile stress, elongation at fracture, reduction in area;
- Basic characteristics obtained in a Charpy impact test impact energy, notch toughness;

> Transition temperature and its determination.



Questions 2.1.

- 1. What are the basic mechanical properties of structural materials?
- 2. What is expressed by strength?
- 3. Which materials have a high strength?
- 4. What is toughness?
- 5. What is the result of a tensile test?
- 6. Into what areas can we divide the tensile diagram?
- 7. Which law applies in elastic (reversible) deformation?
- 8. Which material characteristics can be read from the area of elastic (reversible) deformation?
- 9. What is the difference between contractual and true stress? Which stress is higher?
- 10. What material characteristics can be read from a working (tensile) diagram?
- 11. What is expressed by tensile strength R_m ?
- 12. What is an elongation at fracture?
- 13. What is a reduction in area?
- 14. What is the result of an impact test?
- 15. What is expressed by notch toughness?
- 16. What kind of material characteristics can be obtained from the dependence of impact energy, respectively from the dependence of notch toughness on the temperature?

2.2. Basic mechanisms of materials failure

?)	Time f	for stud	ly: 1.5	hours
			•	



Objective After studying this section you will be able to:

- describe the most important mechanisms of material failure;
- explain the progress of ductile fracture;
- characterize two basic types of brittle fracture.



Lecture

D Types of materials fracture and their progress

As it is apparent from Chapter 2.1 that a basic type of material fractures is a ductile fracture (it's also called ductile, because it is linked to plastic deformations, i.e. with forming), and the opposite is then a brittle fracture. In most cases the ductile (ductile) fracture is desirable, while the brittle fracture is the type of fracture, which all designers (as well as manufacturers of construction materials) are afraid of. A fracture can be viewed in terms of energy. A ductile (ductile) fracture is a so-called high-energy fracture, where there is a need for high energy to do the damage. In contrast, the brittle fracture is a so-called low-energy fracture, where there is just low energy needed to do the damage. That is the main danger.

Now let us briefly describe how these basic types of fractures develop within the examples of metallic materials.

How does the ductile (ductile) fracture develop?

Ductile fracture progress is schematically illustrated in Fig. 2.12. We can imagine that we are performing a tensile test. In the field of non-uniform plastic deformation, cavities begin to develop in a material. These cavities preferably form on a boundary of a metal matrix and "foreign" particles, which may be e.g. non-metallic inclusions, or different kinds of minor phases - carbides, nitrides, inter-metallic phases, etc. Cavities emerge due to the separation of the particle surface from the own metallic matrix, and a cavity is locally created as a result of the ability of the plastic deformation of the material (Fig. 2.12 - a). As the actual stress is growing in the field of non-uniform plastic deformation, there is a growth of cavities in the

direction of applied stress, hence their growth - Fig. 2.12 - b (again due to the fact that the material is capable of plastic deformation). In the case, where newly-emerged cavities are close to each other and are separated by only the narrow area of the metal matrix (the so-called bridge), breakage of this narrow region in the matrix can lead to a subsequent spread of an "associated" larger cavity. This stage of development of a ductile (ductile) fracture is called the coalescence of cavities (Figure 2.12 - c). The actual stress is being further gradually increased causing damage to remaining parts of the matrix (bridges) in the neck, which will result in a final fracture of the material, which usually runs from a macroscopic point of view in a plane perpendicular to the direction of applied stress.



Fig. 2.12 Schematic representation of the early stages of a ductile fracture.

The individual stages of the development of ductile fracture of metallic materials can be summarized as follows:

- cavities formation;
- cavities growth;
- coalescence of cavities;
- final fracture.

A ductile fracture of metallic materials has a characteristic appearance on the fracture surface. At sufficiently high magnification of the fracture surface, an area of so-called dimples is apparent, which correspond to individual cavities. In some cases non-metallic particles may be evident in dimples, on which the cavities have formed. Fracture surfaces are most often displayed using so-called scanning electron microscopy. Examples of fracture surfaces, corresponding to a ductile fracture with dimple morphology are shown in Figure 2.13 a, b. In

Figure 2. 13 b, non-metallic particles are observable in numerous dimples in which the cavities have formed.



Fig. 2.13 The fracture surface of a ductile fracture with dimple morphology (viewed by scanning electron microscopy)

How does a brittle fracture develop?

It has already been stated a brittle fracture is such damage, where the energy required for its development is low. The brittle fracture occurs when the material is not capable of plastic deformation. For a brittle fracture we can distinguish two basic types, which differ by the fracture path, whether it occurs on the boundaries of individual grains (such damage is called an intergranular brittle fracture), or in the internal parts of the grain - over the grain (the so-called transgranular brittle fracture). Sometimes, for a transgranular brittle fracture the term transgranular cleavage fracture is used as well, because the material seems to cleave along certain crystallographic planes. For metals with bcc lattice planes of brittle cleavage are types $\{001\}$.

The progress of transgranular cleavage fracture is schematically illustrated in Fig. 2.14a, whereas Fig. 2.14b displays a corresponding appearance of the fracture surface viewed by scanning electron microscopy.

The progress of an intergranular brittle failure is schematically illustrated in Fig. 2.15a, whereas Fig. 2.15b displays a corresponding appearance of the fracture surface viewed again by scanning electron microscopy.

If a brittle fracture occurs in metallic materials, the case of a transgranular cleavage fracture is more frequent. An intergranular brittle fracture occurs when the grain boundaries are somehow weakened. This most commonly occurs, for example, due to a segregation of harmful elements (e.g. in steels due to the segregation of phosphorus and sulfur) at the grain boundaries.



2.14 Transgranular cleavage fracture a) schematic progression; b) appearance of the fracture surface (scanning electron microscopy)



2.15 Intergranular brittle fracture a) schematic progression; b) appearance of the fracture surface (scanning electron microscopy)



Summary of terms 2.2.

After studying this section the following terms should be clear:

- > Ductile (ductile) fracture and its course/progress;
- Intergranular brittle fracture;
- > Transgranular cleavage fracture.



Questions 2.2.

17. How can we characterize a ductile (ductile) fracture from the energy point of view?

- 18. What term is used for a ductile fracture as well?
- 19. Where does the process of ductile fracture in metal materials begin?
- 20. What is the first stage of a ductile fracture?
- 21. What is the nature/character of a ductile (ductile) fracture on the fracture surface?
- 22. When does the process of brittle fracture in metal materials happen?
- 23. Where does the fracture pass through in the case of an intregranular brittle fracture?
- 24. When does an intregranular brittle fracture in metal materials happen?
- 25. Why is a transgranular brittle fracture also called cleavage fracture?
- 26. Give the Miller indices of planes, where there is a brittle cleavage in metals with a bcc lattice.

2.3. Behaviour of materials with defects; defects growth in materials

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Time for study: 1.5 hours



Objective After studying this section you will be able to:

- explain stress concentration;
- clarify/explain crack growth in materials;
- define and explain the term of the critical size of a crack;
- explain why an unstable crack growth is dangerous.



Lecture

Behaviour of materials with defects

The behaviour of materials during mechanical loading is further complicated by the fact that in practice it is almost impossible to produce material that would not contain any defects. Defects in materials may have different origins, may look differently, and may act variously. Probably the worst types of faults are cracks in the materials. But even these may be present in materials and sometimes their presence may not be reflected throughout their lifetime. On the contrary, at other times cracks can contribute to catastrophic damage and/or to major accidents with far-reaching implications.

But at the same time the cracks may not only be typical defects incurred in the production and processing of materials (welding, etc.). Cracks may also become various interface boundaries, such as a metal matrix interface with non-metallic inclusions, in steels very often manganese sulphides. The cohesive strength of the interface of MnS inclusions - the metal matrix is relatively low. Mechanical stress may damage the interface and thus separate particles of MnS and matrix. In matrix then, as if a cavity crack has formed, this will further act as similar defects depending on the nature of the mechanical stress.

Cracks and other defects in the materials cause the so-called stress concentration. This means that there is a stress near the defect that can be many times higher than the mean (nominal) stress, which acts in its own matrix outside the defect. There is much more mechanical stress around the cracks then. The crack surrounding is therefore much more mechanically stressed. Figure 2.16 shows an elliptical crack of length 2a and the radius of curvature at the crack tip r, loaded with nominal stress σ_{nom} . In the case of a brittle material that is not capable of plastic deformation, the stress in the vicinity of the cracks will continue to grow, to a much higher

value than corresponds to the nominal stress. This phenomenon is called stress concentration. Stress concentration is dangerous, because it can contribute to crack growth.



Fig. 2.16 The stress concentration around the crack in the material without the ability of plastic deformation

In the event of a stress concentration the stress concentration coefficient α can be defined as:

$$\alpha = \frac{\sigma_{\max}}{\sigma_{nom}}$$
eq. 2.10

where σ_{max} is the maximum stress near the crack (in the crack vicinity).

 σ_{nom} is a mean (nominal) stress that acts on the material.

In case of elliptical crack and loading in the field of elastic deformation, the following relationship for the stress concentration coefficient α is applied:

$$\alpha = \frac{\sigma_{\max}}{\sigma_{nom}} = 1 + 2 \cdot \sqrt{\frac{a}{r}}$$
eq. 2.11

where a is a half the crack length;

r is a radius of curvature at the crack tip.

From the following equation 2.11 it is clear, that the stress concentration coefficient increases with an increase of the crack length, and together with a decrease of a radius of curvature at the crack tip.

Note: A crack, with a very low radius of curvature $(r \rightarrow 0)$, is called a **sharp crack**. Sharp cracks are the most dangerous of all.

Crack growth in materials

In the case of mechanical stress, depending on the geometric characteristics of cracks and mechanical stress parameters, three cases may occur:

- cracks do not grow (do not extend);
- cracks grow slowly, by so-called stable growth;
- cracks grow very rapidly, by so-called unstable (or fast) growth, which is sometimes called catastrophic growth;

The difference between stable (slow) crack growth, and unstable (fast) crack growth had been derived for the case of a brittle material which gets damaged in the region of elastic deformation by Mr. Griffith. It was in the 20s of the 20th century. The relation that Mr. Griffith deduced is then called the Griffith relation.

He thought a sharp elliptical crack of a length 2a in a brittle material. And he implemented the energy balance of a process in which the crack grows by the length Δa . The situation is shown in Figure 2.17.



Fig. 2.17 Schematic representation of the crack to derive the Griffith relation

What is happening if there is a crack growth in a brittle material? There are simply two processes going on. During the crack growth, the bonds between atoms are damaged and thus leads to a release of elastic energy W_{el} . At the same time, however, there is the new surface of the crack, which it is necessary to expend certain energy on (W_p) , which is linked with a specific surface energy γ_p .

It would be possible to derive (but we will not), that the released elastic energy can be expressed by the following equation:

$$W_{el} = \pi \cdot a^2 \cdot \frac{\sigma^2}{E}, \qquad \text{eq. 2.12}$$

where a is half the crack length;

 σ is the nominal operating stress;

E is the tensile modulus.

Surface energy W_p can be expressed by:

$$W_p = 4 \cdot \gamma_p \cdot a$$
, eq. 2.13

where γ_p [J.m⁻²] is a specific surface energy, i.e. the energy per unit surface area.

From equations 2.12 and 2.13 it is apparent, that both energies depend on the crack length a. This is shown in Fig. 2.18, where in addition to the values W_{el} and W_p , there is also the sum of the energy accompanying the growth of the crack indicated.



Fig. 2.18 Schematic representation of the energy balance in the growth of a crack in a brittle material

The sum of energy W associated with the crack growth may therefore be written as:

$$W = W_p - W_{el} = -\pi \cdot a^2 \cdot \frac{\sigma^2}{E} + 4 \cdot \gamma_p \cdot a \qquad \text{eq. 2.14}$$

Figure 2.18 shows that the curve showing the total (sum) energy W is the curve with a local maximum. And the position of maxima due to the length (a) is very important. Length a, corresponding to this maximum, is called the **critical crack length**, and can be indicated as a_{cr} , where it separates the area of slow (stable) crack growth and fast (unstable) crack growth.

The critical crack length a_{cr} can be obtained by an equation (2.14) derivative according to length a and first derivative is then put equal to zero. (Do you remember that in the place of a function local extreme, its first derivative equals zero?). If we do so, we get the following equation:

$$\frac{dW}{da} = -2 \cdot \pi \cdot a \cdot \frac{\sigma^2}{E} + 4 \cdot \gamma_p = 0 \qquad \text{eq. 2.15}$$

And out of the equation we can then express the critical crack length a_{cr} as:

$$a_{cr} = \frac{2 \cdot \gamma_p \cdot E}{\pi \cdot \sigma^2} \qquad \text{eq. 2.16}$$

This equation is finally the Griffith relation. It tells us that the critical crack length is directly proportional to the specific surface energy and to the tensile modulus of the material and indirectly proportional to the square of the applied stress. The higher the operating stress, the shorter the critical crack length.

The Griffith relation is sometimes stated in a different form:

$$\sigma = \sqrt{\frac{2 \cdot \gamma_p \cdot E}{\pi \cdot a_{cr}}} \quad \text{eq. 2.17}$$

But we still have not explained yet why it is important to divide cracks into two groups: with stable growth and with unstable growth and what the main significance of the critical crack length is. Fig. 2.18. may help us to explain that. From thermodynamics, you remember, that thermodynamically feasible and spontaneously running is only such a process, where there is a decrease of system energy.

If the crack is shorter than the critical length, the total energy W during its growth increases. This means that in this area the crack does not grow spontaneously, and to take place, the energy must be delivered to the system from outside. How is this happening? Well, for example, there is a period of time when higher stress acts on the material, which leads to a certain growth of the crack. When the stress decreases, the growth of the crack stops. And thus the storyline may be repeated as many times in a row. That is why we say that the crack grows in a stable manner. In some materials and under certain loading conditions, the crack may grow in this way for several years.

But if the crack reaches its critical size, the situation will change dramatically. Its further growth is associated with a decrease in total energy, and therefore, it is a spontaneous action from a thermodynamic point of view. This means that after exceeding the critical length cracks may grow up to enormous proportions (even in meters), and this means a catastrophic collapse of structures, bridges, pressure vessels, etc. Due to disasters which may occur with the unstable growth of cracks this event is also called *catastrophic growth*.

And what are the critical crack sizes for different materials? We know that it depends on the loading stress, so we can only give rough (approximate) values. For example, in glass, the critical length is in the order of hundredths of mm, whereas in some metallic materials in the order of several tens of mm.

The disadvantage of the Griffith relation was that it applied only for brittle materials, and it was not possible to use it, for example, on metallic materials. It was later corrected in the 50s of the 20th century by Mr. Orowan, in a quite elegant way.

In most metallic materials plastic deformation occurs in a stress concentration area (the socalled plastic zone) in front of the crack tip. This is schematically shown in Figure 2.19.



Fig. 2.19 The progress of stress in front of the crack tip in material leading to plastic deformation

- 31

As can be seen from Fig. 2.19, the stress even near the crack (in the vicinity of the crack) does not exceed the yield stress too much. It is in the area where there is a plastic zone forming in front of the crack tip. To create a plastic zone it is necessary to add a certain energy to the material, which can be much higher than the energy of a new surface itself. This had been solved by Mr. Orowan by modification of Griffith relation, when, instead of pure surface energy γ_p he introduced effective surface energy γ_{ef} .

Therefore the Orowan relation is as follows:

$$\sigma = \sqrt{\frac{2 \cdot \gamma_{ef} \cdot E}{\pi \cdot a_{cr}}}$$
 eq. 2.18

The effective surface energy is a sum of "pure" surface energy and so-called plastic work, which expresses the energy required for plastic deformation in front of the tip of the growing crack. This can be expressed as follows:

$$\gamma_{ef} = \gamma_p + \gamma_{pl}, \qquad \text{eq. 2.19}$$

where γ_{pl} is the above-mentioned plastic work.

While pure measured surface energy may reach only values in hundredths of J.m⁻², the plastic work can reach values up to a hundred times higher. The Orowan relation is very valuable, because it allows you to specify the critical length of defects even for relatively ductile materials, where plastic deformation takes places in front of the crack tip.



Summary of terms 2.3.

After studying this section the following terms should be clear:

- The stress concentration near the crack (in the vicinity of the crack), crack sharpness;
- Stable crack growth , unstable (catastrophic) crack growth;
- > Critical crack length; the Griffith relation.
- > Plastic zone in front of the crack tip, the Orowan relation.



Questions 2.3.

- 27. Why is it important to study the behaviour of materials **with defects** in terms of mechanical stress?
- 28. What does the stress concentration coefficient express?

- 29. What does the concentration stress coefficient depend on?
- 30. What do we mean by "sharp" crack?
- 31. How can cracks grow in materials when exposed to mechanical stress?
- 32. What types of energy are involved in derivation of the Griffith relation?
- 33. For what type of material is the Griffith relation valid?
- 34. The original Griffith relation was modified by Mr. Orowan with the introduction of equation term?
- 35. Why is an unstable crack growth very dangerous?

2.4. Stress intensity factor



Time for study: 1 hour



Objective After studying this section you will be able to:

- explain the term stress intensity factor;
- understand the relation between the stress intensity factor and the critical crack size.

Interpretation

D The introduction of the stress intensity factor: the concept

Do not worry, we do not want to overload you with terms of material engineering, which probably will not be your daily bread, but we still need to introduce one more term. The reason is simple. Sometimes for expressing the toughness of materials, the impact energy (respectively the Charpy impact test) is not enough. For example in ceramic materials it would not make sense, therefore another variable is introduced, the so-called stress intensity factor, respectively its critical value. So, let us get down to it *(well begun is half done)*. Let us simplify things as much as possible.

In the sixties with the development of computer technology, mechanical engineers began to calculate the stress, respectively, stress components in front of the crack tip in material loaded with external stress (Fig. 2.20).



Fig. 2.20 The introduction of the stress intensity factor: the concept

They found that the stress component in a certain area in front of the crack tip can be expressed in polar coordinates using the relation:

$$\sigma_i = \frac{K}{\sqrt{2\pi r}} f_i(\Theta)$$
eq. 2.20

where K is the stress intensity factor;

r and Θ are the polar coordinates of the area in which we want to determine the stress components.

In relation to the nominal stress σ_{nom} stress intensity factor can be expressed as follows:

$$K = \sigma_{nom} \sqrt{\pi \cdot a}$$
eq. 2.21

where a is the crack length.

The equation 2.21 shows that with increasing length of the crack the value of the stress intensity factor increases as well. And, when the critical crack length is reached, the stress intensity factor reaches its critical value. The stress intensity factor is mostly determined under tensile loading, and its critical value is referred to as K_{IC} . For the critical conditions the following applies:

$$K_{IC} = \sigma_{nom} \sqrt{\pi \cdot a}_{cr} \qquad \text{eq. 2.22}$$

The critical value of the stress intensity factor is usually expressed in MPa.m^{1/2}. The critical value of the stress intensity factor is under certain conditions material constant, and in some sense it characterizes the toughness of materials. For that reason this quantity is so important and is therefore used. Sometimes the critical value of the stress intensity factor is indicated as fracture toughness. This is inaccurate, but we will not discuss the details here.

The critical value of the stress intensity factor is a very important material characteristic because it can be measured and it can identify the critical size of a defect for a particular operating stress. The concept of a critical crack size has very important practical applications, e.g. in the field of pressure vessels made from steel. Here are selected such materials where the critical crack length is greater than the thickness of the container/vessel wall. Why? Isn't it illogical? No, it isn't.

What would happen if a critical defect size was smaller than the thickness of the container/vessel wall? If, for example a crack from the inner wall surface spread and reached a critical length, at that moment there would be a catastrophic rapid fracture, the pressure
vessel would simply "explode" and a huge problem would arise. On the contrary, if the critical crack size is greater than the thickness of the vessel wall, the situation is much better. If the crack spreads from the inner surface, it can grow even over the entire wall thickness of the vessel, but still in a stable mode of a slow crack growth. The stored medium may begin to leak from the vessel, this leakage can be detected and appropriate action can be taken (most often - the content is pumped out and the vessel is repaired). It is essential that when the condition is met (the critical defect size is greater than the wall thickness) the container does not rupture as a whole, i.e. a serious accident does not happen. This approach must be applied already in the design of pressure vessels and it is known as *"leak before break"-* a leakage before fracture (sometimes abbreviated as LBB).



Summary of terms 2.4.

After studying this section the following terms should be clear:

> Stress intensity factor and its importance.



Questions 2.4.

36. Why is the stress intensity factor important quantity in (the field of) materials?

- 37. In what units is the critical value of the stress intensity factor expressed?
- 38. In what relation should the critical crack length and thickness for pressure vessels be?

<mark>برآبر</mark> ر	The Key - Chapter 2 key: answers to questions
Q1	The basic mechanical properties of engineering materials are strength and toughness.
Q2	Strength expresses the maximum stress that the material can transmit without breaking and without the defect formation.
Q3	Some metallic materials (e.g. some types of steel) and ceramic materials have high strength
04	Toughness expresses the energy required for a fracture.
Q5	The result of tensile test is the so-called working diagram, which is usually the relation of the loading force and absolute extension
Q6	The tensile diagram can usually be divided into three areas: elastic deformation area; uniform plastic deformation area: non-uniform plastic deformation area.
Q7	In the area of elastic deformation in metallic materials Hook's (Hooke's) law applies, i.e. the linear relation between stress and deformation.
Q8	We can get the value of the tensile modulus E from the area of elastic deformation.
Q9	Contracting tension refers to the initial cross-sectional area, while the actual stress is related to immediate value of the cross section during the tensile test. The actual stress is higher, particularly in the area of non-uniform plastic deformation.
Q10	From the working diagram, we subtract the yield stress, tensile stress and eventually elongation as well. From the working diagram contraction cannot be obtained.
Q11	The tensile strength is a ratio of maximum loading force and the initial cross-sectional area of the test bar.
Q12	Elongation at fracture is the maximum relative plastic (permanent) elongation expressed in %.
Q13	Contraction is the maximum relative narrowing of the cross section expressed in %.
Q14	The result of the impact test is impacting work or notch toughness.
Q15	Notch toughness is the ratio of impacting work and the cross sectional area and under the notch. Usually expressed in J.cm ⁻² .
Q16	From the relation of impacting work, respectively notch toughness and temperature (in the case of transit behaviour of material), the so-called transition temperature can be obtained.
Q17	A ductile fracture is characterized as a so-called high-energy fracture.
Q18	For the ductile fracture the term ductile fracture is also used.
Q19	The process of ductile fracture begins on so-called "alien" particles (non-metallic inclusions), or particles of minority phases.
Q20	The first stage of a ductile fracture is the formation of cavities.
Q21	On the fracture surface the ductile fracture is reflected by the presence of dimples.
Q22	A brittle fracture occurs in metallic materials when they are unable of plastic deformation.
Q23	In the case of an intergranular brittle fracture it takes place (occurs) along the grain boundaries.
Q24	The intergranular brittle fracture occurs primarily when the grain boundaries are weakened (for some reason).
Q25	The intergranular brittle fracture is called cleavage fission, because there is a cleavage of material along certain crystallographic planes.
Q26	Miller indices of planes of brittle fracture in the bcc lattice {001}.
Q27	Study materials with defects are necessary because such materials actually exist.
Q28	The concentration stress coefficient expresses the ratio between the maximum and medium stress.

Q29	The concentration stress coefficient depends primarily on the length of cracks, and the
	radius of the curvature at the crack tip.
Q30	The sharp crack is one with a very low radius of curvature (close to zero).
Q31	Cracks can grow either slowly (stably), or fast (unstably, catastrophically).
Q32	In the derivation of the Griffith relation there emerges elastic energy (energy from the
	release of elastic bonds between atoms) and surface energy.
Q33	The Griffith relation is valid for a brittle material in which (where) plastic deformation
_	does not occur.
Q34	Mr. Orowan modified the Griffith relation by introducing a so-called effective surface
	energy as the sum of the net surface energy and plastic work.
Q35	Unstable crack growth is dangerous because it can cause the serious accidents of
	structures, pressure vessels, etc.
Q36	The importance of the stress intensity factor lies in the fact that the critical value reflects
	the toughness of the material.
Q37	The critical value of the stress intensity factor is usually expressed in MPa.m ^{1/2} .
Q38	The critical crack length in the pressure vessel should be greater than the wall thickness
-	of the container.



Additional sources

Ohring M.: *Engineering Materials Science*. San Diego: Academic press, 1995. 827 p. ISBN 0-12-524995-0.

3. STRENGTHENING MECHANISMS IN METALLIC MATERIALS

In the case of construction materials, there are efforts to improve their mechanical properties, especially to increase the strength and toughness of materials. The increase in toughness of materials is very problematic. In contrast, there are several ways leading to increased strength, i.e. the reinforcement of materials. With regard to the focus of our study program, we will give our attention to strengthening of metallic materials. At the outset, we must mention one correction. When we write about strengthening, we would say, probably, that the quantity we want to increase is the ultimate strength. But it is not the case. Given the fact that metallic materials may only be stressed in operation in the elastic deformation region, the key quantity we want to increase in strengthening is the yield point or yield strength. We already know that the yield point is the maximum stress prior to which the material will deform elastically. Above the yield point, plastic deformation occurs, which means that dislocations move in the material, we have to make the movement of dislocations more difficult so that they will begin to move only when exposed to higher stresses. So we try to have obstacles in the material that will hinder the movement of dislocations.

There are several ways to increase the yield point of metallic materials, i.e. to strengthen them The most commonly used mechanisms include:

- strengthening by plastic deformation
- grain boundary strengthening
- solid solution strengthening
- precipitation strengthening

Subsequently, we will give at least basic information to individual mechanisms.

3.1. Strengthening by plastic deformation



Time to study: 1 hour



Objective After reading this part, you should be able to:

- Explain how metallic materials can be strengthened by plastic deformation.
- Specify what determines the degree of strengthening by plastic deformation.
- Describe the main advantages and disadvantages of strengthening by plastic deformation.



Presentation

It is as though the strengthening of metallic materials by plastic deformation contains a certain contradiction in terms. We wrote that the strengthening meant to restrict the movement of dislocations and now we are writing about plastic deformation. More specifically, we can write that it is a plastic deformation that precedes the normal use of the material. We will try to show you how this strengthening occurs through the example of a tensile test. Imagine that we perform a tensile testing of metallic material and record the working diagram. Example is shown in Figure 3.1.





But the tensile test will not be performed until the test bar breaks, but we will disburden it in the region of uniform plastic deformation (approximately at point D in Figure 3.1). It can be seen from Figure 3.1 that in its initial state the material had a yield strength marked σ_{y0} . If we subject the bar to a repeated loading after disburdening, the material will not have the same yield strength σ_{y0} , but its yield strength will correspond to approximately the stress at point D, i.e. the yield strength will be higher (in Figure 3.1, the yield strength under repeated loads is marked σ_{yi}). Previous loading into the plastic deformation region thus led to an increase in yield strength during subsequent loading of the material. How this happened?

We know that when plastic deformation occurs, dislocations start to move in the material, and also new dislocations are formed, i.e. their number increases (to speak professionally, the density of dislocations increases). Every dislocation creates a stress-strain field around itself and thereby the more dislocations are in the material, the more important these fields become; they may interact, which leads to the fact that the movement of dislocations is more and more difficult. We can simply say that the barriers to the movement of dislocations are the dislocations themselves when they are too many in the material. They prevent one another from moving. Plastic deformation thus leads to an increase in the density of dislocations, and it has the effect of increasing the yield strength during subsequent loading.

In practice, of course, the strengthening by plastic deformation does not take place by means of tensile tests, but by cold forming, e.g. cold sheet rolling, cold wire or pipe drawing, etc. Therefore, this strengthening is sometimes also called **deformation strengthening**. Cold forming leads both to the modification of shapes of grains, which is shown in Figure 3.2, and to the increase in the density of dislocations. Dislocations can be almost exclusively observed through transmission electron microscopy (Fig. 3.3).



Fig. 3.2 Shapes of grains prior to cold forming (a) and after cold forming (b)

For determining the increase in yield strength by plastic deformation, the density of dislocations after plastic deformation of the material is important. This is denoted by the letter

 ρ and is defined as the ratio of lengths of dislocation lines to volume. Most frequently it is expressed in cm⁻². The equation for the density of dislocations can be written as follows:

$$\rho = \frac{L_{disl}}{V}$$
 Eq. 3.1

where L_{disl} is the length of dislocation lines,

V is the material volume.

For the materials in an annealed state, the usual density of dislocations is about 10^5 cm⁻², while for the materials in the state after cold forming it is between 10^9 and 10^{11} cm⁻².



Fig. 3.3 Dislocations in aluminium viewed by transmission electron microscopy method The increase in yield strength after strengthening by plastic deformation can be expressed by the equation:

$$\Delta R_e \cong 2.\alpha.G.b.\sqrt{\rho} \approx \sqrt{\rho}$$

Eq. 3.2

where α is a constant equal to about 0.5,

G is the shear modulus,

b is the Burgers vector of dislocations,

 ρ is the dislocation density.

Equation 3.2 shows that the rate of strengthening by plastic deformation is directly proportional to the square root of the dislocation density ρ .

Solved example:

Calculate the increase in yield strength for low carbon steel, for which the density of dislocations after cold forming was found to be $\rho=10^{10}$ cm⁻². Consider the shear modulus G = 70000 MPa and the Burgers vector of dislocations b= 2.8.10⁻¹⁰ m.

Solution:

We substitute the above specified values into Equation 3.2 and enumerate.

$$\Delta \tau \cong 2.\alpha.G.b.\sqrt{\rho} = 2.0, 5.70000.2, 8.10^{-10}.\sqrt{10^{14}} \cong 196 MPa$$

Conclusion: After the said cold forming, the yield strength of steel increases by 196 MPa. (And that's pretty much.)

Strengthening by plastic deformation is used for low carbon steels, but very often also in metals and alloys with fcc lattice, which have only low mechanical properties in the annealed state.

Unfortunately, strengthening by plastic deformation has also some very distinct disadvantages. The greatest disadvantage is a decrease of toughness, the embrittlement of material. In this respect, the strengthening by plastic deformation is probably the most dangerous type of strengthening. The possible decrease of toughness is illustrated in Figure 3.4 a, b, where the increase in yield strength and ultimate strength after cold deformation is indicated for copper, brass and low carbon steel (a), as well as the decrease of ductility depending on the degree of cold deformation (b).



Fig 3.4a The increase in yield strength and ultimate strength for copper, brass and steel depending on the degree of cold deformation



Fig. 3.4b The decrease of ductility for copper, brass and steel depending on the degree of cold deformation

Figure 3.4b shows that the decrease of ductility is rather drastic already after 20% of cold deformation. The decrease of ductility after cold forming to some extent reduces the possibility of using this mechanism of strengthening for those applications where a higher value of material toughness is requested.



After studying this part, following terms should be clear to you:

- > Strengthening by plastic deformation or cold forming
- Density of dislocations



Questions to 3.1.

- 1. What is a barrier to dislocation movement in dislocation strengthening?
- 2. What other term is used for dislocation strengthening?
- 3. How is the dislocation density defined?
- 4. On which parameter namely the rate of strengthening by plastic deformation depends?
- 5. For what metallic materials the strengthening by plastic deformation is used?
- 6. What is the main disadvantage of strengthening by plastic deformation?

3.2. Grain boundary strengthening

Time to study: 1 hour

Objective After reading this part, you should be able to:

- Explain how metallic materials can be strengthened by grain boundary strengthening.
- Specify what determines the degree of grain boundary strengthening.
- Describe the main advantages and disadvantages of grain boundary strengthening.



Presentation

Very important mechanism that allows to increase the yield strength, i.e. strengthening of metallic materials, is the grain boundary strengthening. Generally, the higher yield strength can be expected in materials with a small grain size, i.e. in fine grained materials. In contrast, lower yield strength can be expected in coarse-grained materials. Why is it that fine-grained materials have a higher yield strength, i.e. grain refinement leads to strengthening? We will try to answer in reverse, i.e. to answer why the coarse-grained materials have lower yield strength.

First, we must realize that the grain boundaries represent an obstacle in polycrystalline materials that dislocations cannot overcome. Dislocations are always in their movement restricted to grain, in which they were formed. Imagine a situation which is illustrated in Figure 3.5. Consider a coarse-grained polycrystalline material in which tensile stress σ operates. Then imagine that there is just one grain in this material oriented so that the plane of maximum shear stress (i.e. the stress that sets a dislocation in motion) is identical to the slip plane in this grain (i.e. the plane on which dislocations move). And also imagine that the maximum shear stress τ is just so large that in this single grain a plastic deformation can occur. If plastic deformation takes place, it means that dislocations will move around this grain and new dislocations will be formed. Dislocations will move on slip planes to the boundary of the grain, where they stop. As more dislocation pile up is associated with the existence of a certain stress, which acts even into neighbouring grains. The bigger the grain is, the more dislocations pile up at the grain boundaries and the higher is the stress from this accumulation. This stress will be summed up with the shear stress on the slip planes in

neighbouring grains τ_b , which are less favourably oriented, and the level of stress needed to cause plastic deformation may be exceeded. This means that plastic deformation may occur in a larger number of grains and macroscopic yield point is reached.



Fig. 3.5 Schematic illustration to explain the low yield strength in coarse-grained material

If the material is fine-grained and if plastic deformation is possible in just only one grain under the action of a certain stress σ , the dislocation pile up here at the grain boundaries will be lower. So also the stress from this pile up $\Delta \tau_{pup}$ will be lower, and it is very likely that no plastic deformation occurs in neighbouring grains. This will occur only if a higher stress σ will act in the material. Finer grain thus means an increase in the yield strength of the material.

The dependence of the yield strength upon the grain size is described by Hall-Petch relationship, which can be simply written as follows:

$$\Delta R \cong \tau_0 + \frac{K}{\sqrt{d}}$$
 Eq. 3.3

where τ_0 is the friction stress,

K is a constant,

d is the grain diameter.

In the case of steels with bcc lattice, the following empirical equations are given:

$$R_e = 60 + 0,727.\frac{1}{\sqrt{d}}$$
 Eq. 3.4

$$R_e = 80 + 0.523. \frac{1}{\sqrt{d}}$$
 Eq. 3.5

(d is entered in m, R_e in MPa).

The question is, how far it makes sense to refine the grain size in order that there is still the increase in the yield strength. The limit is indicated by values between 10 and 100 nm. The size of grains in conventional materials is mostly in units of micrometres. Further refinement of grains below the level of micrometres makes sense as another possibility for increasing the yield strength of the material.

Grain boundaries strengthening depends quite significantly on the type of crystal lattice of the metallic material. This type of strengthening is more effective in metals with bcc lattice. For metals having fcc lattice, the strengthening by grain refinement is less efficient, which is evident from Figure 3.6.



Fig. 3.6 The influence of grain size on yield strength for selected materials with bcc and fcc lattice

Solved example:

Use Equation 3.4 to determine how much the yield strength of the steel increases, if there is a decrease in the mean grain size from 10 μ m to 1 μ m.

Solution:

By simply substituting, we get the yield strength of 290 MPa for the grain size 10 μ m, i.e. 0.00001 m.

$$R_e = 60 + 0,727.\frac{1}{\sqrt{0,00001}} = 290MPa$$

For grain size 1 µm, i.e. 0,000001 m, Equation 3.4 gives the yield strength of 787 MPa.

$$R_e = 60 + 0,727.\frac{1}{\sqrt{0,000001}} = 787MPa$$

The increase in yield strength is 787 - 290 = 497 MPa.

Conclusion: Decreasing the grain size from 10 μ m to 1 μ m gives the increase in yield strength of nearly 500 MPa (and this difference is extremely large).

Grain boundary strengthening has a privileged position in a sense among all the strengthening mechanisms, and this privileged position is a positive one. Grain boundary strengthening. i.e. strengthening by grain refinement is the only strengthening method that leads to higher toughness of the material. And this is particularly valuable.



Summary of terms from 3.2.

After studying this part, following terms should be clear to you:

- > Grain boundary strengthening, i.e. strengthening by grain refinement
- > Dislocations pile up at the grain boundaries
- Hall-Petch relationship



Questions to 3.2.

- 7. What is the barrier to the movement of dislocations in grain boundary strengthening?
- 8. What is the main reason for the lower yield strength in coarse-grained materials?
- 9. How to express the dependence of the yield stress on grain size?
- 10. In materials with what type of crystal lattice the grain boundary strengthening is more effective?

- 11. To what size does it have a sense to refine the grain with respect to any possible increase in the yield strength?
- 12. How does the grain boundary strengthening reflect in the material toughness?

3.3. Precipitation strengthening

Time to study: 1.5 hours



Objective After reading this part, you should be able to:

- Explain how to strengthen metallic materials using precipitates.
- Describe the mechanism of intersection of precipitates by dislocations.
- Characterize the mechanism of bowing of precipitates by dislocations.
- Compare both of these mechanisms and explain what structural characteristics of the precipitates they depend on.



Presentation

Another strengthening mechanism, which allows to increase significantly the yield strength of metallic materials is the so called precipitation strengthening. Precipitates are very small particles of minority phases, i.e. those phases which are present in the material in a relatively small amounts (usually about ones of per cents by volume). Minority phases in steels may be carbides or nitrides. In other metallic materials, minority phases are various intermetallic phases, for example in aluminium alloys that can be Al₂Cu phases, in nickel alloys Ni₃Al phases, etc.

The basic precondition for the precipitation strengthening to be effective is that the particles of precipitates are small and close to each other, i.e. there are relatively small distances between them.

More specifically, the precipitates are determined by the following stereological parameters that characterize them more accurately:

Volume fraction of precipitates	$V_f(-)$
Number of particles per unit volume	$N_V(\mathrm{m}^{-3})$
Mean particle diameter (radius)	<i>d (r)</i> (m)
Mean interparticle spacing	λ (m)

Probably the most important parameter is the mean interparticle spacing and particle diameter or radius. For most materials, it is most advantageous when the values of these two parameters are in the tens of nanometres. It is therefore evident that particles of precipitates must be really very small and must be very close to each other so that the precipitation strengthening is effective. This configuration is schematically illustrated in Figure 3.7.

There is a wide range of relationships for the determination of the mean interparticle spacing, let us mention a few at random:

$$\lambda = \frac{4.(1 - V_f).r}{3.V_f}$$
 Eq. 3.6

$$\lambda = \frac{1}{\sqrt{N_V \cdot d}} - \frac{2}{3} \cdot d$$
 Eq. 3.7

For a constant volume fraction of precipitates it is true that the smaller is the particle radius, the smaller is the interparticle spacing (since their number increases).



Fig. 3.7 The characteristic distribution of precipitates for optimal precipitation strengthening

In the case of precipitation strengthening, the barriers to the movement of dislocations are the particles of precipitates. If dislocations are to move in a metal matrix, where there are particles of other phases, often even with a different type of crystal lattice, they need a higher stress to start moving, which therefore means the strengthening, i.e. increase in the yield strength.

If a dislocation moves within the matrix, in which the particles of precipitates are present, there are basically two possible mechanisms of interaction between a dislocation and a precipitate. Which mechanism is applied, it depends primarily on the size of the precipitate and its nature.

Mechanism of intersection of precipitates by dislocations

If precipitates are small and so called coherent with a metal matrix, the **mechanism of intersection of a precipitate by dislocation** applies. But we have to explain what a coherent precipitate is. Coherence is a word derived from Latin and means among other things the continuity. Coherent precipitate is such a precipitate, which has a continuity of its crystallographic planes with crystallographic planes in the matrix. So we can say that certain crystallographic planes of the matrix are continuously passing to the crystallographic planes of the precipitate and then again to the crystallographic planes of the matrix. Any mismatch in the lattice parameters of the precipitate and metal matrix is compensated by elastic deformation. Coherent precipitates with most materials are particles up to about 10 nm, i.e. only very small particles. Example of a coherent precipitate is shown in Figure 3.8. Figure 3.9 then illustrates the mechanism of intersection of precipitates by dislocations.



Fig. 3.8 Example of a coherent precipitate



Fig. 3.9 Schematic illustration of intersection of a precipitate by a dislocation

As shown in Figure 3.9, when the precipitate is intersected by one dislocation, the two parts of the precipitate are displaced (above and below the slip plane in which the dislocation moves) by the value of the Burgers vector of dislocation b. Example of intersection of particles of Ni₃Si precipitates in Ni-6% Si system is shown in Figure 3.10. (*This is a quite exceptional example, because you can see that in this case the particles of precipitates are extremely large.*)

Numerous relationships were derived for the increment of strengthening induced by intersection of precipitates by dislocations. These are mostly semi-empirical relationships, and so they differ from each other. The simplest example is the relationship:

$$\Delta \boldsymbol{R}_{e} \cong \frac{\boldsymbol{\gamma}_{M-P} \cdot \boldsymbol{\pi} \cdot \boldsymbol{r}}{\boldsymbol{b} \cdot \boldsymbol{\lambda}}$$
 Eq. 3.8

where γ_{M-P} is the specific surface energy of matrix – precipitate boundary (usually is between 0.01 and 0.03 J.m⁻²),

r is the precipitate radius,

 λ is the mean interparticle spacing,

b is the Burgers vector of dislocation.

When considering the deformation ε caused by the difference of lattice parameters of matrix and precipitate, we get the following relationship:

$$\Delta \boldsymbol{R}_{e} \cong \boldsymbol{konst.} \boldsymbol{\varepsilon}^{4/3} \boldsymbol{.} \boldsymbol{V}_{f}^{2/3} \boldsymbol{.} \left(\frac{\boldsymbol{r}}{\boldsymbol{b}}\right)^{1/3}$$
Eq. 3.9

where $\boldsymbol{\varepsilon}$ is the elastic deformation caused by the difference of lattice parameters of matrix and precipitate;

 V_f is the volume fraction of precipitate.



Fig. 3.10 Intersection of Ni₃Si particles in Ni-6%Si system (viewed by transmission electron microscopy method)

It will do the trick when we remember that in the case of the mechanism of intersection of precipitates by dislocations, it is true that the larger the precipitates are, the greater is the increase in strengthening. (This follows from the fact that in both Equations 3.8 and 3.9, the precipitate radius appears in the numerator).

Solved example:

Use Equation 3.8 to determine the strengthening increment (increase in the yield strength) by precipitation strengthening using carbide precipitates in the steel, when considering the surface energy of the boundary of 0.02 J.m⁻², mean radius of the precipitates of 20 nm and mean interparticle spacing of 50 nm.

Solution:

We substitute into Equation 3.8 (just be careful about the units, everything will be substituted in SI base units and only the end result will be converted to MPa).

Therefore it applies:

$$\Delta R_e \cong \frac{\gamma_{M-P} \cdot \pi \cdot r}{b \cdot \lambda} = \frac{0.02.3.14 \cdot 1.10^{-9}}{2.8 \cdot 10^{-10} \cdot 50.10^{-9}} = 224.10^6 N \cdot m^{-2} = 224 MPa$$

Conclusion: For specified values, the intersection of precipitates by dislocations will cause an increase in yield strength of 224 MPa in the steel with carbide precipitates.

Mechanism of bowing dislocations around precipitates – Orowan mechanism

If particles of precipitates are larger, and the precipitates are no longer coherent with the matrix (i.e. there is no longer a continuity of crystallographic planes in the matrix and in the precipitate), the mechanism of precipitate intersection cannot be applied, but a different mechanism of interaction precipitates and dislocation can apply. This mechanism is the so-called **bowing of dislocations around precipitates**. This mechanism was first described by Orowan and so it is often called Orowan mechanism. The principle of this mechanism is shown schematically in Figure 3.11.

The mechanism of bowing of dislocations around precipitates works as follows: if a dislocation moves in the material and approaches a precipitate, which is not coherent, and cannot therefore intersect it, the dislocation begins to curve gradually in the vicinity of the precipitate until it forms a closed dislocation loop around the precipitate. The straight parts of dislocation again join together after enlacing the precipitate and the dislocation can move on. Higher stress is needed to bend around a precipitate, which means strengthening, i.e. an increase in yield strength. The example of bowing dislocations around Ni₃Si precipitate in Ni-6% Si system is shown in Figure 3.12.



Fig. 3.11 Principle of Orowan mechanism



Fig. 3.12 Dislocation loops around Ni₃Si particles in Ni-6%Si system (viewed by transmission electron microscopy method)

The strengthening increment in Orowan mechanism can be again expressed in a variety of different relationships, but we will mention only one. Increase in the strengthening can be described by the following equation:

$$\Delta R_e \cong konst. \frac{G.b.V_f^{1/2}}{r}, \qquad \text{Eq. 3.10}$$

Each member has been already described in the previous equations.

The point is that in Equation 3.10, the precipitate particle radius is in the denominator, which means that in bowing of precipitates the smaller the precipitates are, the higher is the

strengthening. This stems from the fact that the smaller is the radius of dislocation curvature, the higher is the stress necessary for the dislocation to curve.

If we compare the two mechanisms of interaction of dislocations with precipitates, we may say that the maximum strengthening is achieved in the area where the mechanism of intersection of precipitates merges into the mechanism of bowing dislocations around precipitates.

The precipitation strengthening is used in a wide variety of steels, e.g. all steels for use at elevated temperatures (in different nodes of thermal power plants) are based on the precipitation strengthening. This strengthening is also used in many non-ferrous metals, such as aluminium, copper and nickel alloys, etc.

The negative feature of the precipitation strengthening (as in the case of strengthening by plastic deformation) is the decrease in plastic properties of the material, i.e. the decrease of toughness. But in the case of the precipitation strengthening, the decrease of toughness is not as dramatic as in the case of strengthening by plastic deformation.



Summary of terms from 3.3.

After studying this part, following terms should be clear to you:

- Precipitation strengthening
- > Intersection of precipitates by dislocations
- Coherent precipitate
- > Bowing of dislocations around precipitates Orowan mechanism



Questions to 3.3.

- 13. What do we understand by the term of precipitates?
- 14. Which stereological parameters of the precipitates are the most important in terms of possible degree of precipitation strengthening?
- 15. What is the basic condition that the precipitates should meet for the precipitation strengthening to be effective?
- 16. How coherent precipitates can be characterized?
- 17. What is the mechanism of interaction that is applied between coherent precipitates and dislocations?
- 18. How does the strengthening increment depend on the radius of precipitates in the intersection of precipitates?
- 19. Up to what size of precipitates the mechanism of intersection of precipitates can be usually applied?

- 20. How the lattice mismatch between the matrix and precipitates is compensated in the case of coherent precipitates?
- 21. What formation a dislocation leaves around the precipitates in the case of bowing of precipitates by dislocations?
- 22. How does the strengthening increment depend on the radius of precipitates in the Orowan mechanism?

3.4. Solid solution strengthening





Objective After reading this part, you should be able to:

- Explain the principle of solid solution strengthening.
- Characterize the difference between the so called elastic interaction and modular interaction.



Presentation

Increase in the yield strength of metallic materials can be even caused by atoms of impurities which are dissolved in the matrix, i.e. they constitute a solid solution with the basic component. Solid solution strengthening can be caused by both substitutionally and interstitially dissolved atoms.

Generally, dissolved atoms have a different size than the basic atoms in the matrix, which generates a stress field in the vicinity of a dissolved atom and associated elastic distortion of the lattice. Atoms of elements of smaller radiuses induce a local shrinkage of the crystal lattice, or they are preferably located into areas of tension field of dislocations (Fig. 3.13a,b). In contrast, the atoms of elements with a larger radius than is the radius of atoms of the basic element induce stretching (dilatation) of the crystal lattice or may be placed into areas of tension field of dislocations (Fig. 3.14a,b). A higher stress is required for the movement of dislocations in a given area, which means the strengthening of material or more precisely, the increase in its yield strength.



Fig. 3.13 Location of dissolved atoms with a smaller radius in the crystal lattice



Fig. 3.14 Location of dissolved atoms with a larger radius in the crystal lattice

The strengthening increment depends both on the degree of lattice distortion induced by a dissolved element, and on its concentration.

This is just one of the existing relationships that describe the increment of strengthening caused by substitutionally dissolved atoms:

$$\Delta R_e \cong G.b.\varepsilon.\sqrt{c}$$
 Eq. 3.11

where G is the shear modulus of the material,

b is the Burgers vector of dislocation,

 $\boldsymbol{\epsilon}$ is the elastic deformation caused by a dissolved atom,

c is the concentration of a dissolved element.

The above described strengthening by dissolved elements is sometimes called the **elastic** interaction.

Besides the elastic interaction, also the **modulus interaction** may take part in the strengthening by dissolved atoms, which reflects the fact that for some elements their bond energy with the basic element is higher than the bond energy between atoms of the basic element. This is shown, inter alia, by higher shear modulus of the material and the corresponding increment can be expressed as follows:

$$\Delta R_e \approx \Delta G. \sqrt{c}$$
 Eq. 3.12

where ΔG is the increase in the shear modulus,

c is the concentration of a dissolved element.

In the case of steel, simple empirical relationships are often used, which include the effect of a higher number of dissolved elements, while an additive character is assumed for the increment of strengthening:

$$\Delta R_e = \sum_{i=1}^n k_i \cdot c_i$$
 Eq. 3.13

where k is the constant that differs for each element dissolved (see Tab. 3.1),

c is the concentration of a dissolved element in % by mass.

Tab. 3.1. Constants k for the solid solution strengthening of steels by substitutionally dissolved atoms

Element	Р	Si	Ti	Mn	Cr	Мо	V
Constant k	350	80	100	50	-10	22	24

From Table 3.1 it is seen that the highest solid solution strengthening of the steel would be ensured by phosphorus, but since it is a harmful element, it is not very useful in practice. In practical terms, in the case of steels the most significant is their strengthening by dissolved silicon atoms.



Summary of terms from 3.4

After studying this part, following terms should be clear to you:

- Solid solution strengthening
- Elastic interaction
- Modulus interaction



Questions to 3.4

- 23. What is the solid solution hardening based on?
- 24. What do we understand by the term of elastic interaction?
- 25. What do we understand by the term of modulus interaction?
- 26. Which element would ensure the highest level of solid solution strengthening in steel?
- 27. Which element is the most important for solid solution strengthening of steels from the practical standpoint?

м <mark>ј</mark> л С	Key to the solution – answers to questions to Chapter 3
Q1	The barrier to the movement of dislocations are dislocations occurred in the previous plastic deformation.
02	Deformation strengthening or strengthening by cold forming.
Q3	The dislocation density is the proportion of the lengths of dislocation lines and volume of the material
Q4	The rate of strengthening by plastic deformation depends primarily on the density of dislocations.
Q5	Strengthening by plastic deformation is used for example in low-carbon steels, copper and aluminium alloys, etc.
Q6	The main disadvantage of strengthening by plastic deformation is a decrease of toughness.
Q7	The barrier to the movement of dislocations are grain boundaries themselves.
Q8	The higher rate of dislocations pile up at the grain boundaries and the associated higher stress from this pile up.
Q9	The yield strength is directly proportional to the inverse of square root of the grain diameter.
Q10	Grain boundary strengthening is more effective for materials with bcc lattice.
Q11	It has a sense to refine the grain to the size of about 10-100 nm.
Q12	Grain boundary strengthening is manifested through increased toughness.
Q13	The precipitates are fine particles of minority phases, carbides, nitrides, intermetallic phases, etc.
Q14	The most important stereological parameters of the precipitates are their diameter and mean interparticle spacing.
Q15	For the precipitation strengthening to be effective, precipitates must be small and close to each other.
Q16	Coherent precipitates are such precipitates, for which there is a continuity of crystallographic planes of the precipitate and the matrix.
Q17	Coherent precipitates are cut by dislocations.
Q18	In the intersection of precipitates, the strengthening increases with the increasing radius of the precipitates.
Q19	Mechanism of intersection of precipitates is applied up to the precipitate size of about 10 nm.
Q20	In coherent precipitates, the lattice mismatch between the precipitates and matrix is compensated by elastic deformation.
Q21	In the case of bowing of precipitates, the dislocation leaves a dislocation loop around the precipitate.
Q22	In bowing of precipitates, the strengthening increment decreases with the increasing radius of the precipitates.
Q23	Solid solution strengthening is primarily based on the different size of dissolved atoms and atoms of the basic element.
Q24	Elastic interaction means the solid solution strengthening based on the different size of atoms of dissolved elements and basic element.
Q25	Modular interaction means the solid solution strengthening based on a higher bond energy between atoms of the dissolved element and of the basic element.
Q26	The highest level of solid solution strengthening in steel would be ensured by phosphorus.
Q27	From the practical standpoint, the most important solid solution strengthening in steels is caused by dissolved silicon atoms.



Other sources

Callister W.D. jr., Rethwisch D. G.: *Fundamentals of Materials Science and Engineering. An Integrated approach.* Hoboken: Wiley, 2008. 3rd ed. 882 p. ISBN 978-0-470-12537-3.

Ohring M.: *Engineering Materials Science*. San Diego: Academic press, 1995. 827 p. ISBN 0-12-524995-0.

Strengthening mechanisms in metallic materials

4. Metallic materials

4.1. Properties of metallic materials



Time for study: 2 hours

Objective After studying this paragraph you will be able to

- divide the alloys of metals
- specify the properties of metallic materials
- explain the difference between accompanying and alloying elements



Lecture

D Types of metallic materials

Metallic materials may occur in the form of pure metals or in the form of alloys. In a completely pure condition, the metals rarely occur, if they are to have good mechanical properties.

Metal alloys can be divided into alloys of iron and non-ferrous metals, and further according to the parent metal which is contained in the alloy as the main component. The best-known and most common **are iron alloys** (about 12000 alloys Fe). Iron alloys are further subdivided into steel and cast iron. The second most common alloys are **alloys of copper** (about 5,000 alloys Cu), where copper is the key element, and are divided into brasses, bronzes, etc. **Aluminium alloys** contain aluminium as a basic element. Among the aluminium alloys (about 2000 alloys) are for example e.g. silumin(s) and duralumin(s). An important group consists of **nickel alloys**.

In addition to the basic metal there are other elements in the alloys that have not been removed during the production of metal, and these **elements** are referred to as **accompanying.** Accompanying elements come into the steel unintentionally. They are divided into harmful impurities and helpful impurities (which balance out or reduce the impact of the harmful elements. Among the impurities is included oxygen, sulphur, phosphorus, or hydrogen. **Added elements** (additives) or alloying elements are added to alloys intentionally in order to improve their properties. The most common alloying elements are Mn, Si, Cr, Ni, Mo, V, Nb, Co, Ti, Al, Cu, Zr, B, N, Be.

Another possible division of metallic materials depends e.g. on their properties (physical, mechanical, resistance to environment, etc.), on practical use or method of production.

According to the density, metallic materials can be divided into light (Mg, Al, Ti alloys) with a density of $\rho < 5 \text{ g} \cdot \text{cm}^{-3}$ and heavy (Fe, Cu, Ni alloys) with a density of $\rho > 5 \text{ g} \cdot \text{cm}^{-3}$. According to the chemical stability we divide metals into noble (e.g. Pt, Au, Pd, Ag) and non-noble (e.g. Mg, Fe, Zn). According to the process of forming, casting or powder metallurgy methods we can distinguish wrought alloys, casting alloys and sintered metals. Depending on the application we can distinguish for example tool steel, spring steel, bearing metals, stainless steel and others.

D Properties of metallic materials

As we mentioned in previous chapters, the material properties are determined by its internal structure, which depends (besides the chemical composition, the properties of atoms and molecules) also on production technology and material processing. By changing the production technology or material processing changes in the structure and thus its properties can be achieved. Material properties can be divided into four groups: chemical, physical, mechanical and technological. A special group of properties is resistance to the degradation processes. The chemical properties of metals are represented by corrosion resistance, physical properties are for example electrical and thermal conductivity, magnetic properties, etc. Mechanical properties are not entirely definite because metals can be either soft, solid, ductile or quite brittle. The most important technological properties are (represented by) formability, ductility and weldability. Resistance to the degradation processes is represented by resistance to a brittle fracture.

The mechanical properties of metals are mostly determined by material characteristics obtained in a tensile test. The basic strength properties are elastic limit (yield stress) – R_e or $R_{p0,2}$ and the tensile stress – R_m . The elastic limit (yield stress) R_e is the maximum stress to which the material deforms elastically (reversibly); tensile stress R_m is the maximum stress which the material is able to transmit without causing defects. The plastic properties of metals are characterized by elongation A, i.e. an elongation at fracture. Elongation is associated with toughness: material of greater ductility is usually characterized by greater toughness.

Tensile modulus (the modulus of elasticity) characterizes the elasticity of the material, referred to as the resistance of the material against elastic deformation when exposed to external forces. The tensile modulus of most materials depends on the strength of the bonds between atoms or ions and the density of bonds. The tensile modulus (sometimes in literature referred as Young modulus) E is given by the ratio of stress σ and deformations ε , shear modulus *G* is given by the ratio of shear stress τ and the shear strain γ .

$E = \sigma / \varepsilon$	eq. 4.1a.
$G = au / \gamma$	eq. 4.1b

Metal materials have a high tensile modulus (from 100 GPa, for the Zn-alloys 400 GPa for W-alloys).

Note: If we know E we can calculate G for metals with a cubic lattice in accordance with the relation $G=E/2(1+\mu)$, where μ is dimensionless - Poisson number, expressing the ratio of transverse contraction. For example, at the normal temperature for steel and magnesium alloy it is $\mu=0, 3$, for cast iron is $\mu=0, 25$, for aluminium and its alloys, bronze and brass it is $\mu=0, 35$.

Very often we want the materials and constructions of those to be light but strong at the same time, e.g. materials for the aerospace and automotive industries. The weight of material depends on the density ρ (kg·m⁻³), which is referred to as the mass *m* (kg) per volume of material *V* (m³).

 $\rho = m/V$ eq. 4.2

The relation between strength and mass measurement is expressed by specific yield stress R_e/ρ , specific strength R_m/ρ or specific modulus E/ρ . These characteristics are important for the design of the material. Fig. 4.1 shows the dependence of strength characteristics on the density for basic groups of technical materials.



Fig. 4.1. Dependence of strength characteristics on the density for basic groups of technical materials.

In most construction materials we require them to be strong and ductile. Metallic materials are loaded almost exclusively in the area of elasticity. If we want to increase the strength of metallic materials, it means we want to increase the elasticity (the limit of proportionality, yield stress), i.e. the stress to which they elastically deform. Because plastic deformation takes place through the movement of dislocations, an increase in the elastic limit (yield) will be based on the condition where we must prevent dislocation movement or make their movement more difficult, i.e. build obstacles (in the way).



Summary of terms 4.1

Metallic alloys can be classified according to the parent metal as ferrous alloys and non-ferrous metals.

Accompanying elements get into steel unintentionally. They are divided into harmful (impurities) and beneficial.

Alloying elements are added to alloys intentionally (on purpose), in order to improve their properties.



Questions 4.1

- 1. What are the basic types of metal alloys?
- 2. Can you name at least two harmful elements in metal alloys?
- 3. What is the function of alloying elements?
- 4. According to what (other) criteria are metals divided?
- 5. What is the principle of materials strengthening?
- 6. How can we strengthen metal material by previous plastic deformation?
- 7. How does the metal strengthening depend on grain size?
- 8. What mechanisms are involved in the interaction of dislocations with metal particles during strengthening by precipitates?
- 9. Which strengthening is more effective: by interstitial or substitution atoms?



1. Can you name the use of certain categories of steel, for example structural steels, tool steels, stainless steels of cast irons?

2. Can you name the use of some non-ferrous alloys, e.g. aluminium alloys, copper alloys, nickel alloys?

4.2. Iron – steels and cast irons

Time for study: 3 hours



Objective After studying this paragraph you will be able to

- explain what is meant by steel
- define what the properties of steels depend on
- classify types of steels and know their use



Lecture

Iron and iron alloys with carbon

Iron alloys represent the most widely used construction material in mechanical engineering. Steel production in recent years, continues to grow (Figure 4.2). Due to the high density of steel, its production still represents the highest proportion of the total material production. Development of iron alloys leads to new types of steels, which compete with other construction materials such as plastics and aluminium alloys. The high density of iron alloys is compensated by high strength properties. From alloys based on iron there develops the most production of high-alloy steels, especially stainless steels, which are applied not only in the food and chemical industries, but increasingly also in construction. A significant advantage of iron and its alloys is easy recycling and energy modesty in comparison with the production of non-ferrous alloys.





D Pure Iron

Pure iron is a soft and ductile (plastic) metal with a relatively low strength. Its basic properties are listed in Table 4.1.

atomic number	26
atomic mass	55,847
melting point (m.p.)	1536°c
density	7,874 g/cm3
tensile modulus	204 GPa
tensile strength / ultimate	180-250 MPa
tensile strength	
yield stress	80-140 MPa
ductility / elongation	50 %

Tab. 4.1. Basic properties of pure iron

Iron is an element which is reflected in the so-called **allotropy**, i.e. a solid state iron occurs in three different crystal modifications:

- Delta iron (iron δ) a high temperature modification of iron in the solid state. It has a body centred cubic lattice (bcc) and is stable in the temperature range 1536-1392 ° C.
- Gamma iron (iron γ) is a medium-temperature modification of iron. It has a face centred cubic lattice (fcc) and is stable in the temperature range 1392-911°C.
- Alpha iron (iron α) is a low temperature modification of iron. It has, as well as iron δ, a body centred cubic lattice (bcc) and is stable in a temperature under 911°C.

We can therefore say that the iron has three different crystal modifications, but only two different types of crystal lattices. Individual crystal modifications and the area of their stability are illustrated in Fig. 4.3.


Fig. 4.3. Crystal modifications of pure iron - cooling curve, area of stability

Fig. 4.3 shows the cooling curve of pure iron. It is evident that the phase transformation of pure iron in the solid state theoretically takes place (happens), as well as solidification, at a constant temperature and the cooling curve will reflect that by the existence of delays.

Carbon in iron

Carbon dissolves in each of the modifications of iron, but only in relatively small quantities. With regard to the relationship between the size of the iron atom and the carbon atom, carbon forms in iron a so-called **interstitial solid solution**. That is, the carbon atoms are located in the cavities of the crystal lattice of different modifications of iron. The solubility of carbon is different for each iron modification.

- Iron δ dissolves therein max. 0,1 mass % of carbon, and at a temperature of 1499°C. The appropriate solid solution is referred to as δ-ferrite.
- Irony dissolves therein max. 2,14 mass % of carbon, and at a temperature of 1147°C. The appropriate solid solution is called **austenite** and it is referred to as γ .
- Iron α dissolves therein max. 0,02 mass % of carbon, and at a temperature of 727°C. The appropriate solid solution is called **ferrite** and it is referred to as α .

Individual areas of occurrence of interstitial solid solutions in equilibrium metastable system diagram Fe - C are indicated in Fig. 4.4.



Fig. 4.4. Individual areas of interstitial solid solutions in equilibrium metastable system diagram Fe - C.

It is worth noting much higher solubility of carbon in austenite. This is related to the type of crystal lattice. Austenite is a solid solution of carbon in iron γ and has a face centered cubic lattice. For this the type of lattice low diffusion ability of an atom is characteristic, and diffusion is difficult, but there is a higher solubility of small interstitial atoms, i.e. the atoms in lattice cavities. This significant difference in the solubility of carbon in two distinct polymorphic forms of iron is of great technological importance, because the whole heat treatment of steel is based on it.

And what happens if there is more carbon in the iron - carbon system than it can be dissolved in the individual modifications of iron? Carbon above the solubility limit may be present as iron carbide Fe_3C - cementite or as a pure carbon, in the form of graphite. Cementite has an orthorhombic lattice, it is hard and brittle, and the maximum solubility of carbon in cementite is about 6.7%. In contrast, graphite crystallizes in the hexagonal system, it is very soft and brittle and contains 100% of carbon. Strength, toughness and plastic properties depend mainly on the presence of graphite in the structure. From a thermodynamic point of view the system iron - carbon with carbon as graphite is more stable than the system iron - carbon with carbon as iron carbide (cementite).

Alloys of iron and carbon are divided into two basic groups, steel and cast iron according to carbon content. Steels are alloys of iron with carbon (and other elements) which contain less than approximately 2 mass % of carbon. Cast iron alloys are conversely alloys of iron with carbon (and other elements), which contain more than 2 mass % of carbon. The carbon





Fig. 4.5. Schematic distribution of steels and cast irons in equilibrium diagram of metastable system Fe - C.

If the system Fe-C contains the carbon in the form of cementite, it is referred to as white cast iron. Alloys that contain carbon in the form of graphite are called graphite (gray) cast iron.

What happens when we cool austenite? Austenite, the interstitial solid solution of carbon in iron γ , exists at elevated temperatures and its maximum solubility is 2,14 mass % of carbon at a temperature of 1147°C (Figure 4.6). Which structures arise depend on the cooling conditions, in particular the cooling rate. With a slow cooling rate (in the air) and at a temperature of 727 ° C the austenite decomposes into a mixture of ferrite and cementite, which we call **pearlite**. Perlite has a characteristic lamellar structure and it is present in the structure of structural and tool steels (Fig. 4.7). The decomposition of austenite to pearlite occurs by the diffusion mechanism. At increased or high rate of the cooling (e.g. cooling in the water or oil) diffusional mechanism is no longer possible or it is limited to a very small interstitial elements such as carbon, and therefore other structural components arise **- bainite and martensite**, which are characterized by greater hardness and strength, but also lower toughness.



Fig. 4.6. Austenite structure



Fig. 4.7. Pearlite structure

Visible are the original austenite grain boundaries and cementite lamellae (in the sketch yellow, in the picture gray), alternating with ferrite lamellae (blue in the sketch, white in the picture on the right).

Steels are still widely used, because their properties can be changed on the one hand by chemical composition, but also (on the other hand) in the way of treatment such as e.g. heat treatment or forming. Steels may be soft and ductile, but also strong, hard, and relatively brittle. The tensile stress of the steel is in the range 350 - 2000 MPa. Currently there is a trend to produce steels having higher functional properties that are both hard and ductile.

D Influence of elements on the properties

The properties of steel are influenced by the amount of carbon and the presence of other elements in the steel.

Carbon in the steels cannot be considered as an alloying element, since it is part of a binary system with iron. Carbon, however, has significant impact on the strength, hardness and hardenability of steels (*ed. the hardenability of steel is its ability to achieve, with a sufficiently rapid cooling from the austenite region, nonequilibrium structures - bainite or martensite*). With the increase of carbon content there increases strength R_m and hardness *HB*, but plastic properties *A*, *Z* and toughness *KCU* are decreasing (Figure 4.8).



Fig. 4.8. The dependence of mechanical properties on the carbon content.

We are trying to reduce **accompanying harmful elements** (impurities) to a minimum. Their amount in the steel depends on the quality of raw materials and production process. According to the amount of impurities the quality of the steel is determined. The most common impurities are sulphur, phosphorus, oxygen, nitrogen and hydrogen.

Sulphur gets into the steel from ore and also from the fuel. It occurs in the steel in the amount of a few hundredths (usually less than 0.020 mass %) or up to thousandths e.g. for steel used at reduced temperatures. Sulphur with iron forms sulphides FeS with a low melting point (985 ° C), which are concentrated in triple points (where there is contact of three grains) and

subsequently along the perimeter of the austenitic grains and (further) weaken their cohesion. This causes problems during hot forming. The adverse effect of sulphur is compensated by the addition of manganese, which has a higher affinity for sulphur (preferably binds well) and forms MnS sulphides. The melting point is higher (1620°C) and the shape is spherical, so there is much less effect on the mechanical properties of the steel. During forming, however, these sulphides deform in the direction of rows causing anisotropy of the properties. Sulphur also deteriorates (makes worse) the weldability and reduces the corrosion resistance. However, sulphur acts favorably on machinability. While machining short chips are forming and therefore the sulphur content for so-called "cutting steels" is increased up to 0.2 - 0.3 mass %. Since sulphur improves friction properties, high sulphur content reduces the friction between the tool and the workpiece.

Phosphorus gets into the steel from the raw materials used in conventional steels and is an undesirable element. Phosphorus in steel is dissolved in solid solution austenite γ . Like sulphur, phosphorus segregates at the grain boundaries and causes temper embrittlement decreases notch toughness, increases the transition temperature, deteriorates the weldability, and increases the tendency to cold cracking. The phosphorus content in the steel may range up to 0.08 mass %, with a lower content than 0.05 mass % increases the resistance to atmospheric corrosion. In the graphitic cast iron with a high phosphorus content (15,6 mass %) iron phosphide Fe₃P is formed, which is hard and low-melting. A higher content of phosphorus increases the fluidity of cast iron, hardness, wear resistance and the friction coefficient as well.

Oxygen gets into the steel during production, precisely during the refining of iron, but subsequently is removed during deoxidation when adding elements, which have a higher affinity for oxygen (Al, Si, Ca). The oxygen remaining in the steel is bound to oxides or silicates. Oxygen and sulphur are the main sources of inclusions (the undesirable compounds of accompanying elements) in the steel. They worsen notch toughness and increase the transition temperature.

Nitrogen gets into the steel from the furnace atmosphere. The maximum solubility of nitrogen in the steel is 0.1 mass % at the temperature of 585 ° C, but normally steel contains thousandths up to 0,02 mass (of it) %. Nitrogen encourages the development of intergranular corrosion under stress when at the grain boundaries stable nitrides of iron Fe₄N are formed. This leads to a reduction in notch toughness, an increase in transition temperature, an increase in the yield stress and the decrease in cold formability. This phenomenon is called the aging of steel.

Hydrogen gets into the steel during production from furnace atmosphere and humidity of the charge, but also during other production steps (e.g. acid pickling or welding). Hydrogen enters the steel in an atomic form and has the greatest diffusion ability of all the elements. The excess hydrogen is presented in the location of defects where hydrogen molecules that cause

high stress are generated. This may lead to the occurrence of cracks and material failure. For removing the hydrogen from the steel, annealing is used at temperatures of 680 to 700°C, at which hydrogen diffuses out of the material. Higher hydrogen content, even if it does not cause material failure directly, leads to a reduction in elongation and reduction in area.

Other harmful elements such as **tin**, **antimony** and **arsenic** are present in the steel in thousandths mass % segregate at the grain boundaries and cause a decrease in notch toughness.

Favorable accompanying elements have an impact on the reduction or elimination of the negative effects of the impurities. Among the most important/significant are manganese and silicon.

Manganese is present in all steels as the basic deoxidizing and desulfurizing additive in the amount of 0.1 to 0.8 mass %. It is dissolved in the ferrite and slightly increases its strength and toughness. Manganese has a higher affinity for oxygen or sulphur than for Fe and produces less harmful oxides MnO and MnS.

Silicon, like the manganese is a deoxidizing element. Being the deoxidizing ingredient, it does not exceed 0.5 mass %. Silicon increases the strength and hardness, but it deteriorates the formability and reduces thermal and electrical conductivity. It supports graphitization in the cast iron.

Alloying elements (alloys) are intentionally added to the steel to improve the desired properties. Their content can be from a few hundredths of percent (e.g. with boron) to tens of percent (e.g. chromium or nickel). The most frequent alloying elements are Cr, Ni, Mn, Si, Mo, W, V, according to which the steel is usually called (manganese steel, chrome and chrome-nickel). Other alloying elements are Co, Ti, Al, Cu, Nb, Zr, B, N, Be.

Elements such as Mn, Si, Ni, Mo, V, W and Cr *increase the mechanical properties*, in particular strength and hardness while maintaining satisfactory toughness.

Hardenability (i.e. ability to achieve hardened steel structures to a certain depth) can be /increased by alloying elements such as Cr, Mn, Mo, V, Ni, and B.

In order to achieve a fine-grained structure, the steel is alloyed with Al, Ti, Nb, Ta and V.

The hardness and resistance to wear and tear is increased by adding carbide forming elements Cr, Mo, V and W. If these carbides are suitably distributed in the structure, they also increase the heat resistance at high temperatures.

Corrosion-resistance can be increased by adding Cr, Ni, Mo, Si, Cu. Ti, Nb and Ta form stable carbides and prevent the intergranular corrosion of stainless steels alloyed with chromium. Cr, Si, Al form stable oxides and enhance/increase *resistance to oxidation* at high temperatures.

The alloying elements usually produce a substitution of solid solutions. To the content of 2 mass % increases strength without reducing the plastic properties or toughness. At higher

concentrations the increase of the strength properties decreases and the decline of plastic properties and toughness increases. More effective is the combination of more alloying elements than a higher content of one additive element.

Distribution and marking of steel *(steel signs are just for information)*

We divide steel according to the method of processing on steel for forming and steel for casting, according to the method of use on structural steel and steel for tools, according to the chemical composition of conventional grades (carbon, alloyed) and stainless (alloyed) steel.

Steels for forming with compliance of the original CSN standards (CSN 42 0002) used to divided into10 classes according to the chemical composition as we can still meet in practice. Steel mark consists of five numbers and two other digits, separated by a dot. In general steel markings look as follows:

Steel 1X1 X2X3X4.X5X6.

The meaning of the individual digits is characteristic for a given steel class.

X₁ along with 1 indicate the steel class 10-19.

- cl. 10, 11, 12 are structural carbon steels (non-alloys),
- cl. 13, 14, 15 and 16 are low and medium alloyed structural steels,
- cl. 17 indicates stainless steel,
- cl. 18 steel produced by powder metallurgy and
- cl. 19 is steel for tools (carbon and alloyed).
- X₂ and X₃ at class 10 and 11 indicates strength in tenths MPa (min. 30) for cutting steel means an average content of C.
- X_2 at class 12 to 16 the sum of medium-sized contents of alloying elements in whole % (at cl. 12 equal to zero).
- X_3 at class 12 to 16 medium-sized content of C in tenths mass %.
- X₄ steel specification (see material data sheets).
- X₅ final state of the steel given by the last heat treatment (unannealed, annealed, refined).
- X₆ degree of the final strengthening by cold forming.

Example: Steel 12 071.21 indicates constructional carbon steel class 12, the carbon content is 0.7 mass % (may move in range of 0,62 to 0.72 mass %), annealing with recrystallization, finished with cold rolling. According to the sheet of material strength $R_m = 570$ to 740 MPa and elongation min. 13 %.

According to European standards (EN 10020) and the new Czech standards (EN 10020-94) wrought steels are defined as the Fe content of C <2 mass % having Fe content greater than the content of any other element present in the alloy. According to the chemical composition,

they are divided into **non-alloy**, wherein the content of each element does not exceed the limit of the elements (Table 4.2) and the **alloy** in which at least one element exceeds the minimum limit. Steels are either marked according to their use (e.g. S indicates construction steel, R steel for rails, E steel for machine) or the field of their chemical composition.

Al	В	Bi	Co	Cr	Cu	La	Mn	Mo	Nb	Ni
0.1	0.0008	0.1	0.1	0.3	0.4	0.05	1.65	0.08	0.06	0.3
Ph	So	S ;	Та	т	V	XX7	7	Oth	er eleme	ents.
10	56	51	Ie	11	v	vv	Zr	except	ting C, I	P, S, N

Table 4.2: Content limit of the elements for non-alloy steel by CSN EN 10020-94

Non-alloy steels are divided into three main quality groups:

Non-alloy steels of conventional grades are used for the heat treatment (in addition to the basic types of annealing), they are set to a minimum value where $R_m < 690$ MPa, $R_e < 360$ MPa, $A_5 < 26$ % and the prescribed content of Si and Mn.

Non-alloy high-quality steel do not have prescribed requirements for the degree of purity (unless of non-metallic inclusions) but they are subject to a higher strength demands. Non-alloy high-quality steel with the content of Mn < 1 mass % intended for refining (corresponding with the class 12 of CSN) is marked C, (and) two digits indicating 100 times mean value of C content in mass % and with a letter indicating further features (properties) or use of steel

Note Refining is a mode of heat treatment.

Example:

C35E is non-alloy steel, medium content of C = 0.35 mass %, with the maximum set of sulphur content.

Non-alloy high-quality steel with the content of Mn < 1 mass %, non-alloy free-cutting steels and alloy steels with a medium content of the individual alloying elements below 5 mass % (not high-speed steel), are intended for refining (corresponding with the classes from 13 to 16 of the CSN) and is marked with two digits indicating 100 times mean value of C content in mass %, chemical symbol of alloying elements and a multiple of its actual content. *Example*:

28Mn6 is non-alloy steel, medium content of C = 0.28 mass %, Mn = 6/4 = 1,5 mass %.

Non-alloy high-quality steels have a higher degree of purity (especially with regard to nonmetallic inclusions) are intended for refining or surface hardening, with specific chemical composition and the specific conditions of production. This includes for example steel with the requirements for impact work in a refining condition, steel with the highest content of phosphorus or sulphur prescribed and steel for the pre-stressing reinforcement of concrete.

Alloy steels

High-quality alloy steels are intended for similar purposes as non-alloy high-quality steels. They are for example weldable fine-grain steel for constructions incl. pressure vessels and pipes, steel alloyed with silicon with special requirements on the magnetic properties or steel intended for the manufacture of rails and more.

High-quality alloy steels have well-defined chemical composition, specific conditions of production and testing. They are divided into <u>stainless</u> (C \leq 1,2 %, Cr \geq 10,5 %), <u>high-speed steel</u> (C \geq 0,60 %, Cr 3-6 %, min. two of the following three elements Mo, W, V with total content \geq 7 %) and <u>other high-quality alloy steel</u>. Alloy steel (except high speed steel) containing at least one element over 5 mass is marked with the letter X, the following figure corresponds to 100 times multiple of the C content in mass %. Additional letters identifying the individual alloying elements and numbers separated by a hyphen determine the contents of individual alloying elements.

Example: X5CrNi18-10 indicates alloy steel with a medium content of C = 0.05 mass (mass) %, Cr = 18 mass %, Ni = 10 mass %.

In addition to the above described marking system, a numeric marking system is also used (according to CSN EN 10 027-2-95). A material's mark is formed by a number, determined by one digit of a major group of material (steel is number 1), followed by a dot and another four digits. The first two digits indicate the number of a steel group, the second two digits of the serial number of the steel. There are conversion tables that are used to compare steel grades with the original marking according to CSN.

Example: 1.4841 (equivalent for a steel specified as 17255 in CSN)



Summary of terms from 4.2.

After studying this section the following terms should be clear:

- Pure iron and its allotropic modifications;
- Carbon in iron cementite/graphite;
- Metastable diagram iron carbon;
- Classification of iron based alloys steels/cast irons;
- Effect of admixture elements on properties of steels harmful elements/alloying elements.

Questions 4.2

- 10. The iron is reflected with so-called allotropy. What does it mean?
- 11. Name the allotropic modifications of iron.
- 12. In what forms is carbon located in iron?
- 13. What is the maximum solubility of carbon in Fe_{γ} ?
- 14. What is the maximum solubility of carbon in Fe_{α} ?
- 15. What is a cementite?
- 16. How do we divide the alloys of iron and carbon?
- 17. What structural components arise during the slow (equilibrium) cooling of austenite?
- 18. What limits of tensile strength can we achieve in steel (the lowest and the highest)?
- 19. What impact has carbon on the properties of steel?
- 20. What are the adverse effects of sulphur in steel?
- 21. Which elements increase the strength and hardness of steel?
- 22. Which elements increase the corrosion resistance of steel?
- 23. How do we divide stainless steels by their structure?
- 24. What type of steel is used for the production of rails?
- 25. What kind of steel is used for the production of stainless cookware (dishes)?

4.3. Alloys of non-ferrous metals

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Time for study: 2 hours



Objective After studying this paragraph you will be able to

- explain how to divide non-ferrous metals
- describe basic properties of aluminium
- classify main groups of aluminium alloys and their properties



Lecture

Non-ferrous metals

Non-ferrous metals is a name for all pure metals excepting iron. These metals have often some specific properties, such as high electric conductivity, thermal conductivity (e.g. copper, aluminium); low density (aluminium, manganese, titanium); high melting point (tungsten); high corrosion resistance. Non-ferrous metals can be divided according to their density to light metals with a density $\rho < 5 \text{ g·cm}^{-3}$ and heavy metals with a density $\rho > 5 \text{ g·cm}^{-3}$. Li, Mg, Be, Al, Ti can be examples of the light metals. Furthermore, non-ferrous metals can be divided according to their melting point into metals with low melting point (to 600°C), e.g. Zn, Sn, Pb; metals with intermediate melting point (in the range from 500°C to approx. 1500°C), e.g. Mn, Cr, Ni, Cu; and metals with high melting point (higher than 1500°C), e.g. Zr, V, Cr, Mo, W.

Alloys of non-ferrous metals can be used in aerospace field or more generally in traffic where a low mass of structure parts is very important. Relation between strength and density is often very positive in these alloys. Aluminium is one of the most important non-ferrous metals and that's why we will focus on it now.

D Aluminium and its alloys

Basic characteristics of aluminium are given in the following overview:

Atomic number Z = 13; atomic mass M = 26,97 Melting point: 660°C Crystal structure – face centered cubic lattice +(fcc) Lattice parameter: a = 0,4041 nm Density (+20°C): $\rho = 2700$ kg.m⁻³ Coefficient of thermal expansion: $\alpha = 23,8.10^{-6} \text{ K}^{-1} (20-100^{\circ}\text{C})$ Coefficient of thermal conductivity: $\lambda = 217,6 \text{ W.m}^{-1}.\text{K}^{-1}$ Electric resistance : $\rho = 2,63 \text{ }\mu\Omega.\text{cm}$

Electric conductivity of aluminium is approx. 65 % of electric conductivity of copper (copper is a standard for electric conductivity measurement).

Main advantages of aluminium are following:

- High electric conductivity (commercial Al has electric conductivity equal to 62 % of electric conductivity of pure copper but Al has lower density, which is also advantageous);
- High thermal conductivity;
- Very good corrosion resistance in certain environments;
- Low density.

Main advantages of aluminium:

The main disadvantage of aluminium represents its low mechanical properties in annealed state, i.e. very low yield strength and very low tensile strength. This disadvantage can be overcome by various strengthening mechanisms, especially by dislocation strengthening and precipitation strengthening.

Division of aluminium alloys:

Aluminium alloys can be divided in the following way:

• Wrought alloys non-hardenable (they cannot be strengthen by precipitation strengthening);

hardenable (by precipitation strengthening)

• Alloys for casting.

The division of aluminium alloys is schematically depicted in the Fig. 4.9.



Fig. 4.9 Division of aluminium alloys

In the following overview the designation of different state of aluminium and its alloys is shown in accordance to Aluminium Association. You needn't learn it, it is just to have an idea about it.

F	as-	as-received state				
0	annealed and recrystallized state					
Η	sta	te after cold deformation:				
	H1X	only cold deformation (X – means degree of deformation)				
		H12 ¹ / ₄ hard state				
		H14 ¹ / ₂ hard state				
		H16 ³ / ₄ hard state				
		H18 4/4 hard state				
		H19 very hard (spring hard) state				
	H2X	cold deformation + recovery annealing $(X 2-9)$				
	H3X	cold deformation + stabilization annealing (X 2-9)				
Т	sta	te after precipitation hardening:				
	T1	quenching after hot deformation + natural ageing (at room temperature);				
	Т3	solution annealing, quenching, cold deformation, natural ageing;				
	T4 As T3, without cold deformation;					
	T5	As T1, but artificial ageing (at higher temperature);				
	T6 As T4, but artificial ageing;					
	Τ7	As T6, but overaged;				
	T8	As T3, but artificial ageing;				
	Т9	As $T6 + cold$ deformation.				

In the following part we will briefly represent some important examples of aluminium alloys.

Aluminium of a commercial purity (Al > 99,0 %)

Similarly as in the case of steels, properties of aluminium are strongly influenced by admixture elements. The most important admixtures (impurities) are iron and silicon and they can be eliminated by electrolytic refining.

Influence of admixtures:

For aluminium of a commercial purity, the most important is effect of admixtures on its electric conductivity, which is shown in Fig. 4.10. The highest drop of electric conductivity of aluminium is provoked by V, Cr, Ti and Mn.



Fig. 4.10 Effect of admixtures on the electric conductivity of aluminium

Effect of admixture on some other properties -

- Ti (0,05 0,10%) nad B (0,005 ,01%) ensure grain refinement during solidification;
- Zr (<0,2%) prevents the grain growth during heat treatment;
- Si (0,5 0,8%) increases creep resistance;
- Ni and Fe increase mechanical properties at elevated temperatures;
- Cu+Ni+Sn+Pb should be lower than 0,1% to ensure good corrosion resistance
- Cr + Mn increase corrosion resistance.

Corrosion resistance of aluminium is given by the formation of Al_2O_3 layer on its surface. Aluminium is corrosion resistant in some acid environments with low oxidation potential, while its resistant is generally insufficient in alkalic environments.

Alloy	Series designation	Remark
Al > 99%	1000	non-hardenable
Al-Cu; Al-Cu-Mg	2000	hardenable
Al-Mn	3000	non-hardenable
Al-Si	4000	
Al-Mg	5000	non-hardenable
Al-Mg-Si	6000	hardenable
Al-Zn-Mg; Al-Zn-Mg-Cu	7000	hardenable
Al and other elements	8000	

In the following table a division of wrought aluminium alloys is given according to Aluminium Association.

Non-hardenable wrought alloys

Series 1000 (Al > 99,0%)

Alloys of this series have only low mechanical properties in annealed state. The properties can be considerably increased by deformation strengthening. With increased purity of these alloys, mechanical properties further decline, while ductility increases. Recrystallization temperature is lowered by increased purity.

A very pure Al (more than 99.9999 %) has recrystallization temperature approximately -30°C. Recrystallization temperature can be increased by addition of Si, Mg, Cu, Mn, Fe, Cr. The effect of chromium is the most pronounced.

Aluminium with a purity around 99.0% has recrystallization temperature in the range from 300 to 400°C.

Examples of mechanical properties of alloys of series 1000 are shown in the following table.

Alloy Chem. comp.	State	R _{p0,2} (MPa)	R _m (MPa)	A (%)	Fatigue limit for 5.10 ⁸ c (MPa)
1060	0	28	70	40	-
Al > 99,6%	H14	90	110	12	-
	H18	125	130	6	-

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1100	0	35	80	35	30
Fe+Si<1%	H14	90	130	9	50
	H18	130	150	6	60

It is evident that in annealed state the mechanical properties, i.e. yield strength and tensile strength are very low. Fortunately, they can be increased by cold deformation. Nevertheless, after cold deformation ductility of alloys drops down considerably.

Alloys of the series 1000 have a very good corrosion resistance.

Where alloys of the series 1000 can be used?

These alloys can be used for example:

- As electric cables content of Ti, V, Cr has to be controlled alloys 1350, 1370;
- For building facings;
- In chemical industry, food industry;
- For low temperature applications;
- As cladding on different aluminium alloys with worse corrosion resistance.

Series 3000 - alloys Al - Mn

Alloys of the series 3000 are widely used for numerous applications in automotive industry, e.g. for various parts of car air-conditioning system. Usually, Mn content doesn't exceed 1.5 %. Basic information about behaviour of these alloys can be deduced from the binary diagram Al-Mn, which is shown in Fig. 4.11.



Fig. 4.11 Binary diagram Al – Mn

Maximum solubility of Mn is 1.8 % at 659°C. The solidification temperature interval is rather narrow, thus only limited segregation can be expected during solidification of these alloys. An intermetallic compound is present in the binary diagram, the stoichiometry of which corresponds to Al_6Mn . This compound is also referred to as β . It brings only limited strengthening as it has a strong tendency to coarsening. Nevertheless, it has a positive effect on the recrystallization temperature.

Solid solution strengthening takes place in this kind of alloys.

Rather often, Mg is added in amount not exceeding 1.2 % to increase solid solution strengthening.

Examples of mechanical properties of some alloys of the series 3000 are shown in the following table.

Alloy Chem. comp.	State	R _{p0,2} (MPa)	R _m (MPa)	A (%)	Fatigue limit for 5.10 ⁸ c (MPa)
3003	0	40	110	30	45
1.2Mn -0.12Cu	H14	145	155	8	62
	H18	185	200	4	70
3004	0	70	180	22	65
1.2Mn - 1.0Mg	H14	200	245	9	110
	H18	250	285	4	115

It is clear from this table that mechanical properties can be improved significantly by deformation strengthening but materials become rather brittle in this case.

Properties and use of alloys of the series 3000:

- Alloys are suitable for both hot and cold working, i.e. different products can be manufactured, such as sheets, rods, wires, tubes, etc.;
- Alloys of this series has a very good resistance to atmospheric corrosion;
- Weldability is also very good;
- Alloys of the series 3000 can replace alloys of the series 1000 in case when higher mechanical properties are required.

Hardenable wrought alloys

Series 2000 - alloys Al - Cu, or Al - Cu - Mg

Aluminium alloys with copper, or eventually also with magnesium and some other elements are called durals (*dur al means hard aluminium – from French*).

The copper content in these alloys is usually in the range 2.5 - 6.3 %; the magnesium content is in the range from 0.5 to 1.5 %.

Precipitation hardening takes place in this kind of alloys resulting in the precipitation of Θ phase, the stoichiometry of which is CuAl₂, resp. CuMgAl₂. Binary diagram Al – Cu can be helpful to understand behaviour of these alloys. It is presented in Fig. 4.12.

Assessed Al-Cuphase diagram.



Fig. 4.12 Binary diagram Al – Cu

Alloys Al-Cu, or Al-Cu-Mg are submitted to so-called precipitation hardening. The aim of this treatment is precipitation of very fine particles of Al_2Cu phase in the metallic matrix. Three main steps can be distinguished in precipitation hardening:

- 1. Firstly, an alloy is heated to the temperature range where only solid solution of copper in aluminium is stable. At the end of this step, the whole material should be formed by solid solution only, i.e. all other phases should dissolve.
- 2. After that, the alloy is cooled rapidly (quenched) to produce supersaturated solid solution of copper in aluminium.
- 3. At the end, the alloy is submitted to so-called ageing, which can take place either at room temperature (natural ageing), or at elevated temperatures (artificial ageing).

During ageing, following processes (steps) can take place:

1. Formation of so-called Guinier-Preston (GP) zones, which represent monoatomic layer of copper in crystal planes {100} in aluminium. GP zones are not yet precipitates, they represent segregation of copper.

- 2. Formation of Θ'' phase with tetragonal lattice. This phase is a coherent precipitate the particles of which are plate-like and very fine (less than 10 nm). Θ'' can precipitate to the temperature of 200°C approximately.
- 3. Formation of Θ' phase (Al₂Cu) with tetragonal lattice. This phase is a semi-coherent precipitate observed to the temperature 300°C. Θ' can be formed from Θ'' precipitates or can engender directly from the supersaturated solid solution. Θ' precipitates ensure together with Θ'' precipitates the highest obtainable hardening.
- 4. Formation of Θ precipitates of Al₂Cu phase, which are non-coherent with the metallic matrix. Θ precipitates are rather large and they are non-desirable from the point of view of mechanical properties as if present mechanical properties, i.e. yield and tensile strength decline in a significant way.

Ageing steps 2-3-4 are shown in Fig. 4.13.



Fig 4.13 Ageing steps 2-3-4 in Al-Cu alloy

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Relation between ageing time and hardness of the Al-Cu alloy is shown in Fig. 4.14.

Fig. 4.14 Effect of ageing time on the hardness of Al-4%Cu alloy at ageing temp. 130°C

It can be deduced from Fig. 4.14 that highest values of hardness are obtained if a mixture of coherent and semi-coherent precipitates is present in the structure. In the case of non-coherent precipitates, the hardness decreases.

Alloy Chem. comp.	State	R _{p0,2} (MPa)	R _m (MPa)	A (%)	Fatigue limit for 5.10 ⁸ c (MPa)
2014	0	100	200	20	90
4.4Cu - 0.5Mg - 0.8Mn	T4	290	420	18	140
– 0.8Si	Т6	430	480	12	125
2017	T4	180	300	27	
4.4Cu – 0.6Mg					
"dural"					
2024	0	100	200	20	90
4.4Cu - 1.5Mg - 0.6Mn	T4	320	460	18	140
"super-dural"	Т6	390	475	10	125

In the following table, examples of mechanical properties of some alloys of the series 2000 are presented.

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It is evident from that table that after precipitation hardening mechanical properties can be very high, which is valuable, especially if we take into account a low density of the alloys.

Properties and use of the alloys of the series 2000:

- These alloys generally have high mechanical properties.
- Unfortunately, the corrosion resistance is reduced in comparison to the series 1000 and 3000.
- Weldability is rather difficult.
- Alloys are widely used in automotive industry, aircraft industry, to manufacture various sporting goods, etc.



Summary of terms from 4.3.

After studying this section the following terms should be clear:

- > Non-ferrous metals and their classification;
- Pure aluminium and its properties;
- Division of aluminium alloys, i.e. wrought alloys/alloys for casting; hardenable/non-hardenable alloys;
- Alloys of the series 1000, 2000, 3000.



Questions 4.3

- 26. What are the most important criteria for division of non-ferrous metals?
- 27. How can be divided aluminium alloys?
- 28. What kind of aluminium alloys represent so-called "durals"?

м <mark>л</mark> л С	The Key - Chapter 4 key: answers to questions
Q1	Basic types of metallic alloys are alloys based on iron, i.e. steels and cast irons, and alloys based on non-ferrous metals.
Q2	The most harmful elements in many metallic alloys are phosphorus and sulphur.
Q3	Alloying elements are added to improve some properties of metallic materials.
Q4	Metals can be divided according to many criteria: one of them is metal density, another
-	one is the temperature of the melting point.
Q5	The strengthening of metallic materials is based on the increase of the yield strength .
Q6	Strengthening of metallic materials by previous plastic deformation is based on the increase of dislocation density. An increment of the yield strength is proportional to the square root of the dislocation density ρ .
Q7	The finer the grain size, the higher is material yield strength.
Q8	Two mechanisms are involved in the interaction of dislocations with precipitates: the cutting of precipitates by dislocations (for coherent precipitates) and bowing of dislocations around precipitates – Orowan's mechanism (for non-coherent precipitates).
Q9	The strengthening by interstitial atoms is more effective than the strengthening by substitutional atoms.
Q10	Allotropy of iron means that iron exists in solid states in three different modifications.
Q11	The allotropic modifications of iron are: iron alpha, iron gamma and iron delta.
Q12	If dissolved, carbon is in interstitial sites in the iron crystal lattice.
Q13	The maximum solubility of carbon in Fe _{γ} is 2.14 mass %.
Q14	The maximum solubility of carbon in Fe _{α} is 0.02 mass %.
Q15	Cementite is a chemical compound the chemical formula of which is Fe ₃ C.
Q16	Alloys of iron and carbon are divided into two main groups: steels (with carbon content
Q17	During the slow cooling of austenite ferrite, pearlite and secondary cementite can be formed.
Q18	The strength of steels can vary from approximately 300 MPa up to 2000 MPa, or even more.
Q19	Carbon increases steel strength but at the same time decreases steel toughness.
Q20	The most important adverse effect of sulphur is a significant reduction of the steel toughness.
Q21	Strength and hardness of steels can be increased by carbon, manganese, silicon, chromium, molybdenum, vanadium, etc.
Q22	The corrosion resistance is increased mainly by chromium addition. The minimum amount of chromium in stainless steels should be 12 %.
Q23	According to their structure, stainless steels are divided into ferritic, austenitic, martensitic and duplex steels.
Q24	Usually, steels with pearlitic structure having approximately eutectoid carbon content are used for the production of rails.
Q25	Most often, austenitic stainless steels containing 18% of chromium and 10% of nickel are
	nowadays used for the production of stainless cookware.
Q26	The most important criteria to classify non-ferrous metals are their density. or the
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	temperature of their melting point.
Q27	Aluminium alloys can be divided into wrought alloys and alloys for casting. Wrought
	alloys are further divided into hardenable alloys(e.g. Al-Cu alloys) and non-hardenable
	alloys (e.g. Al-Mn alloys).
Q28	"Durals" represent hardenable alloys, typically Al-Cu alloys, or Al-Cu-Mg alloys, etc.

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Other sources

Callister W. D. jr., Rethwisch D. G.: *Fundamentals of Materials Science and Engineering. An Integrated approach.* Hoboken: Wiley, 2008. 3rd ed. 882 p. ISBN 978-0-470-12537-3.

Ashby M. F.: *Materials Selection in Mechanical Design*. Oxford: Elsevier Butterworth Heinemann, 2005, 3rd ed. 603 p. ISBN0-7506-6168-2.

Ohring M.: *Engineering Materials Science*. San Diego: Academic press, 1995. 827 p. ISBN 0-12-524995-0.