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DESIGN OF CONSTRUCTIONAL COMPONENTS AND THEIR CONTROLLED AGEING

study support

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Content

Preface

The study materials for the course *Design of constructional components and their controlled ageing* is intended for students of the combined study in the 3rd semester of follow-up master's studies in the field of Progressive Technical Materials. It is used as a substitution for the significantly lower share of direct contact lessons, which makes this study form much more difficult for the students. Of course, it can also be used by full-time students to refresh the subjects covered in lectures during the semester.

The aim of the course is to obtain knowledge about construction philosophies presently used in structure designs, explanation of ageing processes that cause changes of material properties of the structure and their components during long-term operation, and the description of the main degradation mechanisms that might lead to loss of integrity of the structure during long-term operation.

After studying this documentation, the student will have knowledge about the impact of long-term operation of equipment on properties of used construction materials. The student will be able to define risks of creation of sudden and unstable fractures, fatigue fractures, fractures caused by creeps and corrosion-mechanical damage.

During the creation of this text I tried to achieve maximum clarity when explaining the subject matter. If, however, you find the explanations in any of the subchapters unclear, you are welcome to send me an email to the e-mail address karel.matocha@vsb.cz, so that I can make necessary changes.

An integral part of the materials is the *Study Guide*, which explains how to work with the study materials.

Study Guide

The basic study unit is chapters and their sub-chapters.

- Read the whole chapter.
- Study the overview of terms.
- Look at the questions and try to answer them.
- The next step is solution of tasks.

If you have any problems and don't know how to solve them, please contact the lecturers on the e-mail addresses provided in the preface.

Within semestral projects students will process test protocols for results of experiments consisting of special tests in the field of fatigue, fracture behaviour and creep of construction materials. Before the test itself, all students are required to pass the credit test.

1. Mechanical properties of construction materials

Time to study: 1.0 hour

Aim: **After studying this chapter you should be able to:**

- **Define the meaning of mechanical properties of construction materials.**
- **Describe the difference between basic and special mechanical properties.**
- **Name possible utilization of test results of mechanical properties of construction materials.**

Lecture

Mechanical properties (yield strength $R_{p,0,2}$, ultimate tensile strength R_m, ductility A, contraction Z, fracture toughness, FATT, impact strength KCV, fatigue limit $\sigma_{C,}$ creep strength $R_{mT/t/T}$, limit value of fatigue crack growth due to stress corrosion cracking, etc.) are properties of a construction material that decide its suitability for the intended function and practical use. These properties express the ability of the material to resist mechanical stress and the operational environment. Study and improvement of mechanical properties of construction materials is motivated by their optimum use during the production of construction components. Results of mechanical property tests of construction materials can have the following applications:

1) Selection of suitable material during construction design.
2) Production control.
3) Study of the impact of chemical composition, heat processing, production technology, temperature and environment on material properties, i.e. research and development purposes.

4) Assessment of degradation of material properties due to long-term operation of the equipment, assessment of crack defects, i.e. estimations of the remaining life of structures and analysis of causes of structure failures.

Mechanical properties are divided into basic and special. Basic mechanical properties express general quality requirements on the material and are therefore usually stated in material sheets (attestation). Quantitatively they are expressed by material characteristics, such as ultimate tensile strength R_m, yield strength R_{eH}, $R_{p,0,2}$, ductility A, contraction Z, hardness H, impact strength KCV. These properties are therefore not associated with a specific fracture process (fatigue fracture, fracture caused by creep at high temperatures, stress corrosion fracture).

Special mechanical properties are directly related to a certain type of fracture process and are usually included in concrete technical conditions. Special mechanical properties include for instance fatigue limit $\sigma_{C,}$ fracture toughness, stress-strain cyclic curve, limit value of stress intensity factor for growth of fatigue cracks, creep strength $R_{mT/t/T}$, limit value of stress intensity factor for growth of corrosion cracks, uniform corrosion speed, etc.

Σ

Overview of terms: After studying this chapter you should understand the following terms:

- **Mechanical properties of construction materials**
- **Basic mechanical properties**
- **Special mechanical properties**

Questions to the covered material:

1) How are mechanical properties of construction materials divided?

2) How would you characterize special mechanical properties?

3) What is the application of test results of mechanical properties of construction materials?

4) Would you say the strain-stress cyclic curve belongs to basic or special mechanical properties?

Tasks

Try to define the difference between basic and special mechanical properties and list material characteristics belonging to each group.

2. Basic concepts of construction designs

Time to study: 1.5 hours

Aim: **After studying this chapter you should be able to:**

- **List two basic concepts of construction designs.**
- **Describe the difference between these two basic concepts of construction designs.**
- **Describe the two methods of realizing construction design using the damage tolerance approach.**
- **Define three basic types of crack nucleation.**
- **Define the division of construction designs based on working temperatures.**
- **Define limit temperature.**

Lecture

2.1 Introduction

Designers, calculation specialists and technologists should strive to design a component or structure that meets a whole range of requirements. The basic requirements on the structure are to perform the required function for the designed service life. The construction design must also respect the principles of optimum production technology, assembly, inspection and repairs. That is the only way to create a competitive design and ensure it will bring the expected profit to its manufacturer, as well as the user.

Within the past decades we have witnessed a clear increase of machine and equipment outputs, increase of operating temperatures, as well as the effort to reduce material and energy consumption for production and operation. These facts lead to the use of new types of steel with increased performance specifications. Due to the fact that steels with higher yield strength and ultimate strength values require increased technological discipline during welding, and that these steels are sensitive to the operating environment and presence of both construction and strength notches, it is necessary to ensure that the required production technology of the structure is followed in order to prevent the creation of crack defects, both in the construction phase and during operation. That is why new structures place much stricter requirements on margins of performance specifications of used materials than in the past. This is connected with a risk of higher frequency of defects and accidents. There are currently two basic concepts of construction designs:

1) Safe-life construction design concept

2) Damage tolerance approach to construction design

2.2 Safe-life design concept

This construction design concept had been the only used philosophy until the 50's. This concept is traditional and is still used. In accordance with this philosophy there is no defect initiation and growth during the designed life of the structure. The structure must be therefore designed, manufactured and operated with such bearing capacity margins to ensure the risk of accident does not exceed the agreed value during the designed service life. The above-mentioned probability of reaching the limit state of a structure is usually extremely low (less than 5 %). After this period of time the component or structure must be taken out of operation regardless of its actual residual service life. This concept is used namely for designing key components with critical consequences of a possible defect. It is clear from what has been stated above that the concept might lead to a premature and therefore uneconomic disposal of the component. Construction designs in accordance with this concept are based on:

- tensile test results ($R_{p0,2}$, R_{eH}, R_m, A_5, Z),
- fatigue test results on smooth cylindrical objects both in the area of high cycle fatigue (life curve σ_a – N_f, Wöhler curve), as well as of low cycle fatigue (life curve ε_{at} – N_f, Manson – Coffin curve),

- bending impact test results (heat dependence of impact load, T_{28}, FATT, side extension). Determined transit temperatures are relative to minimum temperatures recommended for the concrete steel.

2.3. Damage tolerance approach to construction design

The damage tolerance approach to construction design has been gradually implemented and used since the 1970's. There are two basic differences between these approaches. The damage tolerance approach allows initiation and stable growth of defects during operation of the structure and it therefore tolerates the possibility of crack defects in a new structure caused by technological operations during the construction. In addition to cracks created prior to operation of the structure, cracks might also be initiated during the structure operation. There are three basic types of initiation:

1) Initiation induced under cyclic stress conditions A typical example are aircraft designs. However, chassis of all types of vehicles are also affected by cyclical forces. Variable forces are present also in cranes, pressure vessels and all types of rotating machines.
2) Initiation under conditions of the simultaneous action of corrosion environment and tensile stress (due to external load or internal tension). This type of nucleation (and consequently crack growth) is typical for chemical industrial equipment and for structures that are constantly in contact with the water environment.
3) Initiation under the conditions of the simultaneous action of high temperatures and tensile stress - creep at high temperatures. These conditions are typical for certain steam and gas turbines, steam boilers, etc.

The transition from the safe-life design to the damage tolerance approach led to the development and implementation of new test methods for assessment of stable crack growth and fracture behaviour of materials. A new science discipline - "fracture mechanics" has been established and a whole range of testing methods have been developed to assess the stable crack growth and fracture behaviour of materials, both in the sphere of linear fracture mechanics and elastic plastic fracture mechanics. In principle this concept can be implemented using two approaches:

a) Fail-safe approach
b) slow crack growth approach (in aviation called FSC - fly to safe crack)

2.3.1 Damage tolerance approach

The desired objective can be achieved by:

- active backup of the structure by parallel elements transferring the load. Defect of one element must not significantly reduce the bearing capacity of the concrete node and the structure as such,
- passive backup of the structure. In this case the load is transferred to secondary load bearing elements only in case of an defect of primary load bearing elements,
- using crack stopper to prevent further growth.

The structure must therefore meet specific requirements on the residual strength in case of a defect. The reliability is ensured (while allowing a structure defect) by reasonable residual strength and the operation period during which the defect is to be discovered.

2.3.2 Slow (stable) crack growth approach

This approach assumes a stable, slow crack growth. At the same time, the damage does not reach critical values during the designed service life (e.g. in case of a brittle-type fracture). The service operation is ensured by frequent inspection with high probability of discovering any defects before the end of the residual life and strength of the component.

How does a body with crack behave under the operating conditions? Depending on the operating conditions, body shape, the environment and material, the crack behaviour is determined by one of the following options:

1) the crack does not grow. The operating conditions (stress level and environment aggressiveness) do not exceed limit values required for growth.
2) the crack growth is stable. The crack growth speed is relatively small. The time required for the crack to grow through the whole load bearing cross section might exceed the designed service life.
3) the crack growth is unstable - the crack growth corresponds approximately with the sound propagation speed in the material.

Due to practical reasons it is necessary to eliminate the possibility of unstable growth. Elimination of stable (slow) growth would be desirable as well. However, practical experience shows that this cannot be achieved. Stable crack growth can be divided into three basic categories based on the operating conditions:

1) stable crack growth caused by cyclic stress, or more precisely the simultaneous action of cyclic stress and corrosion environment. Higher temperatures and presence of the corrosion environment speed up the whole process.
2) stable crack growth caused by the simultaneous action of tensile stress and corrosion environment (stress corrosion cracking)
3) stable crack growth caused by static tensile stress and high temperatures (crack growth under creep conditions).

2.4 Division of construction designs based on working temperatures

Structures are divided in terms of working temperatures to structures working in the range of temperatures where the main degradation mechanism is material fatigue, stress corrosion cracking and/or sudden unstable fracture, and to structures working in the range of temperatures where the main degradation mechanism is creep, or more precisely the combination of creep and material fatigue. The creep strength in the range of temperatures where creep applies is always lower than the material yield strength. (see Fig 2.1). "Limit temperature" T_g is the temperature where creep needs to be considered as one of the main degradation mechanisms during the construction design. It is defined as the intersection of the heat dependence of yield strength R_e ($R_{p,0,2}$) determined by a tensile test and heat dependence of the creep strength $R_{mT/t/T}$ (see Fig 2.1).

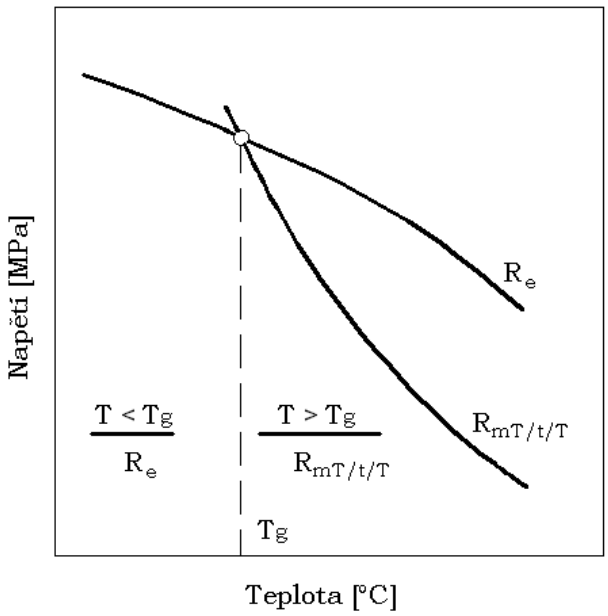

Fig 2.1 Schematic representation of the range of working temperature with application of creep as the main degradation mechanism.

$R_{mT/t/T}$ is static tensile stress leading to a defect after the time t and at temperature T and is determined by creep tests until failure. At working temperature T < Tg the creep strength is significantly higher than the yield strength and this degradation mechanism therefore does not need to be considered in the construction design. That is why static yield strength is used to determine the allowable stress (for low-alloy steel T < approximately 450°) Creep processes are present at working temperature $T \geq T_g$ and creep strength $R_{mT/t/T}$ or creep limit $R_{\varepsilon/t/T.}$ Creep strength $R_{mT/t/T}$ represent the tensile strength that causes fracture at the selected temperature and after a pre-defined period of time. Creep limit $R_{\varepsilon/t/T}$ represents the stress that causes deformation of a specific size at the selected temperature after a pre-defined period of time. Creep limit is usually defined for ε = 0.2% (for construction of turbines), or ε = 1.0 % (for construction of boilers). The usual calculation time for high-pressure boilers and turbines is 2.25×10^5 hours and 2×10^4 hours for aircraft engines.

Σ

Overview of terms: After studying this chapter you should understand the following terms:

- **Safe-life construction design**
- **Damage tolerance approach to construction design**
- **Limit temperature**
- **Creep strength $R_{mT/t/T}$**
- **Creep limit $R_{\varepsilon/t/T}$**

Questions to the covered material:

1) What types of construction designs can you name?
2) What is difference between a Safe-life and Damage Tolerance construction design?
3) What are the types of crack nucleation?
4) Into what categories can stable crack growth be divided?
5) What is the difference between creep strength $R_{mT/t/T}$ and creep limit $R_{\varepsilon/t/T}$?
6) What is determined by the limit temperature T_g?

Tasks

Determine the limit temperature T_g. from the heat dependence of yield strength $R_{p,0,2}$ and creep limit R_{mT} for 100,000 hours of steel 10CrMo9-10 (15 313, T22, 1.7380).

10GrMo9-10 Minimum contractual yield strength $R_{p0,2}$ at increased temperatures

Temperature[°C(	100	150	200	250	300	350	400	450	500
$R_{p0,2}$ [MPa]	249	241	234	224	219	212	207	193	180

10CrMo9-10 Creep strength values for 100,000 hours.

Temperature[°C]	450	460	470	480	490	500	510	520	530
R_{mT}/100 000/T [MPa]	229	212	194	177	160	141	124	105	95

Continued

Temperature[°C]	540	550	560	570	580	590	600
R_{mT}/100 000/T [MPa]	81	70	61	53	46	40	35

3. Limit state of a structure

Time to study: 1.0 hour

Aim: **After studying this chapter you should be able to:**

- **Define limit state of a structure.**
- **Define state variable.**
- **Name the factors that influence the limit state of a structure.**
- **Name the most important limit states of structures.**

Lecture

Limit state of a structure refers to the moment when the structure is no longer able to fulfill its designed function due to various reasons. Factors influencing the limit state of a structure can be divided to:

1. external factors - shape, size of the structure (wall thickness), time flow of stress forces, environment, temperature,
2. internal factors - construction material, its chemical composition, technological and heat processing.

The combination of external and internal factor can lead to some of the following limit states:

1) fatigue fracture of the structure - occurs in structures that are stressed by time-varying forces,
2) brittle fracture - this type of fracture refers to a structure fracture that occurs at a load value lower than the yield strength,
3) high temperature fracture (creep) - this type of limit state occurs in components operating at higher temperatures,

4) fracture caused by stress corrosion cracking - this type of limit state occurs in case of long-term stress with simultaneous action of tensile stress and corrosion environment,

5) excessive plastic deformation - plastic collapse of the structure,

6) elastic instability - occurs in thin components of structures stressed by a compressive force.

Limit states 1-4 are defined by a component fracture. State variable then refers to input quantities (or quantities following from input quantities) that describe (namely quantitatively) the state of the structure for the considered limit state. For example, under failure-free conditions, the following variables might appear:

- reduced stress $\sigma_{red.}$
- stress intensity factor K
- crack size
- accumulated damage during cyclic stress D = n/N (n is the number of applied cycles, N is the number of cycles until failure)

By far the most common and most important limit state from the engineering point of view is the fatigue fracture or corrosion fatigue faction that represents 80 % of all operating fractures. Other important limit states include brittle (sudden instable) fracture, creep fracture and corrosion cracking fracture.

Overview of terms: After studying this chapter you should understand the following terms:

- **Mechanical properties of construction materials**
- **Basic and special mechanical properties.**
- **Limit state of a structure**
- **State variable**

Questions to the covered material:

1) What is the limit state of a structure?

2) What factors influence the limit state of a structure?

3) What does state variable mean?

4. Controlled ageing of construction components

Time to study: 1.5 hours

Aim: **After studying this chapter you should be able to:**

- **Define safety margin.**
- **Define safety coefficient.**
- **Define structure ageing.**
- **Name the factors that influence the structure ageing.**
- **Define controlled ageing of construction components.**
- **List the steps of the controlled ageing process.**

Lecture

The safety margin of operation of critical components of equipment operated on a long-term basis determined in the construction design might be significantly reduced during the planned service life due to their ageing (see Fig 4.1). "Safety margin" refers to the level safety ensuring integrity and operational reliability of critical components of the equipment for standard operating conditions. It can be expressed by the safety coefficient k_p

$$k_p = \frac{S}{\sigma_{max.}} \qquad (4.1)$$

where

S is the material strength ($R_{p,0,2}$ and/or ultimate strength R_m)

$\sigma_{max.}$ is the maximum allowable stress

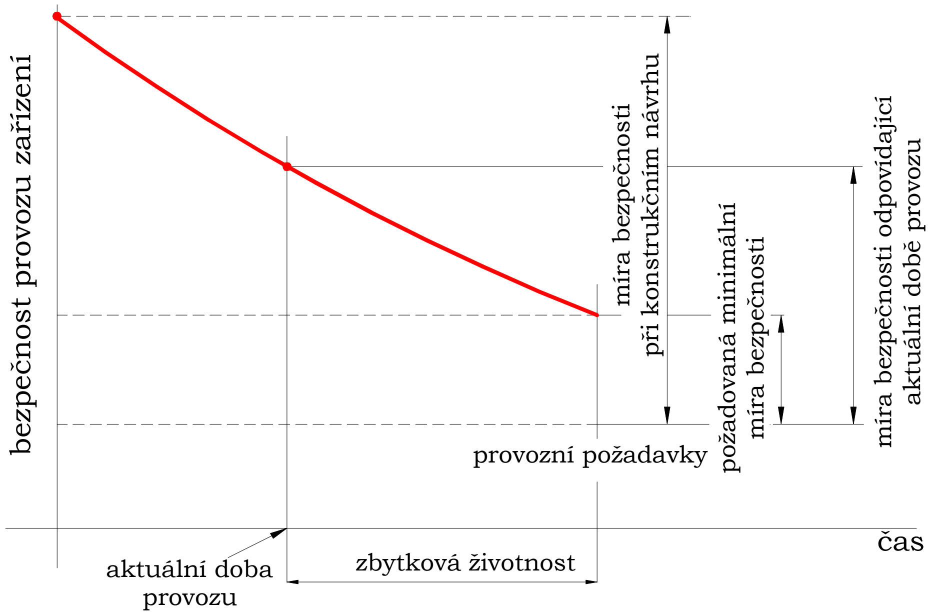

Fig. 4.1 Effect of long-term operation on the safety margin of the operated equipment

In addition to the maximum allowable stress, designs of construction components operating at lower temperatures also consider the transition temperature criterion TT.

$$T_{min.} = TT + \Delta T \qquad (4.2)$$

where

$T_{min.}$ is the minimum working temperature of the component

TT is the transition temperature

ΔT is the increment to the transition temperature.

It can vary depending on:

- ❖ the scope and frequency of exceeding the designed operating conditions (operating conditions considered in the construction design),
- ❖ change of material properties during long-term operation of the equipment.

Structure ageing refers to processes that can lead to the following during the structure's service life:

1) changes of material properties caused by

a) heat-activated processes (relaxation of stress and internal tension, disintegration of the original structure, precipitation of secondary phases, their growth and coarsening)

b) deformation induced actions (strain ageing, strain hardening/softening caused by action of time-varying external forces)

2) application of degradation mechanisms, such as fatigue or corrosion fatigue, corrosion cracking, creep, hydrogen embrittlement, radiation embrittlement, areal corrosion, localized forms of corrosion, erosion.

The application of these processes depends on:

- material properties of the starting semi-finished products,
- technological procedures used during the equipment production,
- properties of the surrounding environment,
- operating conditions.

Degradation of material properties can lead to loss of operational reliability or even to loss of integrity of the operated equipment due to initiation and growth of cracks caused by application of some of the limit states related with loss of cohesion. Limit state of a structure refers to the moment when the structure is no longer able to fulfill its designed function due to various reasons. Relevant criteria (connected with the ability of the product to fulfill the required function due to technical, economic, ecological or other serious reasons) and limit values must be determined in technical conditions that are governed by standards, directives or mutual agreement. Structure defect analyses prove that failure causes can be divided into four basic categories:

1. unsuitably used material,
2. errors in the design and construction,
3. defects in production and assembly,
4. unsuitably operated equipment.

Controlled ageing of construction elements refers to the prediction and/or detection of the moment when the degradation of a structure or its part reaches a stage where the minimum required safety margin is reached (and when corrective measures are required). The controlled ageing process consists of three basic steps:

1) Selection of structure parts or machinery components important in terms of the structure safety
2) Definition of dominant ageing mechanisms in the selected parts and definition and development of methods for monitoring and mitigation of component ageing. A combination of several mechanisms might contribute to the ageing process.
3) Controlling ageing using efficient procedures during the equipment operation and maintenance (optimization of operation modes, optimization of operating inspection intervals, optimization of the long-term repair plan). The state of safety can be monitored using measurements and assessment of operating parameters and conditions.

The following chapters provide descriptions of ageing mechanisms of construction materials caused by heat and strain ageing and the main degradation mechanisms applied
during long-term operation of structures and equipment working at high temperatures, including material fatigue, creep and stress corrosion cracking.

Σ

Overview of terms: After studying this chapter you should understand the following terms:

- **Safety margin.**
- **Structure ageing.**
- **Limit state of a structure.**
- **Controlled ageing of construction components.**
- **Safety coefficient.**

Questions to the covered material:

1) What does safety margin mean?
2) What is structure ageing?
3) Which processes belong to heat-activated processes?
4) Which degradation mechanisms can you name?
5) What are the main reasons of structure failures?
6) What does controlled ageing mean?
7) What other criterion, in addition to the maximum allowable stress, plays an important role when designing construction components operating at lower temperatures?

5. Ageing mechanisms of construction materials

Time to study: 1.5 hours

Aim: **After studying this chapter you should be able to:**

- **Define ageing.**
- **Name the two basic types of ageing.**
- **Describe the basic principle of ageing.**
- **Name the most serious forms of embrittlement.**
- **Generally characterize strain ageing.**
- **Define the two stages of strain ageing.**
- **Describe the characteristics of dynamic strain ageing.**

Lecture

Ageing of material is gradual (due to time or use) deterioration of mostly mechanical and physical properties. There are two basic types of ageing:

1) thermal ageing,
2) strain ageing.

Based on the temperature during which ageing occurs we can distinguish:

- natural ageing (occurs at ambient temperature)
- ageing at higher temperatures.

5.1 Thermal ageing

Thermal ageing represents a process of change of material properties due to the disintegration of oversaturated solid ferrite solution over a long period of time without any external mechanical load. In literature this process is called Thermal Aging Embrittlement, Thermal Aging. Ferrite, a solid solution of carbon and other interstitial and substitution elements in iron α, is an important phase of ferritic steels. Interstitial elements (namely C and N), the presence of which in steels always needs to be taken into consideration, cause relatively significant changes of properties even in small amounts. The stability of this interstitial hardening might be quite low and property changes might become obvious even at ambient temperature. Changes that take place in the solid solution are referred to as disintegration of oversaturated solid solution. The possibility of solid solution oversaturation is caused by decreasing solubility of carbon and nitrogen in ferrite when the temperature drops. The basic principle of ageing is the interaction of carbon and nitrogen atoms with dislocations and/or precipitations of equilibrium or non-equilibrium structural phases containing C and N. Ageing manifests especially in low carbon steel, namely up to 0.2 % C, because in higher content steel the property changes are covered by the effect of the contained pearlite. Ageing gradually leads to:

- decreased ductility, notch toughness and fracture toughness of the material
- increased transition temperature,
- increased lower and upper limit of notch toughness.

The progress of ageing and property changes depends on the degree of oversaturation by C and N atoms. There exist different forms of thermal ageing, whereas a whole range of them can lead to a brittle fracture of the given component. The most serious forms of embrittlement include:

- **blue brittleness** is caused by nitrogen that enters the steel during the production process; heating of this steel increases the rigidity and hardness and reduces toughness. The largest brittleness is achieved at 300 °C, when the steel turns blue in contact with the air.
- **Quench-age embrittlement** This ageing occurs in low carbon steels due to the ferrite oversaturation with carbon and nitrogen. The embrittlement is usually caused by fast cooling of the steel from temperatures closely below A_{C3} and it can be minimized by quenching at lower temperatures.
- **Ageing in the temperature range of 400 – 550 °C (reversible embrittlement).** Embrittlement in this range of temperatures occurs in alloyed construction steels.

Development of this embrittlement depends both on temperature and time. If the steel is operated in this critical temperature interval, the notch toughness might decrease significantly (see Fig 4.1). Embrittled steel can be "restored" by heating above this temperature interval. This type of embrittlement is supported by P if its content exceeds 0.015%. In addition, Ni also has a negative effect, especially in combination with P. Sensitivity to this embrittlement can be reduced by adding 0.15 – 0.50 % Mo.

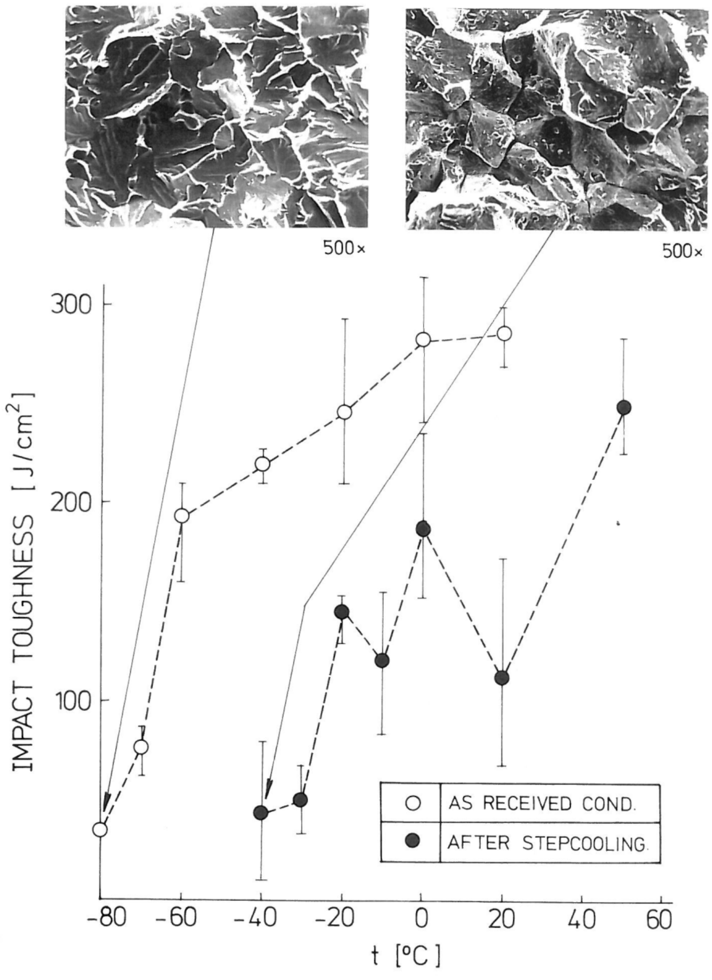

Fig 5.1 Temperature dependence of notch toughness of steel 10GN2MFA in the delivered state and after slow (240 hours) step-cooling from a temperature of 595 °C.

- **Embrittlement at a temperature of 475 °C.** This embrittlement occurs in ferritic chromium steels that contain more than 13 % of chromium. The embrittlement is created at a temperature range of 400 to 550 °C. This embrittlement is named by the temperature that causes it most significantly. Steels with a Cr content exceeding 25 % only require several minutes at a temperature of 475 °C. That is why tempering temperatures within the range of 400 to 600 °C are not used for chromium stainless steel. Prolonged exploitation at higher temperatures of all types of stainless chromium and austenitic carbide-nickel steels leads to priority precipitation of chromium carbide along grain borders and steels are susceptible to intercrystallic corrosion.

- **Embrittlement at a temperature of 500 –570 °C.** Precipitation of certain carbides (Mo_2C, W_2C, V_4C_3) in steels alloyed with carbide-forming elements is associated with an increase of hardness. This phenomenon is successfully used namely for low-alloy CrMo and CrMoV fire-resisting steels (15128, 15313). It is called secondary hardening. However, it leads to a reduced notch toughness. That is why these types of steel must be used in a so-called "overaged" state when working at higher temperatures, i.e. a state where tempering at a sufficiently high temperature results in coarsening of carbides/nitrides and the toughness is again increased (see Fig 4.2).

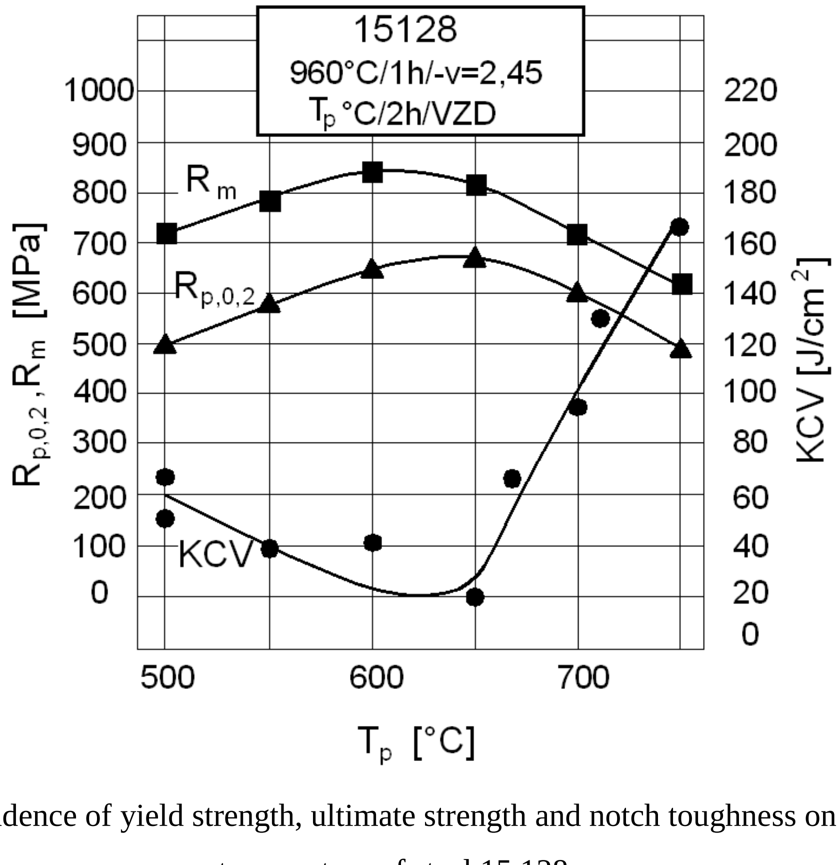

Fig. 5.2 Dependence of yield strength, ultimate strength and notch toughness on tempering temperature of steel 15 128

5.2 Strain ageing

Strain ageing refers to a process consisting of material property changes after and/or during plastic deformation. There are two types of deformation ageing:

1) static strain ageing, where material properties change after plastic deformation,
2) dynamic strain ageing, where material properties changes during deformation.

Signs of this type of ageing can also be found in approximately equilibrium steels, i.e. where the solid iron solution α is not significantly oversaturated by interstitial elements. This is caused by filling of free dislocations that were created during forming by carbon and nitrogen atoms from solid solution α. In carbon and low-alloy steels, more important role in this process is played by nitrogen, namely due to its better solubility in iron α.

5.2.1 General characteristics of strain ageing

σ – ε dependence during the tensile test at an ambient temperature of low-carbon annealed steel corresponds to curve "a" represented in Fig 4. 3. If the test object is under tensile stress up to point A over its lower yield strength (see Fig 4.3), then unstressed and immediately stressed again, then the σ – ε dependence will follow the same curve (curve "a") and there will be no sharp yield point (neither upper $R_{eH,}$ nor lower R_{eL}) as at the beginning of stressing (see point B).

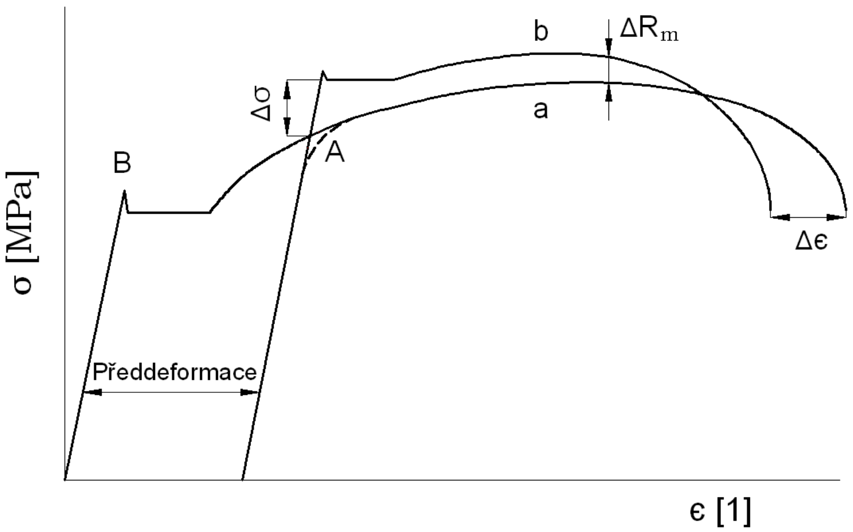

Fig. 5.3 σ – ε dependence for low-carbon annealed steel after stressing up to point A, subsequent unstressing and immediate repeated stressing (curve "a") and after stressing after ageing (curve "b")

However, if the test object is unstressed in point A and then is aged at ambient or increased temperature, repeated stressing will lead to a sharp yield point and the achieved dependence then corresponds to curve "b" in Fig 5.3. The yield strength measured after ageing is higher. Increase of the yield strength is a characteristic sign of strain ageing. The ultimate strength R_m can also increase and ductility A and contraction Z can decrease; however, these changes might not always occur. Strain ageing affects other mechanical and physical characteristics of the material:

- transition temperature malleable – brittle fracture
- fatigue limit
- electrical and magnetic properties
- Creep strength

If we remove C and N from the steel, the occurrence of a sharp yield point and strain ageing is reduced. Sharp yield point and ageing are caused by migration of C and N atoms to dislocations and subsequent limitation of their movement.

5.2.2 Static strain ageing after tensile deformation

Changes observed in material characteristics determined by a tensile stress after strain ageing are interpreted within two stages of the ageing process.

In the first stage C and N atoms migrate to dislocations and create Cottrell atmospheres. In this stage the affected characteristics are the lower yield point R_{eL}, Lüders deformation and transition temperature determined by bending impact tests. $\sigma – \varepsilon$ dependence in the area of hardening, the ultimate strength R_m, ductility A and contraction Z are not affected since the atmospheres are dispersed. . Occurrence of only the first ageing stage is typical for steels with low content of C and N.

The second stage is characterized by formation of precipitates on dislocations. Precipitation causes increased yield point, ultimate strength, hardening speed and decreased ductility A and contraction Z. Long ageing periods, namely at increased temperatures, might lead to overaging. This is characterized by a slight decrease of the yield point, ultimate strength and slight increase of ductility and contraction due to coarsening of precipitates. Overaging occurs at temperatures exceeding 250 °C. The ageing speed increases at higher temperatures. However, changes of mechanical properties are not significantly influenced by temperature.

5.2.3 Dynamic strain ageing

At a temperature range of 125 ÷ 300°C low-carbon steels show signs of increased speed of strain hardening accompanied by increased ultimate strength R_m and decreased ductility A. At the same time, the shape of the σ – ε curve changes from smooth to "serrating yielding") (See Fig 5.4)

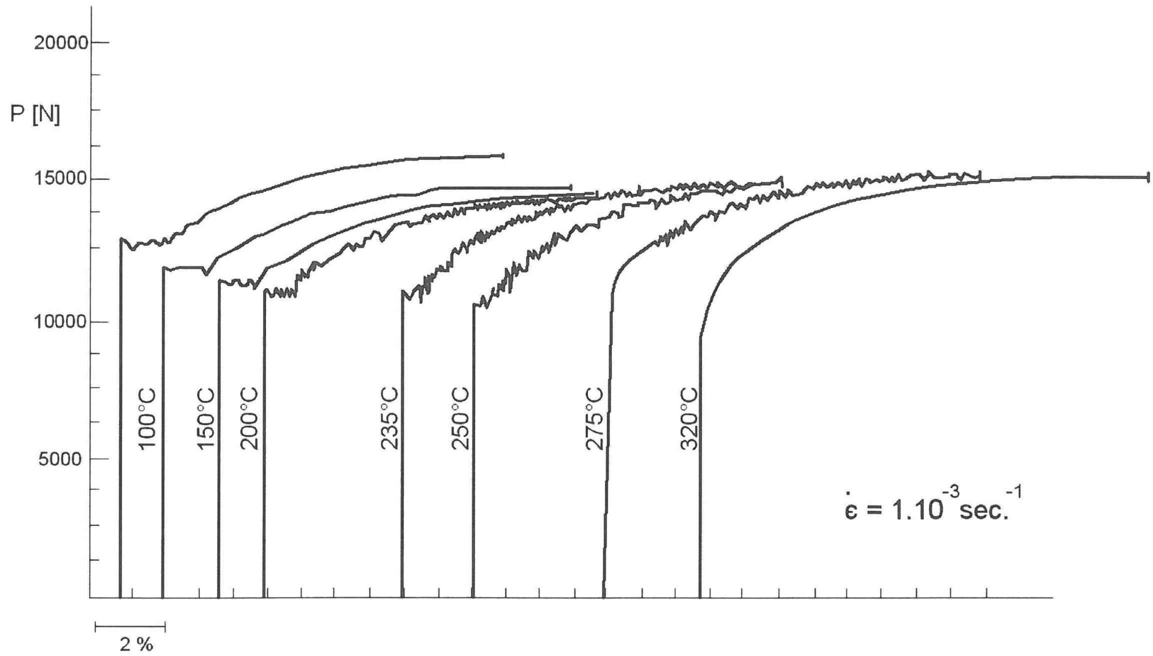

Fig 5.4 Strength - deformation dependence for steel 10GN2MFA at a temperature range of 100°C – 320°C.

Fig 5.5 represents Wöhler curves of fire-resistant steel 12 021.1 at an ambient temperature and temperature of 300 °C. Higher fatigue strength and increased area of slanted branch of the Wöhler curve at 300 °C are caused by dynamic strain ageing of steel.

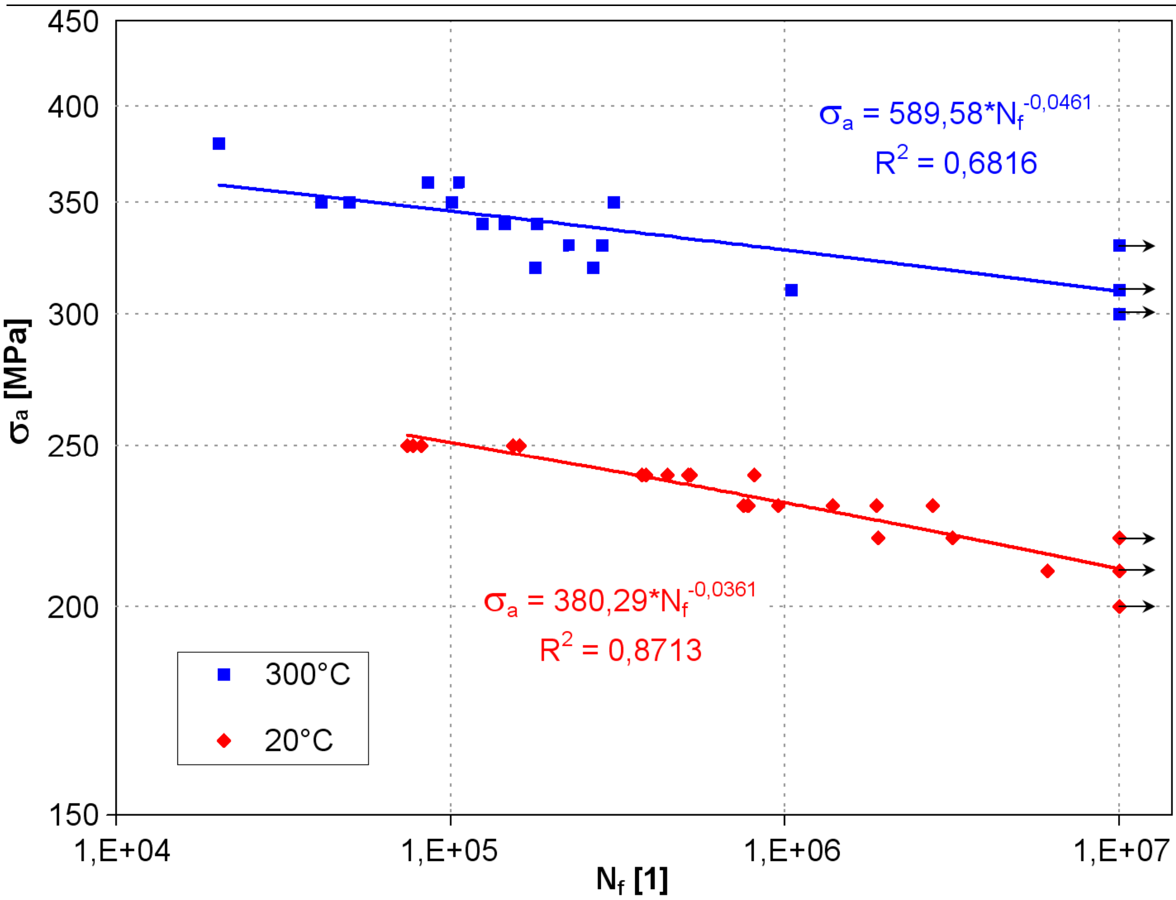

Fig 5.5 Wöhler curve of steel 12 021.1 at ambient temperature and temperature of 300°C

Σ

Overview of terms: After studying this chapter you should understand the following terms:

- **Material ageing.**
- **Thermal ageing.**
- **Deformation ageing**
- **Quench-age embrittlement.**
- **Blue brittleness.**
- **Embrittlement at a temperature of 475 °C.**
- **Embrittlement at a temperature of 500 – 570 °C.**
- **Static and dynamic strain ageing.**

Questions to the covered material:

1) What does material ageing mean?
2) What are the two basic types of ageing?
3) What is the basic principle of ageing?
4) What are the most serious forms of ageing?
5) What are the types of strain ageing?
6) What is a characteristic for dynamic strain ageing?
7) Which mechanical and physical characteristics are affected by strain ageing?

6. Material fatigue

Time to study: 2.5 hours

Aim: **After studying this chapter you should be able to**

- **Define material fatigue.**
- **Define vibration and cyclic stress.**
- **Define cycle asymmetry.**
- **Describe individual methods of cyclic stress depending on the cycle asymmetry.**
- **Explain the difference between a high-cycle and low-cycle fatigue.**
- **Describe individual stages of the fatigue process.**
- **Name the basic characteristics of material fatigue.**
- **Describe three stages of the growth of fatigue crack in the air at ambient temperature.**
- **Define the threshold value of the stress intensity factor for growth of fatigue cracks K_p.**

Lecture

The following chapter is dedicated to degradation the degradation process caused by time-varying external stress.

6.1 Definition of material fatigue

If a component and structure is exposed to variable external forces, they can fracture after a certain period of time, even though the maximum stress level is significantly lower than the material yield strength. The material undergoes a gradual failure process, so-called material fatigue. The existence of

fatigue of metals is conditioned and determined by cyclic plastic deformation. Cyclic plastic deformation can be caused by mechanical or thermal load or the
combination of both. For instance, cyclic plastic strain amplitude at the fatigue limit (stress amplitude that does not cause fatigue fracture) is in the 10^{-5} order regardless of the type of material. One-way, non-recurring deformation of this order does not lead to any significant changes in the material structure or its properties. Only multiple repeating of plastic deformation, despite being so small that generally speaking it represents an elastic load, leads to cumulative damage resulting in fatigue fracture.

If the number of cycles until failure is in the 10^5 order and above, it is referred to as high-cycle fatigue; if the number of cycles until failure is 10^4 or less, it constitutes low-cycle fatigue. This division should be considered a convention, even though there is no deeper reason behind it.

If the direction of external forces of the same maximum size in both directions changes, it is considered alternating stress. If only the size changes in time and not the direction, the stress is considered transient or pulsating. A common example with different force amplitudes and different character of their time variability is called vibration stress. If the variability of forces has stabilized to have the same highest and lowest points at the same change frequency, it is considered simple cyclic stress that constitutes a special example of vibration stress.

Cycle characteristics in simple cyclic stress can differ depending on the ratio of the highest and lowest stress (see Fig 6.1). Mean cycle stress σ_m and stress amplitude σ_a can be expressed by the following relations

$$\sigma_m = \frac{\sigma_h + \sigma_d}{2}, \sigma_a = \frac{\sigma_h - \sigma_d}{2} \quad (6.1)$$

Cycle asymmetry can be expressed by the following relations

$$R = \frac{\sigma_d}{\sigma_h} \quad (6.2)$$

or

$$P = \frac{\sigma_h}{\sigma_a} \tag{5.3}$$

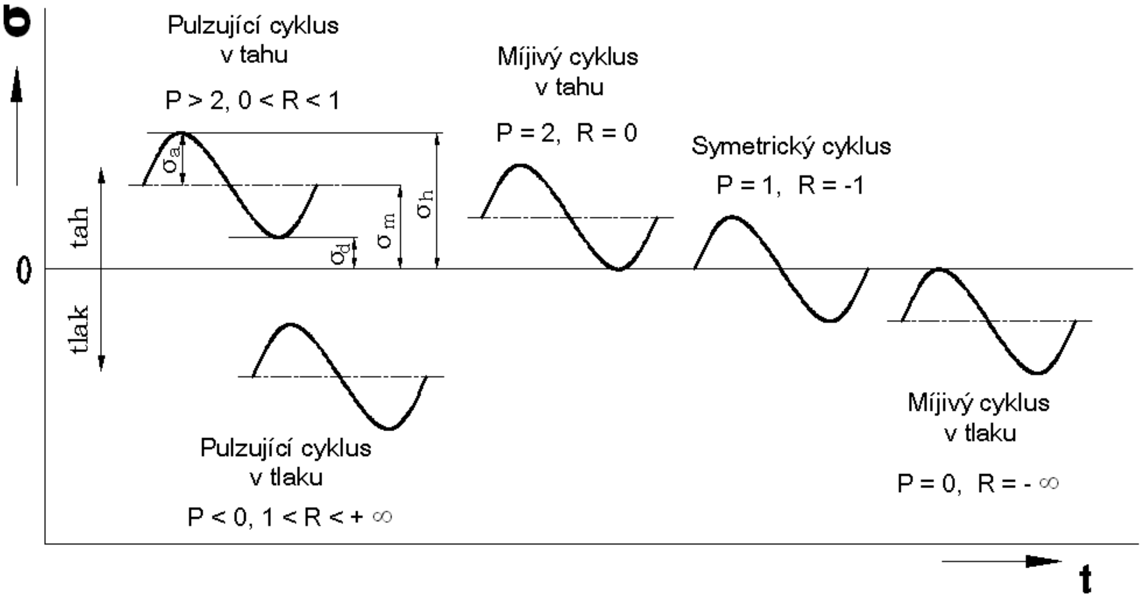

Fig 6.1 Schematic representation of individual types of cyclic stress

The whole fatigue process can be divided approximately into three stages. (see Fig 6.2).

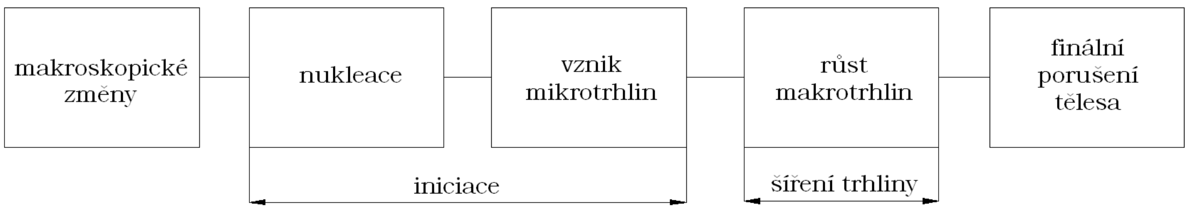

Fig 6.2 Chronology of individual stages of the fatigue process in an object without technological defects.

6.2 Stages of the fatigue process

6.2.1 Stage of changes of mechanical properties

This stage is characterized by changes in the whole volume of stressed metal. During cyclic stress, mechanical properties change first due to the changes in density and spatial arrangement of grid defects. In this context mechanical properties refer to such properties that characterize material resistance to deformation caused by external forces (yield strength, ultimate strength, dependence of stress amplitude on strain amplitude during the cyclic stress). The material resistance to cyclic deformation might increase (cyclic hardening) or decrease (cyclic softening) during the fatigue process, depending on the type of material, stress conditions and temperature. However, significant changes recede after a certain number of cycles - mechanical properties become saturated. The best method to detect mechanical properties is direct measurement of hysteretic loop parameters - dependences of stress amplitude ($_a$ on the total deformation amplitude ($_{at}$ measured during cyclic stress (see Fig 6.2).

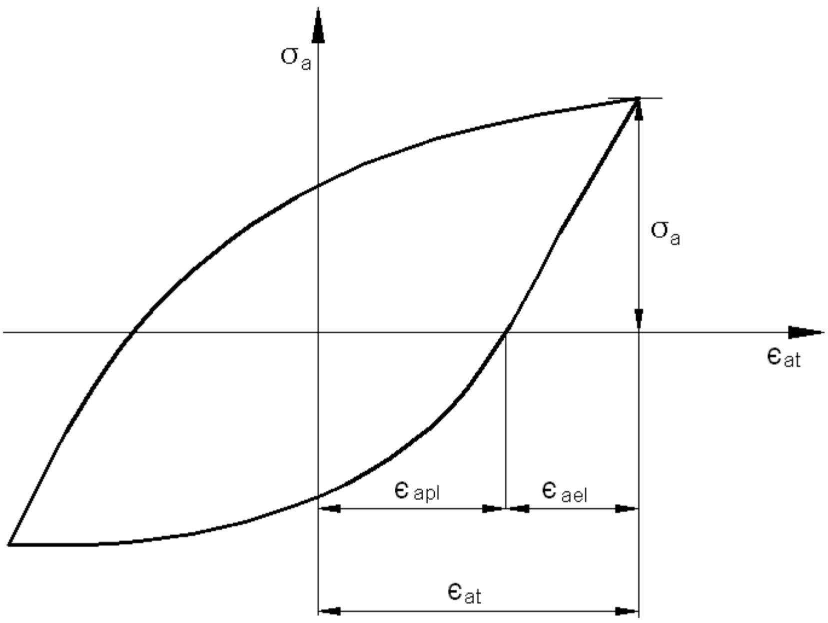

Fig. 6.2 Schematic representation of a hysteretic loop

Cyclic hardening is typical for annealed materials. Cyclic softening, on the other hand, is typical for material hardened by

- strain hardening
- precipitation hardening
- hardening by martensitic transformation
- dispersive hardening by foreign particle in the matrix

If the ration of the ultimate strength R_m to yield strength (R_e,R_p0,2) exceeds 1.4, cyclic hardening will occur. If this ratio is lower than 1.2, cyclic softening will occur. After the end of the stage of mechanical property changes, the stress amplitude as well as the deformation amplitude reach their saturated values and a stable hysteretic loop is created.

A curve placed through peak points of stable hysteretic loops shows the dependence between the stress amplitude and the plastic strain amplitude in a stabilized state that is referred to as cyclic stress-strain curve. This is a very important material characteristic because it describes the plastic reaction of metal for most of its service life. All experimental data, both for low-cycle and high-cycle spheres, point to the conclusion that the cyclic stress-strain curve can be expressed by the following relation (6.1)

$$\sigma_a = K.(\varepsilon_{apl})^n \qquad (6.1)$$

where K is the cyclic strength coefficient

n´ is the fatigue hardening exponent

The tensile diagram represents the dependence on deformation in the first quarter-cycle; the cyclic stress-strain curve represents the same dependence after hardening and/or softening of the material.

6.2.2 Crack initiation stage

At the end of the stage of mechanical property changes, subtle slip lines are created on the surface. Complex slip bundles called "persistent slip bands" are formed with increasing number of cycles. Persistent slip band are located in crystallographic slip planes, which are typical for the given type of metal and its atomic structure. Fatigue microscopic cracks are created in the persistent slip band, namely in the rugged surface relief that form very sharp notches. A microscopic crack is created when the stress concentration surrounding surface notches cannot be relaxed by slip processes in the surrounding matrix.

6.2.3 Crack growth stage

In the first stage of its growth the crack spreads in the slip band and in crystallographic planes of surrounding grains (see Fig 6.3). As the crack length increases, the crack deflects from the slip plane and turns perpendicularly towards the main stress and it is possible to identify a plastic zone at its front caused by high-concentration stress. This second stage is referred to as the macroscopic crack growth stage. The crack length for transition from the first stage (called short crack stage) to the macroscopic crack growth stage depends namely on the type of material and ranges between 0.1 and 1.00 mm. Dependence of the growth speed of short cracks on their size is represented in Fig 6.4.

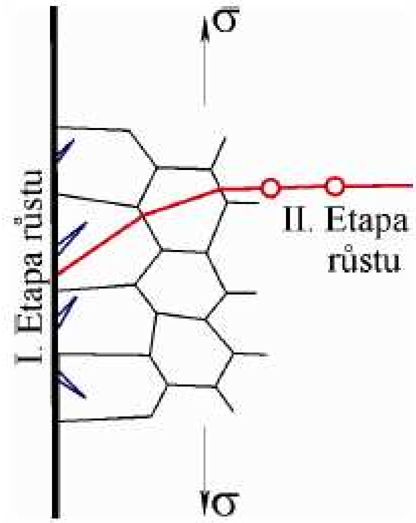

Fig 6.3 Schematic representation of two stages of fatigue crack growth.

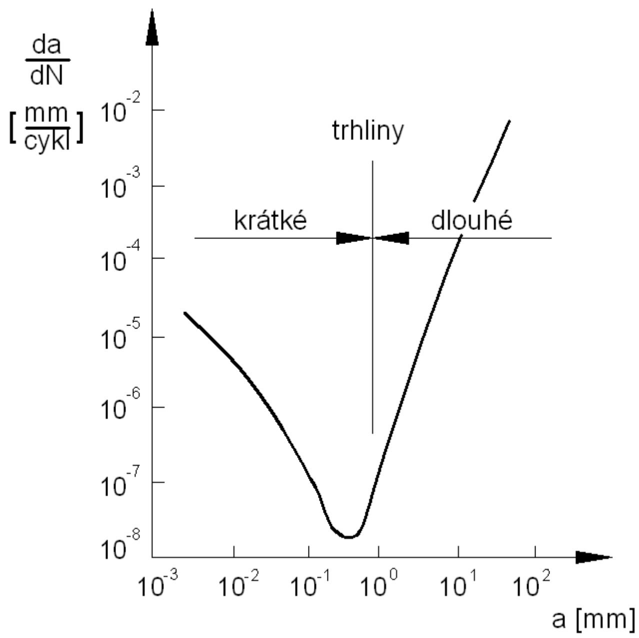

Fig 6.4. Dependence of the growth speed of short cracks on their size

Dependence of the growth speed of macroscopic fatigue cracks on the stress intensity factor amplitude ΔK on air at ambient temperature is schematically represented in Fig 6.5. As shown in this picture, the log da/dN vs. log (K dependence can be divided into 3 basic areas (A, B, C) in terms of the range of fatigue crack growth. In the area of slow fatigue crack growth ($10^{-8} \div 10^{-6}$ mm / cycle) and therefore in the area of low

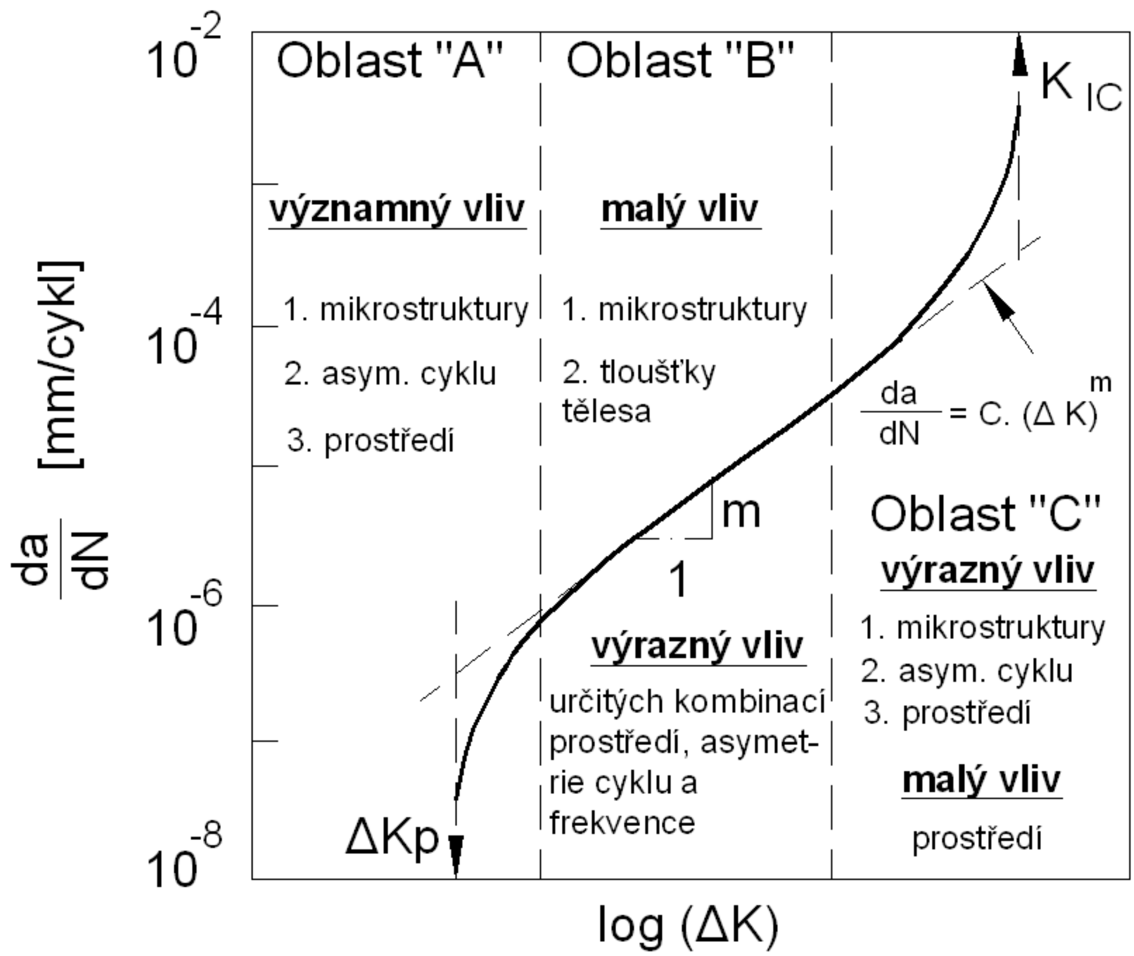

Fig 6.5 Schematic representation of general shape of the da/dN vs. ΔK dependence without the presence of corrosive environment.

values of the stress intensity factor amplitude ΔK (area A), the da/dN vs. ΔK dependence is asymptotic to the threshold value ΔK_p, under which macroscopic fatigue cracks cease to grow. The growth speed of macroscopic fatigue cracks in this area strongly depends on the material microstructure and asymmetry of the R cycle. In the middle range of speeds (area B), where the growth speed of macroscopic fatigue cracks ranges within 10^{-6}- 10^{-4} mm/cycle, the curve in log-log coordinates is linear and fatigue crack growth speed can be expressed by the Paris-Erdogan's relation:

$$\frac{da}{dN} = C(\Delta K)^m \qquad (6.2)$$

where c, m are material constants

The crack growth speed in this area is not very sensitive to the material microstructure and thickness of the test object. At high crack growth speeds (area C), when the maximum stress intensity factor approaches fracture toughness K_{IC} during the load cycle K_{max} , the crack growth is usually increasingly affected by other failure micromechanisms that are present usually at static fractures (transcrystalline malleable or fissile fractures, intercrystallic decohesion) and the crack growth becomes sensitive to macrostructure and asymmetry of the R cycle. From a practical point of view this area is not very significant since it applies only for a relatively small percentage of all stress cycles. Fig 6.6 shows the study results of the impact of the cycle asymmetry on the fatigue crack growth kinetics in low-alloy steel 38ChN3MFA.

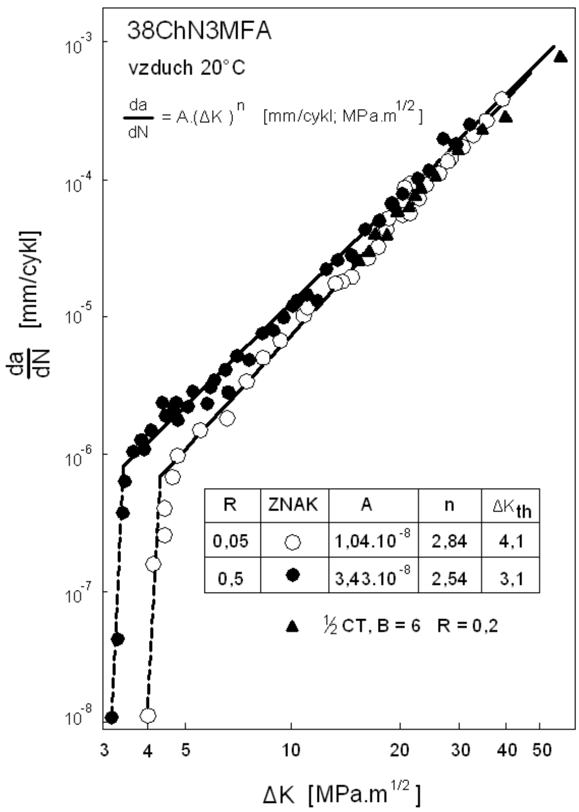

Fig 6.6 Impact of the cycle asymmetry on the fatigue crack growth kinetics on air and at ambient temperature in low-alloy steel 38ChN3MFA.

Fig 6.6 clearly shows that the change of cycle asymmetry from R = 0.5 to R = 0.05 affect namely the threshold value of stress intensity factor ΔKth.

The fatigue crack morphology is characterized in many metals and alloys by fatigue striation (see Fig 6.7). Fig 6.8 represents the dependence of macroscopic speed of fatigue crack growth and fatigue striation spacing on ΔK for low-alloy steel 10GN2MFA. A comparison of the dependences of the macroscopic speed of fatigue crack growth and fatigue striation spacing on ΔK clearly shows that the validity area of Paris' law can be divided into two sections: For ΔK < 20 MPa.m$^{1/2}$ the macroscopic speed of fatigue crack growth is significantly lower than the fatigue striation spacing. This fact can be interpreted as a result of so-called "blank cycles" that do not increase the fatigue crack length. For ΔK > 20 MPa.m$^{1/2}$ the striation spacing corresponds to the macroscopic speed of fatigue crack growth.

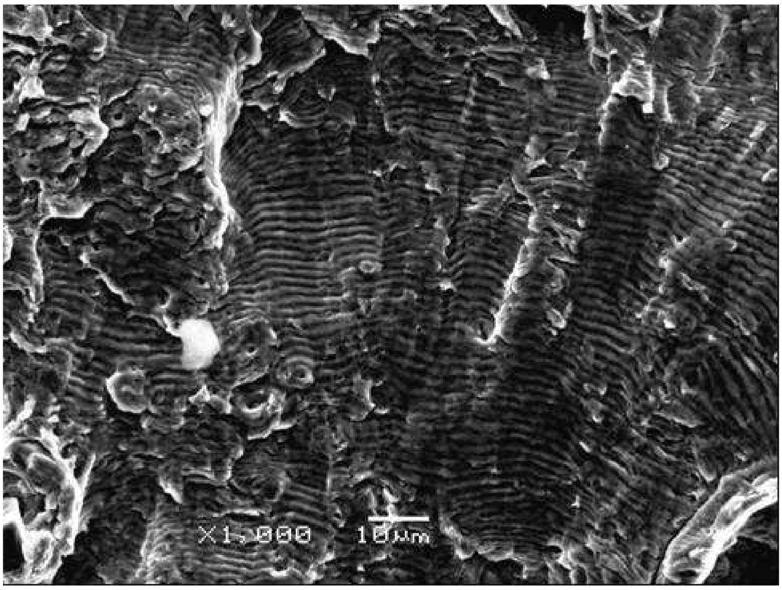

Fig 6.7 Striation on a fracture surface of a test object made of steel 08Ch18N10T, air-cycled at ambient temperature

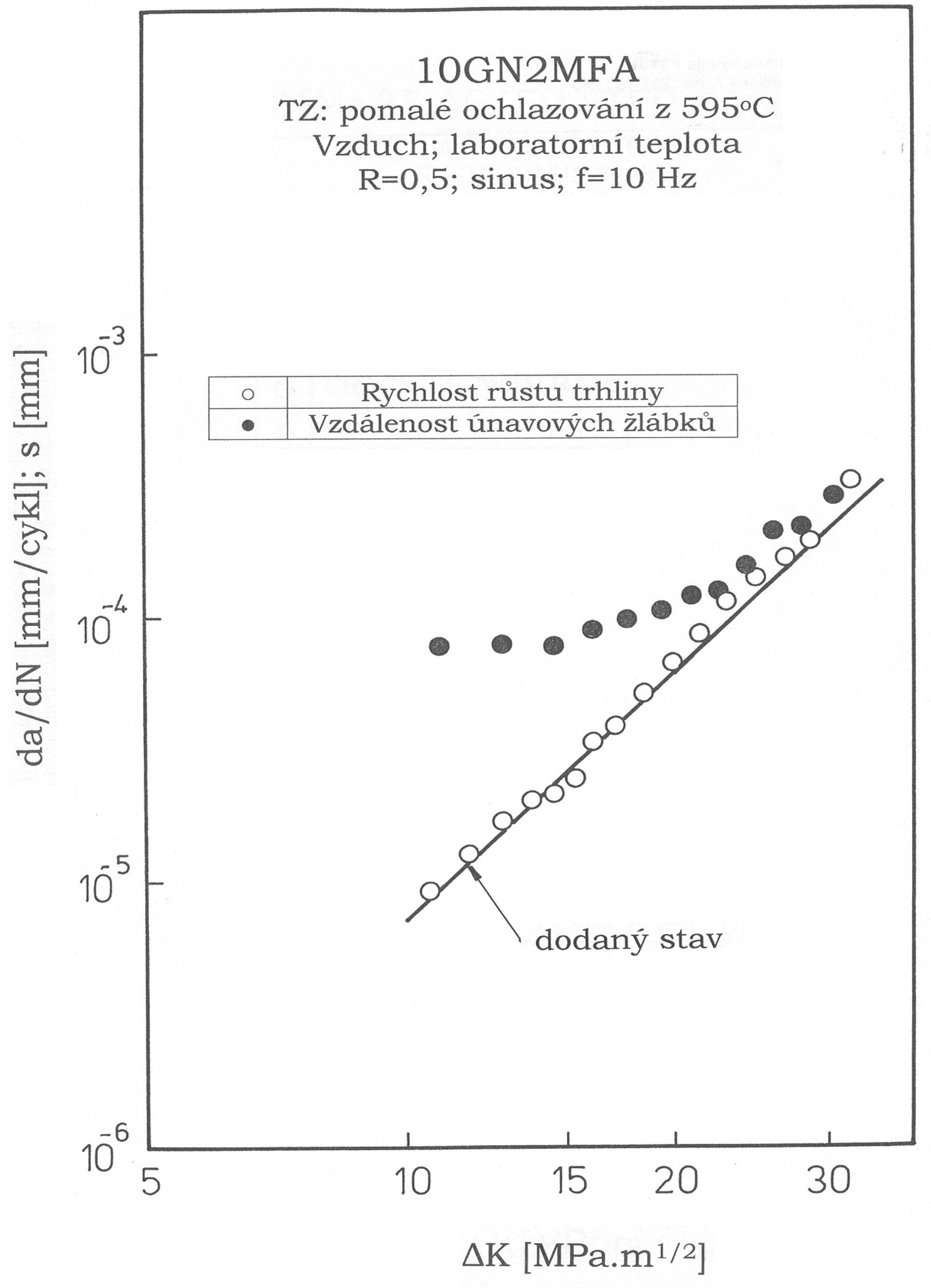

Fig 6.8 Measurement results of macroscopic speed of fatigue crack growth and fatigue striation spacing on ΔK.

6.3 Mechanical characteristics used to calculate cyclically stressed components.

6.3.1 Total life curve σ_a – N_f (Wöhler curve)

The Wöhler curve was named after its author, who studied the fatigue strength of vehicle chassis based on rotating bending tests over 130 years ago. It is used to express the dependency of stress amplitude σ_a on the number of cycles until fracture N_f. Usually, smooth cylindrical test objects are subjected to homogenous tensile-compressive stress (R = -1) or transient tension (R = 0); sometimes alternating bending, i.e. rotating bending, is used. The Wöhler curve is characterized by an increase of the number of cycles until fracture together with a decrease of the stress amplitude. A typical curve in log σ_a – log N_f coordinates is schematically represented in Fig 6.9.

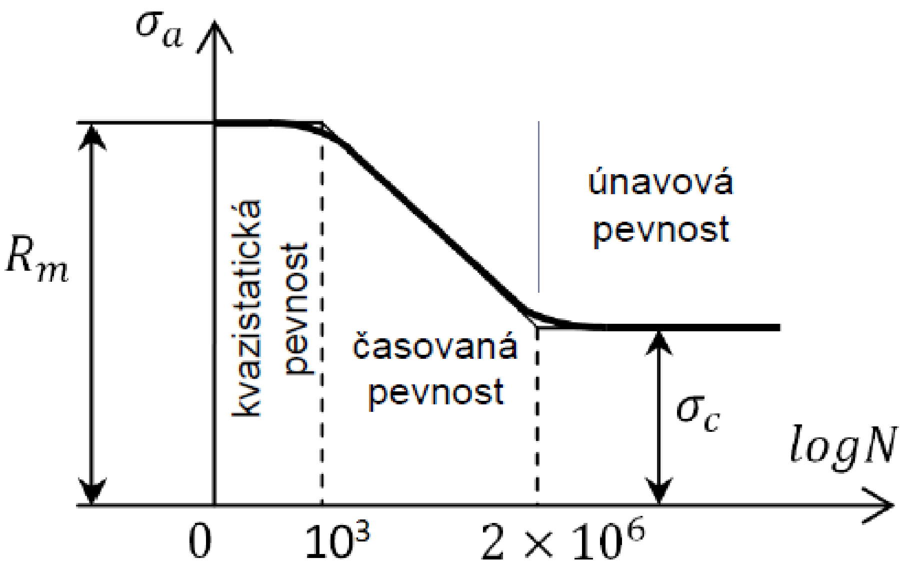

Fig. 6.9 Schematic representation of the σ_a – N_f life curve (Wöhler curve)

The stress amplitude that no longer causes fatigue fracture is called the fatigue strength. Fatigue strength in alternating tension-compression (R = -1) is referred to as σ_c, fatigue strength in transient tension (R = 0) is referred to as σ_{hc}. The occurrence of fatigue strength is typical for steels with BCC grid and for certain other interstitial alloys. Fatigue strength is not observed in metals and alloys with cubic face centered grid (austenitic steels, Al-based alloys) even after the application of 10^7 to 10^9 cycles and the stress amplitude decreases as the number of cycles to failure increases. A so-called contractual fatigue strength is used in these situations, i.e. it is determined by the stress amplitude that does not lead to fatigue fracture after a pre-defined number of cycles. The standard number of cycles for determining the fatigue strength of steels, cast iron, copper and their alloys is $N_f = 10^7$. At least 8 test rods constitute a group for the purposes of determining the slant branch of the fatigue curve. Dependencies in $\log \sigma_a - \log N_f$ or $\sigma_a - \log N_f$ coordinates are interlaced with values measured on rods of one group in the time strength area. These dependencies are represented by regression curves with a survival probability of 50 %.

The Wöhler curve and the fatigue strength are influenced not only by the R cycle asymmetry but also by the temperature, presence of corrosive environment and metallurgical properties of the material. Fig 6.10 represents the impact of the level of forging on the slanted branch of the Wöhler curve and on the fatigue strength for $N = 1x10^7$ cycles for steel 16540.6.

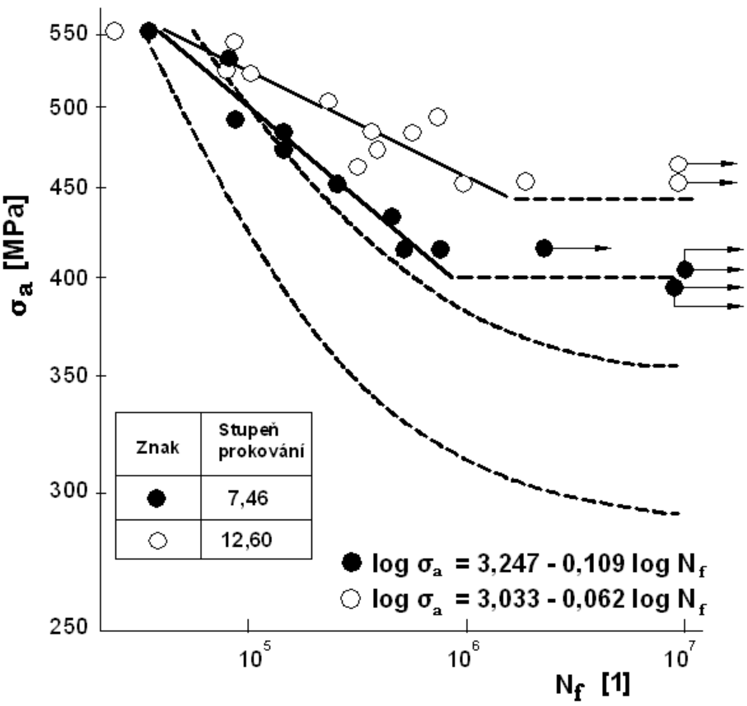

Fig 6.10 Impact of the level of forging on the slanted branch of the Wöhler curve and on the fatigue strength for $N = 1x10^7$ cycles for steel 16540.6.

6.3.1.1 Impact of mean cycle stress σ_m on fatigue strength.

Fatigue strength is crucial for most practical calculations of the majority of components under cyclic stress since it determines the permanent fatigue strength. Basic Wöhler curves are usually determined for the two most important cycle types, i.e. the alternating cycle with R = -1 and transient cycle with R = 0. For instance, σ_c = 0.36 for alternating tensile-compressive stress for steels with the ultimate strength R_m ranging from 500 MPa to 1500 MPa. R_m, transient tensile fatigue strength σ_{hc} = 0.59. R_m, torsional fatigue strength τ_{kc} = 0.21. R_m, transient torsional fatigue strength τ_{hc} = 0.1. R_m and rotating bending fatigue strength σ_{oc} = 0.36. R_m.

Many machine components are subjected to cyclic stress with non-zero mean stress. Between alternating tensile - compressive strength and transient cycles lies an area of alternating tensile stress (- 1 < R < 0). Between alternating tensile stress and static tensile stress lies the area of pulsating tensile stress (0 < R < 1), (see Fig 6.1).

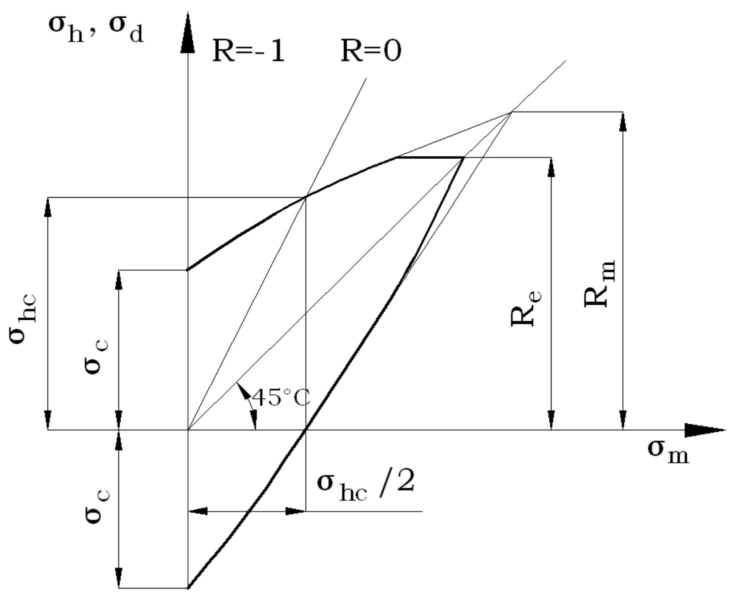

Fig 6.12 Smith diagram - dependence of mean stress on upper and lower cycle stress.

Fatigue strength for other than alternating or transient cycles is determined by the Smith diagram (see Fig 6.12) The Smith diagram represents dependence of mean stress on upper and lower cycle stress for the fatigue strength. The fatigue curve is created by joining three points. Standardized fatigue strength of a rod at alternating stress, fatigue strength of this rod at transient stress and static fatigue strength. The diagram is limited by the limit of plastic macro deformations because the designer cannot allow higher permanent macro deformations. There is a whole range of diagrams besides the Smith diagram to describe the limit state. Fig 6.13 schematically represents a Haigh diagram that shows the dependence of the limit stress amplitude σ_{ac} on the mean stress σ_m. Upper stress is limited by the yield strength. Both diagrams allow determining the maximum amplitude size for the entered mean cycle stress in such a way so as to ensure unlimited life of the component.

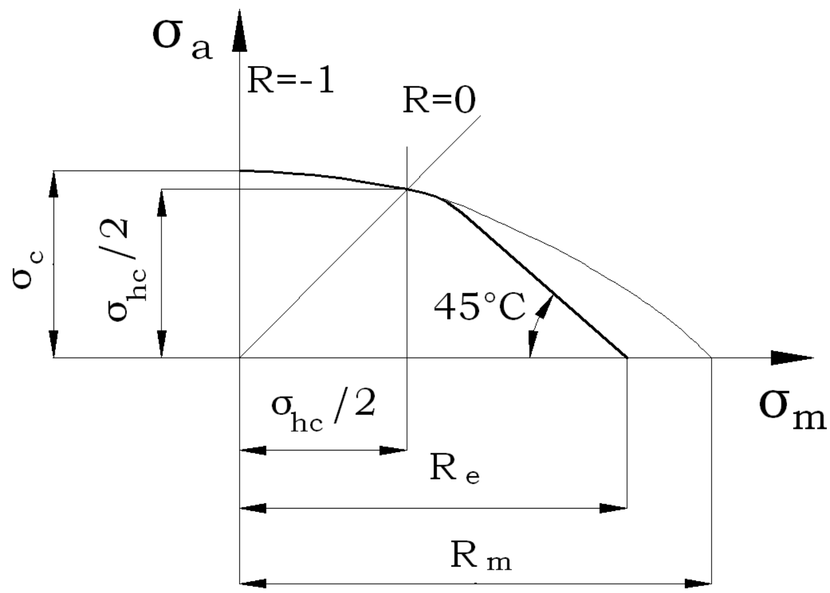

Fig 6.13 Schematic representation of Haigh diagram

Haigh diagram (for tensile-compressive stress) for $\sigma \geq 0$ can be expressed by the following equations:

1) Goodman line

$$\frac{\sigma_a}{\sigma_c} = 1 - \frac{\sigma_m}{R_m} \quad (6.2)$$

2) Gerber parabola

$$\frac{\sigma_a}{\sigma_c} = 1 - \frac{\sigma_m}{R_e} \quad (6.3)$$

3) Sodeberg line

$$\frac{\sigma_a}{\sigma_c} = 1 - \frac{\sigma_m}{R_e} \qquad (6.4)$$

6.3.2 Life curve ε_{at} – N_f (Manson – Coffin curve)

There is a whole range of experimental proofs that metals exhibit varying resistance to cyclic stress and strain in the area of low-cycle fatigue. Interpretation of the fatigue process using the total deformation amplitude consisting of elastic and plastic deformation only appears in the last thirty years This procedure has its practical justifications since the material for instance in construction notches is exposed to total cyclic deformation. Manson proposed a dependence of the number of cycles until failure on the total deformation amplitude in the following form (see Fig. 6.14):

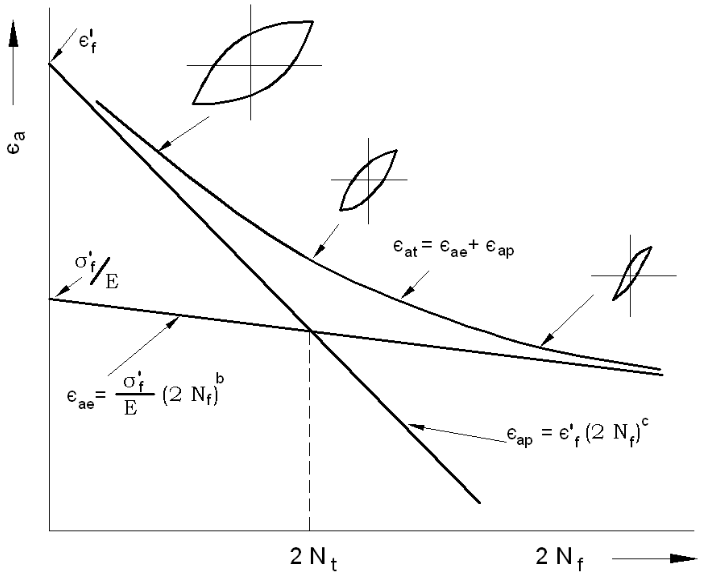

Fig 6.14 Schematic representation of curves ε_{ael} – N_f and ε_{apl} - N_f

$$\varepsilon_{at} = \varepsilon_{al} + \varepsilon_{ap} = \frac{\sigma_f{}'}{E}(2N_f)^b + \varepsilon_f{}'(2N_f)^c \qquad (6.5)$$

where E is the tensile modulus
σ_f' is the fatigue strength coefficient
ε_f'' is the fatigue ductility coefficient
b is the fatigue strength exponent
c is the fatigue life exponent

Life curves ε_{at}=f(N_f) and cyclic stress-strain curves σ_a = f(ε_{apl}) are determined during cyclic stress with constant tensile-compressive total strain amplitude ε_{at} (hard loading) on a series of smooth cylindrical test objects (see Fig 6.15). Total strain amplitudes are selected in such a way that the number of cycles until failure N_f cover the interval of $10^2 \div 10^5$ cycles. Hysteretic loops are recorded in selected time intervals during the test. These loops are used to determine the elastic and plastic component of the total strain amplitude (see Fig 6.16).

Fig 6.15 Smooth cylindrical object with longitudinal deformation sensor

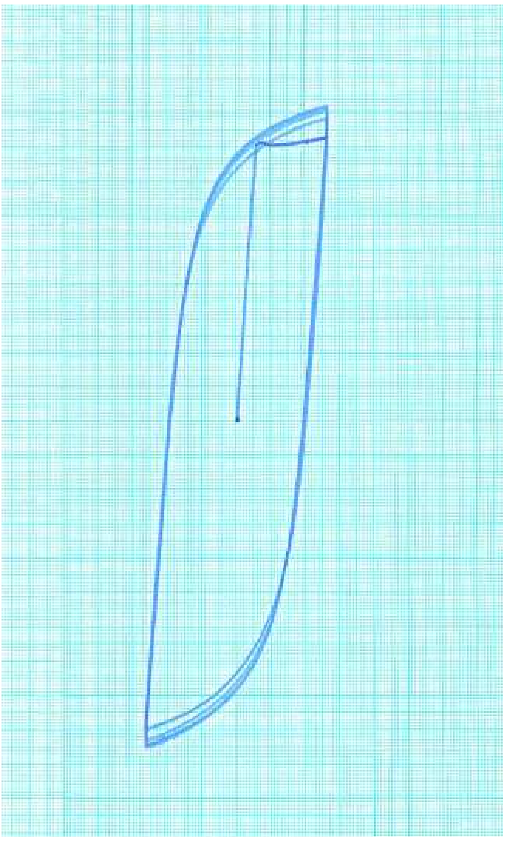

Fig 6.16 Hysteretic loops recorded during the test with $\varepsilon_{at} = 0.01$.

6.3.3 Construction fatigue curves in accordance with ASME

JE components in accordance with ASME Code are calculated in the construction design phase using construction fatigue curves listed in section III, div 1–APPENDICES. The construction curve used for carbon, low-alloy and high-strength steels for temperatures below 371 °C is represented in Fig 6.17. The construction curve used for high-alloy steels for temperatures below 427 °C is represented in Fig 6.18.

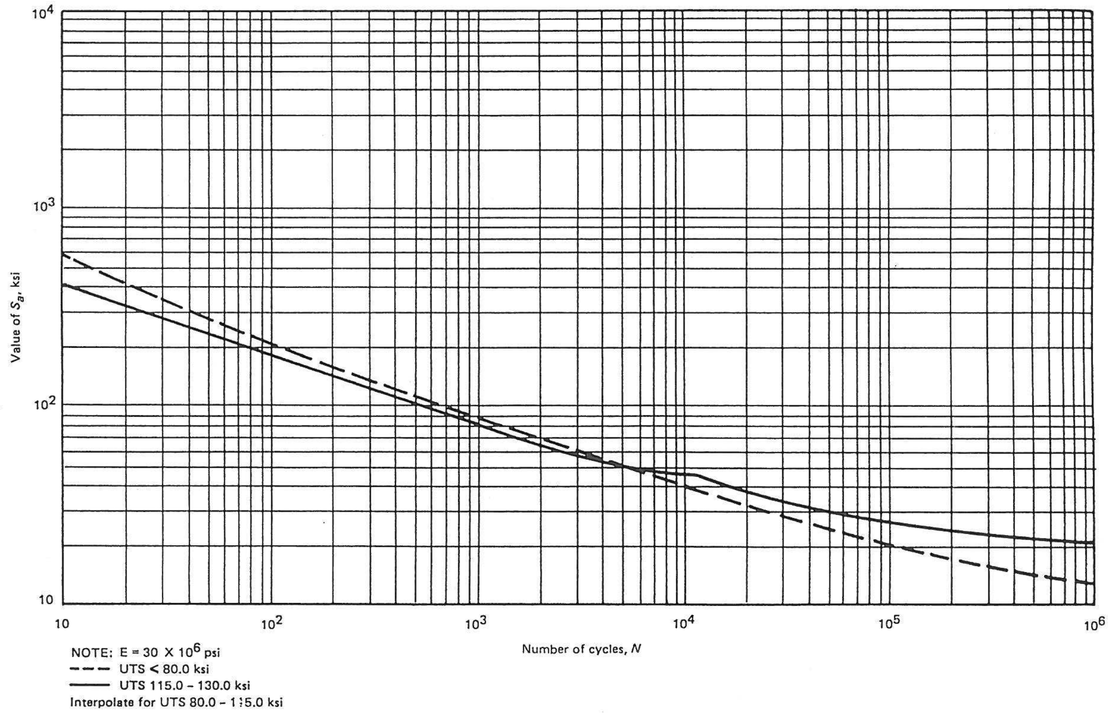

Fig 6.17. Construction fatigue curves in accordance with ASME CODE for carbon, low-alloy and high-strength steel for temperatures t < 371°C.

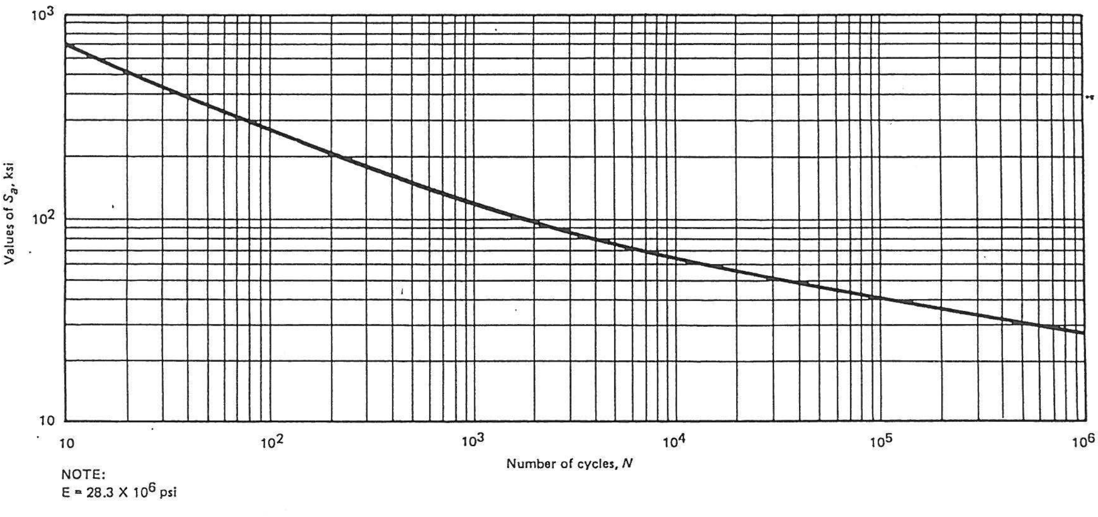

Fig 6.18 Construction fatigue curve in accordance with ASME Code for austenitic steels for temperatures < 427°C.

These construction curves were obtained by transformation of experimentally determined life curves at hard stress (ε_{at} = const.). Stress amplitude values were obtained by multiplying total strain amplitudes by elasticity module E. Experimental curves "stress -

number of cycles until failure" obtained in this way were transformed considering the safety coefficient to stress $n_\sigma = 2$, or safety coefficient to the number of cycles $n_N = 20$. The more conservative of such transformed experimental curves was used as the construction curve.

Overview of terms

After studying this chapter you should understand the following terms:

- **Material fatigue.**
- **High-cycle and low-cycle fatigue.**
- **Cycle asymmetry.**
- **Cyclic softening and hardening.**
- **Cyclic stress-strain curve.**
- **Fatigue striation.**
- **Wöhler curve.**
- **Fatigue limit.**
- **Smith and Haigh diagram.**
- **Manson - Coffin curve.**
- **Construction fatigue curves.**

Questions to the covered material

1) What does material fatigue mean?
2) What is low-cycle fatigue?
3) Define cycle asymmetry.
4) In what types of materials does cyclic softening occur?
5) What does the stress - strain cyclic curve describe?
6) What is the division of the fatigue crack growth stage?

7) Define the threshold value of the stress intensity factor amplitude for growth of fatigue cracks.

8) What information can be obtained from the Wöhler curve?

9) What information can be obtained from the Manson - Coffin curve?

10) Which diagrams describe the impact of mean cycle stress on the fatigue limit?

Tasks

1) Determine the cyclic stress-strain curve and fatigue strength coefficient σ_f, fatigue strength exponent b, fatigue ductility exponent ε_f fatigue ductility coefficient c of Manson – Coffin curve for steel 08Ch18N10T at ambient temperature. Results of tests carried out at a hard cycle (ε_{at} = const.) are listed in table I.

Table I Results of fatigue tests of basic material 08Ch18N10T at ambient temperature

ε_{at} [1]	$\varepsilon_{apl.}$ [1]	$\varepsilon_{ael.}$ [1]	σ_a [1]	N_f [1]
1.46	1.20	0.26	454	399
1.24	0.97	0.27	435	531
0.98	0.76	0.22	403	1093
0.74	0.54	0.20	351	1630
0.50	0.34	0.16	292	4520
0.40	0.25	0.15	287	7270
0.35	0.20	0.15	274	14080
0.30	0.17	0.13	249	27720
0.25	0.12	0.13	252	68260

2) Draw and describe the progress of basic characteristic stress cycles at tensile and compressive stress. Define asymmetry parameters P and R.

7. Material creep at increased temperatures

Time to study:

Aim: After studying this chapter you should be able to:

- **Define creep.**
- **Name factors that influence the application of creep.**
- **Explain the limit temperature T_g**
- **Describe three stages on the high-temperature creep curve.**
- **Name basic characteristics of material creep resistance.**
- **Describe the division of creep tests**
- **Describe methods of result extrapolation from creep tests**

Lecture

7.1 Definition of creep

In terms of deformation, the response of material to the applied external load can be divided to three basic types:

1) elastic deformation - reversible, time-dependant It depends only on stress and temperature because the elastic module depends on temperature,
2) anelastic deformation - reversible, time-dependent,
3) plastic deformation - irreversible deformation, time-independent and/or time-dependent (creep).

With the exception of steam boilers (19th century), all energy and chemical equipment working at static stress at increased temperatures was developed in 20th century. All this equipment operates at temperatures, during which the time-dependent deformation and associated fracture processes need to be taken into consideration.

Creep refers to slow plastic deformation of material that occurs at increased temperature under time-dependent external stress.

Generally speaking, the response of equipment operating at increased temperatures and the application of creep depends on:

- stress level
- temperature
- chemical composition of material
- material structure

The creep strength in the range of temperatures where creep applies is always lower than the material yield strength (see chapter 2, Fig 2.1). "Limit temperature" T_g is a temperature above which creep constitutes one of the main degradation mechanisms. It is defined as the intersection of the heat dependence of yield strength R_e ($R_{p,0,2}$) determined by a tensile test and heat dependence of the creep strength $R_{mT/t/T}$ (see chapter 2, Fig 2.1). $R_{mT/t/T}$ is the static tensile stress leading to a defect after the time t and at temperature T and is determined by creep tests until failure.

7.2 Creep curve ε – t

The creep curve expresses the time-dependence of deformation at constant temperature and tensile stress level. The high-temperature creep curve ($T \approx 0.4\ T_t$ and above for steels and $T \approx 0.8\ T_t$ for nickel alloys) is divided into three time stages (see Fig. 7.1)

In the first stage, which is called primary (transit) creep, the creep speed decreases with time since the strain hardening is more significant than dehardening. At temperatures $T \leq 0.3\ T_t$ where T_t refers to melting temperature, primary creep is the only deformation response of the material. It is sometimes referred to as logarithmic creep and occurs even without heat activation.

The second stage is characterized by a linear relation between deformation and time and is called the secondary creep. This type of creep occurs only at sufficiently high temperatures ($T \geq 0.4.T_t$), when the recuperation process is able to compensate for the effect of strain hardening. This creep type is the most significant from the practical point of view. At stress significantly

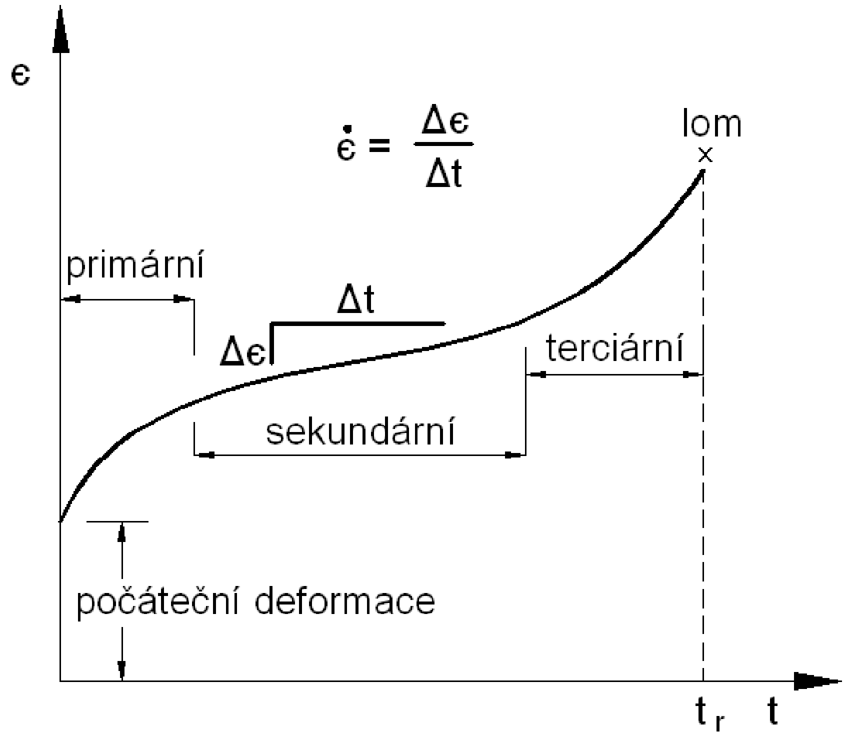

Fig 7.1 Schematic representation of the three time stages on the high-temperature creep curve.

lower than the yield strength it represents a significant part of the total life of a component operating at increased temperatures. On the other hand, if the applied stress is high, the secondary creep is reduced up to
a point of inflection between the primary and terciary creep.

The third stage referred to as the tertiary creep is characterized by a steep increase of the deformation speed up to fracture creation. Fractures are initiated as cavities at the grain borders, which creates the intercrystallic character of the fracture (see fig. 7.2)

7.3 Basic characteristics of material creep resistance

Basic characteristics of material creep resistance include:

1) Secondary creep speed $\dot{\varepsilon}_s = \frac{\Delta\varepsilon}{\Delta t}$ - creep speed in the secondary stage (stabilized creep stage).

2) Creep strength $R_{mT/t/T}$ – tensile strength which causes fracture after a pre-defined period of time at a selected temperature.

3) Creep limit $R_{\varepsilon/t/T}$ – represents the stress that causes deformation of a specific size at the selected temperature after a pre-defined period of time. Creep limit is usually defined for ε =

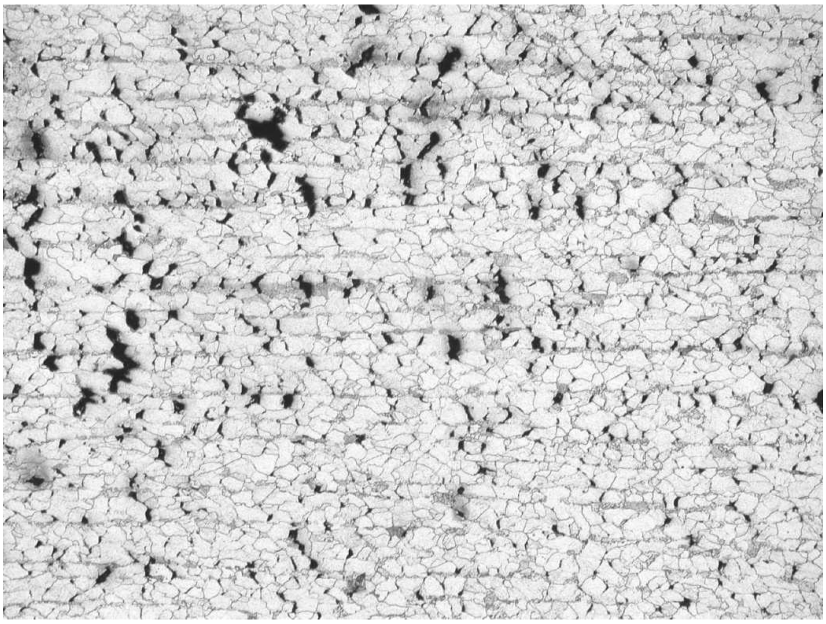

Fig 7.2 Example of creep cavity damage

4) = 0.2% (for construction of turbines), or ε = 1.0 % (for construction of boilers). The usual calculation time for high-pressure boilers and turbines is $2.25x10^5$ hours and $2x10^4$ hours for aircraft engines.

5) Homologous temperature - the ratio of working temperature T and melting temperature T_t.

Fracture ductility A_r [%], or fracture contraction Z [%] are also determined during creep tests as additional characteristics determining the long-term material plasticity.

7.4 Tests of creep behaviour of metal materials

Tests of creep behaviour of metal materials are carried out in accordance with ČSN EN ISO 204 Metallic materials – Uniaxial creep testing in tension – Method of test. The test consists of heating the test object to a nominal temperature and its deformation by constant tensile load or constant tensile stress applied along the longitudinal axis for a certain period of time or until fracture. Creep tests are divided to:

1) Tests with measured deformation that enable determining the secondary creep speed and the creep limit $R_{\varepsilon/t/T}$ depending on the stress and temperature from creep curves ε – t determined using
   - continuous deformation measurement in time that enables construction of the whole creep curve
   - interrupted tests, during which test objects are destressed in regular intervals and the creep deformation is measured usually using a centre punch located in the measuring part of the test object.
2) Tests until fracture at constant load to determine the creep strength $R_{mT/t/T}$. Creep strength values are determined usually based on short-term creep tests and subsequent interpolation or extrapolation of results for calculation periods. Increase of the test duration guarantees higher certainty and accuracy of extrapolation of creep test results and enables verification of methods used to transfer results from short-term results.

7.4.1 Basic parameters of creep tests.

The parameters of creep characteristics tests can also significantly affect creep test results and their reliability. The realization of creep tests follows a general scheme that states that the tests need to be carried out at 2 to 4 temperature levels graded by 25 to 50 °C and at several stress values for each selected temperature, whereas the test stress should be evenly distributed along areas with low and high values. At the same time the shortest time until fracture should not be less than approximately 200 hours and the longest time until the test object failure should be at least 1/3 of the planned material life (this condition is often expressed as the extrapolation ratio = 3). The highest testing temperature is also determined and it should not exceed the expected working temperature by more than 50 °C.

7.5 Methods of result extrapolation from creep tests

When designing energy and chemical equipment or structures whose components will be exposed to high temperatures and stress during operation, where creep needs to be considered as one of the dominant degradation mechanisms, it is necessary to know the long-term creep characteristics that are determined from creep test results. In order to obtain creep characteristics for equipment components with an expected life of approximately 200,000 operating hours (typical designed service life of fossil fuel boilers) it is necessary to use the results of short creep tests since the performance of long-term tests is very time-demanding and therefore uneconomic. However, in order to ensure the determined creep strength for a period of 200,000 hours is reliable, it is still necessary to ensure the maximum time to fracture of the completed test at the given temperature is at least 70,000 hours (i.e. 8 years). This condition is required when developing new materials and determining their creep resistance. Creep tests in a range of 1,000 to 30,000 hours are most commonly used in practice and for materials already entered in corresponding material standards and long-term creep characteristics for 10^5 hours are then obtained from these tests using various extrapolation methods. By comparing such obtained creep strength values with material data it is possible to assess the compliance of the material with its specification. The most commonly used extrapolation methods for creep test results are divided into two basic groups:

- graphic methods
- parameter methods
-

7.5.1 Graphic methods of result extrapolation from creep tests

Graphic methods are usually considered easier than parameter methods. They are also used to assess the residual life of material after exploitation. The basic principle of graphic methods of result extrapolation can be summarized into three basic points:

- compilation of a scatter diagram, usually in bilogaritmic (**log σ–log t**) or semilogaritmic system (**σ–log t**),
- drawing of isotherms $\mathbf{R_{mT}=f(T)}$ or $\mathbf{R_T=f(T)}$, or $\mathbf{t_r=f(T)}$ within the range of obtained results,
- extension of isotherms by extrapolation to the required operation period (for instance $2x10^5$ h) and deduction of extrapolated properties, alternatively to the selected working temperatures, which is a procedure most commonly used to determine the residual service life.

The biggest issue with graphic extrapolation methods seems to be the shortcomings following from the used coordinate system and related range of test durations. For tests until fracture in a wide range of stress values it sometimes happens that the inclination of the line interleaved with experimental points of the $\sigma - t_r$ dependence in semilogaritmic or bilogaritmic coordinates is not constant and the whole line is therefore divided into several sections with different inclination. Each change of inclination then corresponds to the transition from one

creep deformation mechanism to another. The dependence of stress – time until fracture is generally represented by the curve that bends towards lower stress values (longer times until fracture) and the results might be dangerously overvaluated during the assessment of creep test results (see Fig 7.3).

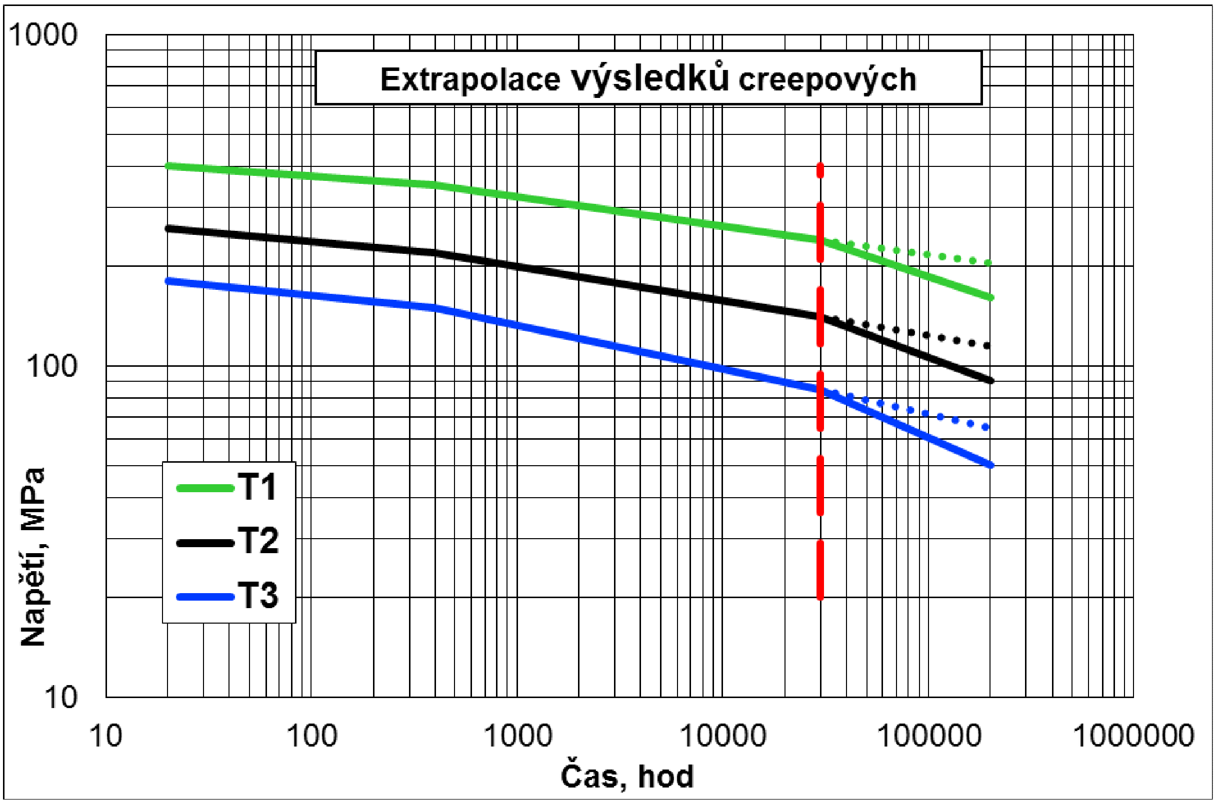

Fig. 7.3 Overvaluation of creep strength during extrapolation of results

This figure shows that short-time results of creep tests (limited in this case to 30,000 hours, extrapolation is marked by the dotted line) might lead to overvaluation of the real creep strength if the material does not show signs of change of the deformation mechanism in the given temperature-time interval.

An opposite problem occurs when assessing tests until fracture in semilogaritmic coordinates **σ–log t**, when the line equation has the following form:

$$\log t_r = \log B - \beta.\sigma.\log e \quad (7.1)$$

This dependence is then determined by the curve that moves towards higher stress values and the extrapolation results might be therefore significantly undervaluated. The general rule is that if the test is not long enough, it is not possible to accurately determine which of the systems is more suitable for extrapolation.

however, representation in bilogaritmic system **log σ–log t** is more suitable for lower temperatures and the semilogaritmic coordinates are more suitable for higher temperatures (in the recuperation area).

7.5.2 Parameter methods of result extrapolation from creep tests

The basic principle of parameter methods of extrapolation consists of the use of data from relatively short-term creep tests that are usually carried out at temperatures higher than the operating temperature. This is because the probability that the same physical creep mechanism will be applied during the test and in operating conditions is much higher in this case. Two basic variables of creep tests - temperature and time - are therefore converted to a single parameter, which is the function of applied stress.

The best known and most widely used equations and correlation parameters include:

- Methods based on the Arrhenius equation:
  - Larson–Miller (L-M),
  - Sherby–Dorn (S-D),
  - Manson–Haferd (M-H),
  - Seifert.
- Methods based on empiric equations:
  - SVÚM.

7.5.2.1 Larson – Miller (L-M) parameter method

The parameter relation proposed by Larson-Miller is derived on the basis of the Arrhenius equation, which represents the creep speed as a function of stress and determines it as a time change of heat-activated processes expressed in the following form:

$$f(\sigma) = \dot{\varepsilon} = \frac{d\varepsilon}{dt} = A \cdot e^{\left(\frac{-Q}{RT}\right)}, \qquad (7.2)$$

where: A – constant,

Q – activation energy,

R – universal gas constant (8.314 $Jmol^{-1}K^{-1}$),

T – temperature.

If we assume for the sake of simplification that the real creep speed remains constant during the whole test, then the following applies:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{\varepsilon}{t} \qquad (7.3)$$

where: ε – permanent deformation size at the end of the test,

t – time until fracture.

The original Arrhenius equation (7.2) then has the following form:

$$\frac{1}{t} = \frac{A}{\varepsilon} \cdot e^{\left(\frac{-Q}{RT}\right)}. \qquad (7.4)$$

If we set A/ε = C, then a logarithm of the equation (4) yields:

$$\frac{Q}{2{,}3R} = T(C + log t_r) = P_{LM}, \qquad (7.5)$$

where: P_{LM} – Larson–Miller parameter of correlation,

C – material constant without a physical significance.

The accuracy of obtained results significantly depends on the value of the constant C, which is assumed by the model to be independent of the stress, temperature and probably also of the material. However, in practice it has been observed that the constant C is higher for higher temperatures and lower for lower temperatures. Incorrectly selected constant C can cause errors from ± 10 up to ± 40%. The value of constant C can be interpreted as an extrapolated intersection in the **$logt_r$-1/T** dependence (Fig 7.4). For the L-M parameter method, isostress lines intersect at values 1/T=0 and log t_r = - C.

The parameter relation proposed by Larson-Miller is usually expressed as the linear function **log σ**, which yields the following form of the equation (7.5):

$$T(C + logt) = a_0 + a_1 \cdot log\sigma \qquad (7.6)$$

However, this linear regression equation ceased to be used due to the fact that there is no linear dependency of log t on log σ in the wide range of stress values, which implies that the L-M parameter dependency on log σ is also not linear. That is why the most commonly used equation is the L-M equation of the 2nd or 3rd order, where the dependency of the L-M parameter on log σ is polynomial. For example, the L-M equation of the 3rd order has the following form:

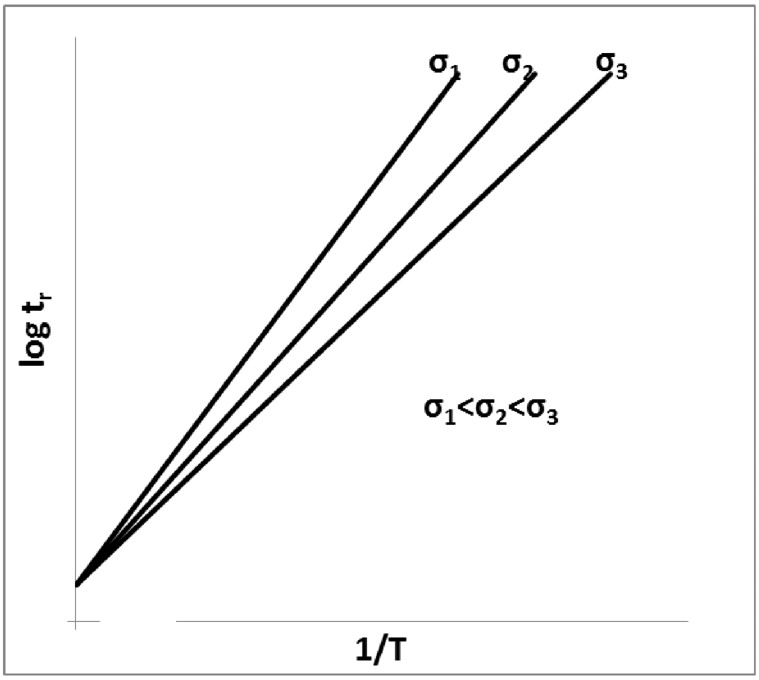

Fig. 7.4 Relation between temperature, stress and time until fracture in the Larson-Miller model

$$T(C + logt) = a_0 + a_1 \cdot log\sigma + a_2 \cdot log^2\sigma + a_3 \cdot log^3\sigma. \qquad (7.7)$$

However, polynomial equations of higher orders cannot be used for higher time extrapolation because soon after leaving the last experimental point the function diverts to the ordinate axis, or alternatively creates a parabolic curve, which has no relation to the actual behaviour of fire-resistant materials.

7.5.2.2 Sherby – Dorn (S-D) parameter method

This approach considers creep as a heat-activated process which, just like in the L-M parameter, is based on the Arrhenius relation. If creep is a heat-activated process, then a change of temperature at otherwise constant conditions must affect the creep speed. The S-D criterion is based on the following parameter:

$$t \cdot e^{\frac{-Q}{RT}}, \qquad (7.8)$$

based on this parameter it can be stated that the deformation value ε at constant stress is defined by the function of a variable that can be represented as follows:

$$\theta = t \cdot e^{\frac{-Q}{RT}} \qquad (7.9)$$

and which is a function of temperature and time. Certain creep deformation at a given stress expressed by the θ_i function then corresponds to two different temperatures and times, provided that the following relation applies for these two pairs:

$$\theta_i = t_1 \cdot e^{\frac{-Q}{RT_1}} = \ldots\ldots = t_n \cdot e^{\frac{-Q}{RT_n}} \qquad (7.10)$$

Afterwards, by applying a logarithm to the equation (7.10), while taking into account the fracture condition $\theta=\theta_r$ and time $t=t_r$, we obtain a S-D parameter equation in the following form:

$$P_{S-D} = log\theta_r = logt_r - Q/RT, \qquad (7.11)$$

where $P_{S\text{-}D}$ is the Sherby-Dorn parameter

The Sherby-Dorn parameter is based on the same theoretical foundation as the Larson-Miller parameter, yet it stems from different assumptions and it yields different equations. The main difference between these two parameters is namely the dependence of activation energy on stress. The L-M parameter assumes the dependency of activation energy on stress, whereas the S-D parameter does not. The activation energy is therefore the direction of log t_r dependency on 1/T (see Fig 7.5).

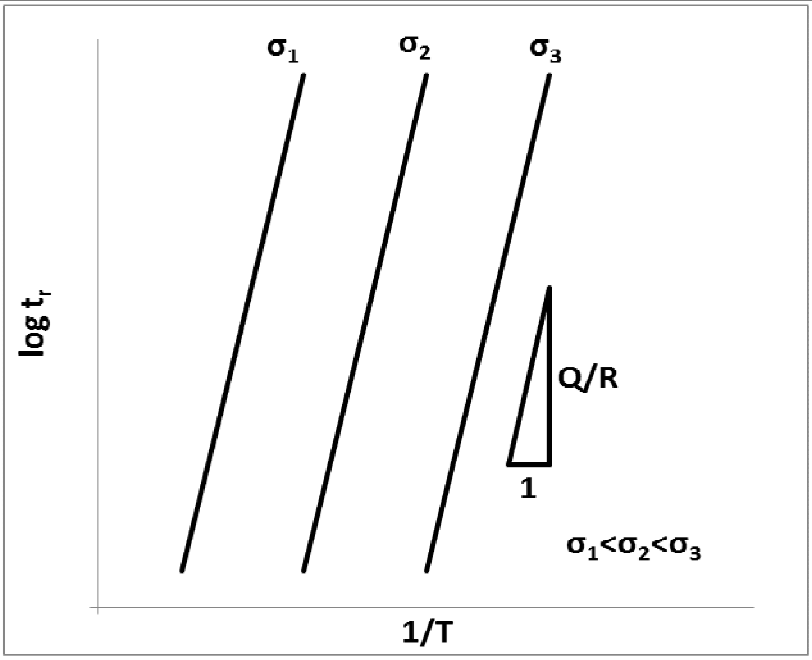

Fig. 7.5 Relation between temperature, stress and time until fracture in the Sherby-Dorn model

7.5.2.3 Manson – Haferd (M – H) Parameter method

Manson-Haferd proposed a parameter relation based purely on empirical knowledge, where creep tests were performed at constant load and variable temperature. Their observations discovered deviations when the L-M parameter equation was used. They assumed that these deviations are caused by non-linear dependence of log t_r on 1/T. The M-H parameter is therefore based on the empirical knowledge that the dependence of log t_r on 1/T can be replaced in many cases by the dependence of log t_r on T and it forms a line for constant stress. Lines corresponding to various stress values converge around a single point with coordinates [T_a, log t_a] (see Fig 7.6). The M-H parameter for a given stress value is determined as the reversed direction value of the given line in the following form:

$$P_{M-H} = \frac{\log t_r - \log t_a}{T - T_a} \qquad (7.12)$$

where: P_{M-H} - Manson-Haferd parameter,

log t_a, T_a – material characteristics.

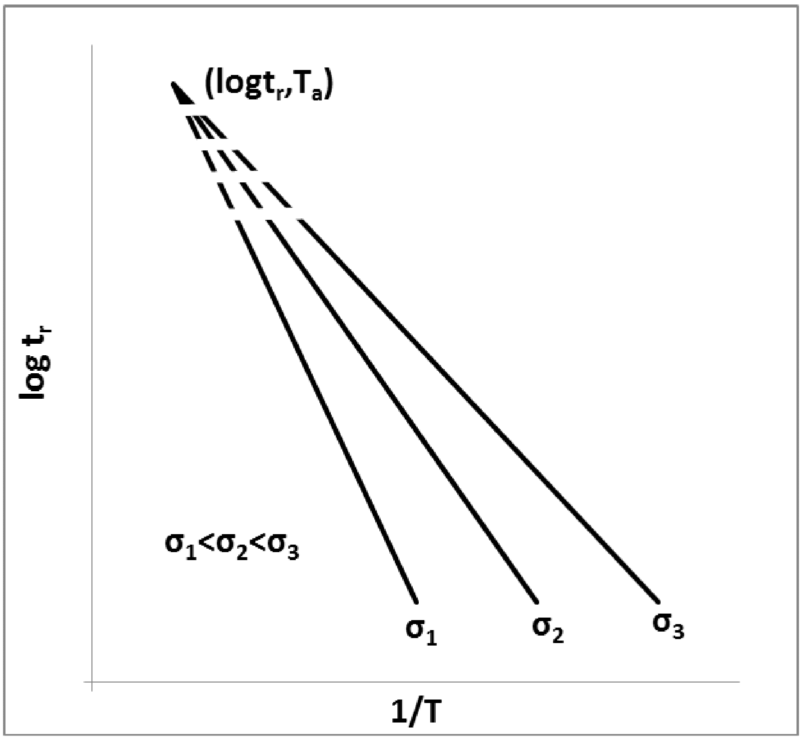

Fig. 7.6 Relation between temperature, stress and time until fracture in the Manson-Haferd model

7.5.2.4 Seifert method

Another frequently used parameter method is the Seifert equation. This equation expresses the applied stress (creep strength) as a square function of the heat-time parameter P in the following form:

$$\log\sigma = A_0 + A_1 P + A_2 P^2 \qquad (7.13)$$

where: σ is the applied stress (creep strength),

$A_{0,1,2}$ are constants,

P is the heat-time parameter defined for this equation by the following relation:

$$P = T(C + \log t_r) \cdot 10^{-4} \qquad (7.14)$$

7.5.2.5 SVÚM equation

The equation often used in the Czech Republic for extrapolation of creep test results was developed in the former State Development Institute for Material (SVÚM) and its parameters used to be listed for some of the most commonly used fire-resistant steels in the Czech Republic directly in material standards. Unlike the previous equations, this equation is not based on physical models, i.e. the Arrhenius equation, but purely on empirical equations that represent the dependence of time until fracture on the applied stress and temperature by the following functions:

$$log(t) = A_1 + A_2 \cdot f(T) + A_3 \cdot f(T) \cdot g(\sigma) + A_4 \cdot g(\sigma) \quad (7.15)$$

$$f(T) = log\left|\frac{1}{T} - \frac{1}{A_5}\right| \quad (7.16)$$

$$g(\sigma) = log[sinh(\sigma \cdot T \cdot A_6)] \quad (7.17)$$

where T is the temperature,

A_{1-6} are constants.

It is a matter of fact that computing technology is required for the computation of such complex sets of equations with multiple variables without linear dependence.

Overview of terms

After studying this chapter you should understand the following terms:

- **Anelastic deformation**
- **Creep**
- **Limit temperature**
- **Creep curve**
- **Secondary creep speed**
- **Creep strength**
- **Creep limit**
- **Homologous temperature**
- **Larson–Miller parameter**
- **Sherby – Dorn parameter**

Questions to the covered material

1) What does creep mean?
2) What is determined by the limit temperature T_g?
3) Define the creep strength.
4) What is homologous temperature?
5) What extrapolation methods of creep test results can you name?
6) What parameter extrapolation methods of creep test results can you name?
7) How is the Larson–Miller parameter expressed?

Tasks

The table below lists results of creep tests of steel P22 at temperatures 525°C, 550°C, 575°C and 600°C. Draw the stress dependence on the Larson - Miller parameter in the form $P_{L\text{-}M}$ = (T + 273). [$C_{L\text{-}M}$ + log(t)], $C_{L\text{-}M}$ = 20.

Number tests	**Temperature T (°C)**	**Stress σ (MPa)**	**Time t (hours)**	**Ductility (%)**	**Contraction (%)**
1	525	280	14	43.6	83.2
2	525	255	57	32.8	85.5
3	525	235	173	38.4	85.2
4	525	210	359	48.8	87.7
5	525	190	726	62.6	88.3
6	525	165	2602	45.6	85.9
7	525	145	5772	41.6	83.3
8	525	125	16072	35.6	78.3
9	525	115	30734	38.6	79.3
10	550	240	160	32.0	87.0
11	550	215	327	60.0	89.3
12	550	190	399	46.8	86.7
13	550	165	422	58.8	88.2
14	550	145	962	48.4	84.2
15	550	125	2834	42.8	87.7
16	550	105	11309	46.3	83.0
17	575	180	49	57.6	85.3
18	575	150	211	56.0	86.8
19	575	130	798	54.0	86.9
20	575	110	2065	48.8	83.6
21	575	90	6407	51.9	87.2
22	575	80	16491	41.8	78.0
23	575	75	19699	28.0	70.0
24	600	155	51	55.2	87.3
25	600	140	124	44.6	81.9
26	600	110	466	60.8	91.1
27	600	95	849	56.4	91.7
28	600	85	1398	56.4	91.7
29	600	65	4891	52.0	83.5
30	600	50	15633	56.3	92.5
31	600	40	21040	40.6	93.7