VSB - Technical University of Ostrava

Composite materials

Study support

coursebook / textbook

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Study instructions

Composite materials

You've received an educational package for the subject Composite Materials of the 4th semester of the Heat Engineering and Ceramic Materials study program containing an integrated textbook including study guideline for part-time study.

1. Prerequisites

To study this subject successfully, you are expected to complete the subject Glass and Ceramic Materials and Inorganic Binding Materials (binders).

2. The aim of the subject and learning outcomes

The aim of this subject is to acquaint students with the basic principles of composite effects, interactions at an interface, the properties and possibilities of applying specific types of materials and different preparation technologies for composites as well as to create a student comprehensive basis and to facilitate orientation in the field of composite materials.

After studying the subject, students should be able to have:

Knowledge outcomes

- students will be able to formulate the basic principles of composite action/ effect behaviour
- students will be able to characterize the types of materials for the matrix and the reinforcing phase, and methods for their preparation

Skills outcomes:
- students will be able to explain the interaction between matrices and reinforcement, and the effects on the properties of composite materials

- students will be able to describe the preparation technologies of composite materials and will learn about specific applications

Who is the subject intended for?

The subject is registered as part of the master study of Heat Engineering and Ceramic Materials in the Metallurgical Engineering study program, but it can be studied by any other interested party from other fields, if the required prerequisites are met.

This study support is divided into sections and chapters corresponding with a logical division of the studied material, but do not have the same extent. The estimated time to study a chapter may differ significantly, and therefore large chapters are further divided into numbered subsections which correspond with the structure described below.

When studying each chapter we recommend the following procedure:

Individual chapters have defined objectives, which students should reach after reading the chapter. Understanding the subject of the matter can be verified at the end of each chapter where all concepts, key terms and comprehensive questions that students should not have problem to answer are listed. Each chapter is accompanied by a list of used references and literature which can be helpful when studying the subject in a broader context.

Communicating with teachers:

During the semester, there is direct contact with a teacher in the form of several hour blocks when students can apply their questions about the course material directly to the teacher. Students also have the possibility of direct communication with the teacher through individual consultations or may communicate with a teacher via email, for example. Specific requirements concerning the organization of the semester, credits, respectively the exam, will be introduced to students at the first lesson of the semester.

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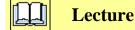
1. Composite as technical material

Time to study: 2 hours

Goal After studying this paragraph you will be able to

- define composites and characterize the difference compared to conventional materials
- distinguish the basic components of the composite, their properties, functions and materials
- describe the conditions under which it is possible to prepare a composite material

Lecture

1.1. Composite as a technical material

Why composite?

The possibilities of traditional materials such as metals and their alloys are so exhausted that even when using the most modern techniques it may be difficult to achieve the highest material characteristics and thus higher performance parameters, the durability and reliability of the proposed structures and equipment.

The use of composites

For fields such as rocketry and aviation, the automotive and chemical industries, electrical constructions and many other areas, composites are indispensable in a variety of applications today.

Advantages and disadvantages of composites

The advantage of composites as structural materials is to obtain a material of a higher strength, toughness, stiffness, but also a higher resistance to creep, corrosion, wear or fatigue compared to conventional materials. In addition, with a suitable combination of components we can also obtain a composite of specific properties (thermal, electrical, optical). The disadvantage of composite materials, in comparison with traditional materials, is its difficult workability and relatively higher price.

1.2. The definition of a composite

The term composite means composed, therefore it should be material that is composed of two or more components. However, this would mean that most natural and synthetic materials and alloys belong to this category. The definition should be clarified.

As composites can be considered material composed of two or more components (phases), where at least one of them is solid, reaching the properties which cannot be provided by any of the components separately or not even by their mere sum. The properties of composites are achieved by cooperation the individual phases called the synergistic effects.

1.3. The composition of a composite

A composite material is composed primarily of **a matrix**, i.e. a continuous phase, which is armoured with **a reinforcement** (reinforcement is a secondary phase), which is usually the discontinuous phase.

The matrix

The matrix combines the individual particles of reinforcement, protecting them against external influences and prevents their violation. The basic function of the matrix is to transmit the external load onto the reinforced phase. For the matrix, a good bond strength with the reinforcing phase material (i.e. perfect wettability without chemical interaction at the interface of the matrix and reinforcement) is required. Among other requirements for the matrix, a low weight is commonly included. In comparison with the reinforcement phase, a matrix has generally lower strength and greater plasticity.

The reinforcement

The reinforcement phase transmits the bulk of the external loads. It is expected to have high strength and a modulus of elasticity E (E is about one order higher than that of the matrix), as well as a small deformation at a fracture with a high proportion of elastic deformation. Regarding the tensile behaviour of the composite it is given by the shape, concentration and orientation of reinforcement.

The shape of reinforcement particles can be considered approximately as a sphere (the powder form of reinforcement) or as a cylinder (fibres). Their size and distribution then determine the texture of the composite.

The concentration is a density of the reinforcing phase, expressed in terms of volume or the quantity of weight. It is one of the most important parameters that affect the properties of the composite material.

The orientation of the reinforcing phase affects the isotropy of the system. If the reinforcing particles have the shape and dimensions in all directions about the same (for example powders), the composite behaves basically as an isotropic material, therefore its properties are the same in all directions. On the contrary systems reinforced with cylindrical reinforcement (fibres) show an anisotropy of properties.

Individual types of matrices and reinforcements and their classification are evident from Figure 1.

Fig. 1 Types of matrices and reinforcements.

1.4. The Matrix

According to Figure 1, there are three basic groups of matrix material:

- Metal/Metallic
- Macromolecule and inorganic - polymeric, bitumen
- Mineral - based on inorganic binders, ceramic, glass, carbon

Metallic Matrices

Metallic matrices have good electrical and thermal conductivity, are malleable, have good wear and heat resistance, and also provide the possibility of coating and bonding.

The most widely used metallic matrices are aluminium, magnesium, titanium and their alloys and for very high temperature nickel-based alloys, for electrical purposes matrices of copper or silver are used.

Polymeric Matrices

Polymeric matrices are the most common type in production. In comparison with metals they have low weight, high strength, are corrosion resistant, do not require surface treatment, absorb vibrations and have low thermal and electrical conductivity. The mechanical properties vary according to the type of polymer, whether it is a thermoplastic, thermoset or elastomer. For the production of composites all three types of polymers are used. Thermoplastics are mostly chemically resistant and tougher than thermosets, while for elastomers, the dominant feature is its elongation.

Due to their low density, they are most widely used in aircraft design. The disadvantage is the low thermal stability of polymers. The most important composites have a thermoset matrix.

Ceramic and glass matrices

Ceramics is inorganic non-metallic heterogeneous material consisting of crystalline substances of varying composition and configuration. Ceramic materials generally have good chemical resistance, lows thermal conductivity, a high melting point, high hardness and compression strength and are electrically non-conductive. The main disadvantage is the considerable brittleness, poor workability, and high sensitivity to internal defects. They are suitable for use at high temperatures.

Glass is an amorphous substance, which was formed by the solidification of the melt without crystallization. The properties of glass and ceramics are close.

1.5.   The reinforcement

The reinforcing phases are mostly divided according to the geometry of their individual particles into:

- particulate
- fibre
- skeletal

❑ **Particulate (dispersion) reinforcement**

Particles in composites are typically used not only to improve the mechanical properties, but often (also) to improve or modify properties such as heat resistance, electrical conductivity, damping of vibrations, wear resistance, hardness, resistance to high temperatures, etc. As the particulate reinforcement, respectively dispersion, there can be used practically anything, but most frequently the dispersion of ceramic particles is used.

Dispersions usually consist of powders with particles of various shapes (spherical, pyramidal, lamellar, etc.) and various sizes. As particulate dispersions (filler powder) there are usually used powders of inorganic compounds such as oxides (MgO, ZnO, BeO, Al_2O_3, ZrO_2, etc.), carbides (SiC, TiC, B_4C, Al_4C_3, etc.), nitrides (Si_3N_4, BN), borides, or silicates (kaolin, mica, glass beads, etc.).

Glass is often used for weight reduction in the form of solid or hollow glass beads.

According to their size we distinguish the particles as follows:

- Particles of 2 mm – 10^{-3} mm
- Dispersions 10^{-3} – 10^{-5} mm (0.01 to 1 μm), recognizable by a scanning electron microscope

- Nanoparticles under 10^{-5} mm (below 10 nm), recognizable by a transmission electron microscope

The particles in the matrix should be distributed (completely) evenly. Clustering of the particles at the grain boundaries of the matrix (a risk especially within a metal) during the solidification of the matrix is very undesirable. It is therefore necessary when producing the composite by adding dispersion particles to the melt to (often) use intensive mixing.

❑ Dispersion reinforced composites

Dispersion strengthened composites resemble precipitation-reinforced metal alloys (hardening). They differ as follows:

At low temperatures, the listed alloys have better properties (a higher increase in strength) than dispersion strengthened composites - the reason is better adhesion.

However, at higher temperatures, the precipitate may partially dissolve or coagulate, thereby deteriorating the properties of these alloys. In dispersion-reinforced composites the properties are very little dependent on temperature. The particles are selected so that when increasing the temperature they will neither dissolve nor coagulate.

For the dispersion reinforced composites it is ideal to use a dispersion of about 10 to 15% of the particles (with) size of 10 to 100 nm. When evenly distributed in the matrix dispersion efficiently eliminates the movement of dislocations and thus limits the plastic deformation of the composite.

Dispersion increases primarily ultimate tensile stress and yield stress and suppresses any creep of the matrix.

❑ Particle reinforced composites

Large particles can no longer effectively prevent the movement of dislocation, but will take part of the load from the matrix.

The optimal particles are of a few µm, where the amount in a matrix should be of 25% (but not more than 50%) so that the reinforcement is noticeable. For armouring usually solid brittle particles are used - very often ceramic.

❑ Composites with hollow particles

Often, especially in composites with a plastic matrix the excessive density of particles disturbs the density of the matrix. Where the weight of the composite is decisive, we begin to use hollow spheres instead of the ordinary particles. Because of a particle size of dozens up to hundreds of µm they are among armouring particles.

They are often made of glass, sometimes of corundum as well.

❑ Fibre reinforcement

Fibers are stronger than the same compact (dense/thick) materials. Fibre strength depends mainly on its cross-section. With decreasing cross-section the fibre strength increases (due to applying the strengthening processes, depending on the degree of deformation). Fibers usually have a circular cross-section and a diameter in a wide range. To compare, a human hair has a diameter of 0.05 mm and spider fibers have 0.015 mm.

According to their diameter we distinguish the fibers as follows:

- nanofibers - to 100 nm
- microfibers - 0.1 to 1 μm - whiskers
- middle-sized fibers - 1 to 10 μm - carbon, glass, textile
- coarse (rough) fibers - over 10 μm - B, SiC, etc.

According to original material we distinguish fibers as follows:

- natural
- glass
- graphite and carbon
- polymer - aramid, nylon
- ceramic
- metal
- fiber single crystals/monocrystals (whiskers)

Natural fibers

Natural fibers may have surprisingly good properties. For example, a spider fiber with a diameter of 0.02 - 7 μm has a tensile strength of 1140 MPa and an elongation of 31%.

Natural fibers have often a very complex fiber structure - e.g. cotton fibers.

Among natural fibers are not only those of the spider and cotton, but also flax, jute, hemp, coconut, and more. The basis of all these fibers is cellulose. Most of these fibers is biodegradable.

Contemporary (modern) tendencies are represented by the production of cellulose nanofibers by the fiberization of wood. The issue of natural fibers used in composites is very current for developing countries because it often represents their best raw material.

Glass fibers

Glass fibers are mainly used to reinforce polymer matrices. They have relatively high strength but a comparatively low modulus of elasticity and are fragile. They mostly occur in the form of various fabrics.

Their basic characteristics are:

- density of about 2.5 g.cm^{-3}
- toughness (stiffness/firmness) roughly as aluminium - 1/3 steel firmness, E = 80 to 100 GPa
- small fatigue strength
- thermal conductivity is less than half that of steel
- thermal expansion is less than half of the thermal expansion of steel

The most commonly/frequently used types of glass for fiber production:

- E glass (borosilicate) - electrical insulation
- S glass (silica-magnesium glass) - high-strength composites
- A glass (contains SiO_2, K_2O, CaO, MgO a Al_2O_3) - thermal insulation
- C glass (pyrex) - chemical applications

Glass fibers rank among traditional fibers, which are produced by rapid drawing from the melt. Due to their relatively simple manufacturing glass fibers are cheaper compared to others.

Carbon and graphite fibers

Basic characteristics of these fibers:

- ten times higher rigidity and half the density (1.8 to 2 g.cm^{-3}, contains 90 - 95 % pure carbon) over the glass fibers
- elongation at a rupture is smaller than with glass fibers
- tensile strength at room temperature is lower than that of the glass or aramids, but it does not decrease with temperature up to 1000 °C
- excellent thermal properties, if they are protected against oxidation, stable and chemically inert to 1000 °C, with protection against oxidation stable to 2000 °C
- minimal thermal expansivity, sometimes even contractility
- unlike glass high fatigue resistance
- electrical conductivity
- double up to a hundred times more expensive than glass
- they are very strongly anisotropic
- often have poor adhesion to the matrix, therefore, it is necessary to modify the surface

The fibers can contain various amounts of graphite, accordingly, they are referred to as:

Carbon - with a predominance of amorphous carbon

Graphite - with a predominance of crystalline graphite

Preparation methods:

- pyrolysis of polymers - the most common method today - synthetic polymers - polyacrylonitrile (PAN), natural polymers - different pitches
- Pyrolysis of hydrocarbons - even nanofiber formation is possible
- evaporation from the arc discharge between carbon electrodes - the positive pressure of argon - whiskers

Polymeric fibers

Polymeric fibers are usually designed for polymeric matrices. The disadvantage of all polymeric fibers is higher temperature sensitivity, as well as their poor wettability. The reason is the low surface energy of the fibers and therefore they require modification of the surface (surface treatment).

The basic properties of polymer fibers:

- low density of about 1 g.cm^{-3}
- medium-high strength
- low stiffness
- usually a relatively large elongation at a fracture
- in principle, chemically resistant, attacked only by strong acids and lyes
- degrading effect of UV radiation in the presence of oxygen

A typical representative of this type of fiber is KEVLAR (aramid - aromatic polyamide), its basic characteristics are:
- strength of about 2.8 GPa
- at a density of 1.44 g.cm^{-3} excellent relative strength - five times that of steel
- deformation at a fracture slightly smaller than in glass, but larger than graphite
- during long-term heating above 175 °C Kevlar fibers degrade
- the negative coefficient of thermal expansion

Ceramic fibers

Ceramic based fibers are characterised by a relatively low weight, high strength and high modulus of elasticity. These include primarily boron fibers, carbon fibers, and further carbide, nitride and oxide fibers.

Boron is one of the substances that are very difficult to make malleable and is highly reactive, so for use in a metal matrix a thin layer of SiC is applied on the fibers.

Carbon fibers are the most important among ceramic fibers. They are produced in the form of carbon or graphite fibers, which varies in the final processing temperature. In the first case, carbonization ends at a temperature of 900 – 1500 °C, in the second case, graphitization is carried out at a temperature of 2600 – 2800 °C. Graphitization increases the modulus of elasticity while the strength decreases. The advantage of carbon fibers is their very low density.

Other types of ceramic fibers are simple compounds, most commonly oxides (MgO, ZnO_2, TiO_2, Al_2O_3, and SiO_2), mixed oxides (mullite $3Al_2O_3.2SiO_2$ or spinel $MgO. Al_2O_3$), carbides (SiC, TiC, B_4C), nitrides or metal compounds.

Basic characteristics of ceramic fibers:

- high thermal resistance and stability
- used in composites with metal and ceramic matrices for high temperatures
- high rigidity
- lower density than metals, but higher than plastics or carbon fibers
- low thermal expansion
- low dependence of strength on the temperature
- unlike carbon, glass and aramid they withstand even greater pressure (more than fibers they often approximate needles or rods - have considerable bending stiffness)
- usually have only a very small slenderness ratio - are relatively short

SiC fibers, as one of the most abundant, have two basic methods of production according to whether they were to be continuous or short.

Metallic fibers

Metal fibers are among the cheapest, but they are relatively heavy. They are used to reinforce the metal matrices. Due to their specific weight (density) they are not too preferred. The main role in the preparation of the composite metal-metal is played by the compatibility of the fibers and the matrix.

For reinforcement of metal matrices for temperatures up to 300°C fibers of carbon steel are used. For the reinforcement of metal matrices for a high temperature, fibers made of heat resistant metal are used, for example tungsten or molybdenum. Specifically, these are the most commonly used fibers:

- steel - often strengthening aluminium alloys
- tungsten - for strengthening heat resistant materials, but they are very heavy
- boric - very light, yet rigid and solid; their production is relatively difficult; typical representative - Borsic fibers: where a layer of boron is applied on a thin tungsten wire by a chemical deposition of BCl_3 vapour and its surface is protected against oxidation (or any boron diffusion into the matrix) by a thin layer of SiC
- recently, extensive research into the fibers of the metallic glasses has been carried out

Whiskers

Whiskers are special thin crystals with a minimal amount of defects within the structure.

Whiskers with its properties exceed other reinforcing phases. These are single crystals/monocrystals whose characteristics depend mainly on the conditions of growth, and the perfection of the surface and diameter. It is necessary to distinguish whiskers from monocrystal fibers of the same chemical composition - those have a number of free, moving dislocations. The most important characteristic of whiskers is a high modulus of elasticity.

Basic properties of whiskers:

- the diameter of less than 1 μm, length of 3 - 4 mm, a slenderness ratio above 1000 - they usually behave as long discontinuous fibers
- there should always be a special type of cultivation - so they contain only one screw dislocation in the middle
- they can be obtained from a variety of substances by the condensation of vapour within the vacuum
- the strength is about 1/10 E, up to this value a whisker deforms only flexibly, after exceeding this value, it deforms as a regular monocrystalline fiber

❑ **Skeletal reinforcement**

Skeletal reinforcement is one in which the matrix and secondary phase creates skeletal formations which are mutually mechanically penetrated. In this case we distinguish a matrix and armouring skeleton. The technology of preparation consists of the infiltration of the matrix skeleton by a liquid substance (a low-melting metal or polymer) which solidifies in the pores of the matrix and creates the armouring skeleton. A master skeleton is a porous body of metal, ceramics or graphite prepared by powder metallurgy techniques.

2. Identification and properties of composites

Time to study: 1 hour

Goal After studying this paragraph you will be able to

- define the basic types of composite materials
- describe the principle of synergy and its possible application
- distinguish the composite materials according to the content and the concentration of individual components

Interpretation

2.1. Composite action

When forming metal alloys metal bonds are applied, in polymeric materials covalent bonds are applied and in ceramic systems ionic or ion-covalent bonds are applied. Formation of composite materials is based on a mutual **synergy effect** (i.e. cooperation) of surfaces of the involved phases (matrices, reinforcement) at their interface. An important precondition for good connections of the connected phases is their mutual adhesion. In order to stabilize their connection the reinforcement matrix must be wetted. Wetting may be applied by physical or chemical sorption, or also by a chemical reaction of the matrix with the surface of the reinforcement. The last case is undesirable because it leads either to a distortion of the reinforcement or secondly to the formation of a brittle interphase, which deteriorates the properties of the composite.

To be a perfectly compact composite the matrix must well wet the reinforcement. This is achieved if the energy of the free surface of the reinforcement is high and the surface energy of the matrix is minimized as possible. **Wettability** is defined by a so-called contact angle θ (wetting angle), which originates at the interface between a liquid and gas with the surface of the solid phase. A good wettability condition is met by a low contact angle, i.e. the value of cos θ is close to one. Otherwise it is poor wettability.

The easiest way to prepare composites is having the matrix in the liquid state.

2.2. Classification of composites

According to the matrix material

- Metal Matrix Composites (reinforced metals, cermets, alloys) - MMC
- Polymer Matrix Composites based on macromolecular substances (reinforced polymers) - PMC
- Ceramic Matrix Composites (ceramic and other inorganic composites: ceramics, glass, carbon) - CMC

According to the structure or geometry of the reinforcement

- dispersive composites - contain very fine particles, dispersion

- particulate composites (particulate, granular) - contain larger particles of regular shapes (spheres, platelets) or irregular shapes
- fibrous composites - contain long or short fibers that may be oriented or unoriented, be of various origins (glass, carbon, polymeric, textile, etc.)

In practice, composites are classified according to the geometric shape on a particulate and fiber composites.

Particulate composites

Particles as a reinforcing phase are dispersed in a matrix and do not own an aggregate structure. They may have a spherical, lamellar, rod or irregular shape where one dimension of such a reinforcement unit does not significantly exceed the dimensions of others. A metal, polymeric, or ceramic matrix is used. The most often used particles are: oxides, nitrides, carbides and borides.

Particles in the composite limit the development of the plastic deformation in the matrix material, and participate in the transmission of stress, but to a much lesser extent than the fibers in the fiberous composites.

Particle reinforcement (**filler**) is used to improve the properties of matrix materials, for example to modify thermal and electrical conductivity and the behaviour at high temperatures, to reduce friction, increase wear resistance, improve machinability, increase hardness, and reduce contraction.

Generally speaking, from the mechanical point of view, the particles in the matrix of the composite cause strengthening

Dispersive strengthening is typical primarily for the metal matrix composites - such a composite has a greater tensile modulus, higher thermal stability and reduced contraction.

Granular strengthening is based on separate particles of different sizes and their different volume share in the matrix. Optimum strengthening occurs at approximately the same particle size and their even distribution. Such composites are used particularly to obtain specific combinations of performance and not only to increase their strength. A concrete system with a crushed aggregate can be given as an example of granular reinforcement.

Fibrous composites

For fiberous composites the units of reinforcement (fibers) in one direction are significantly larger than in other directions.

Synergistic interaction (synergy) between solid and rigid fibers with a ductile or brittle matrix allows for the construction of composites with high strength, stiffness and toughness. These composites have the widest range of application.

2.3. Basic types of composites

Generally (speaking) almost every material used today is a composite. Materials in a pure form are almost unknown. A strict definition determining what exactly is or is not a composite does not existing, it is always a matter of perspective and criteria for assessing the material.

Composites can be divided into two basic groups:

Traditional/Conventional composites

- alloys
- materials with a paint or finished surface
- dispersion
- layered (laminated) materials

New composites

- associated materials (sandwiches)
- fiber reinforced systems
- granular systems (large particles)
- penetrated systems

2.4. Properties defining a composite

- the characteristics of the phases - mechanical properties, isotropy and anisotropy of phases, ...
- the volume of the phases - the geometry and arrangement of phases in the system
- the interaction with a surrounding environment
- the history of a material - it should be taken into account how phase composites were created, material aging , ...

2.5. Structural classification of composites

The composite as a whole is formed by a superstructure. The structure of the individual phases, which are contained in the composite is called an infrastructure. The term microstructure is designed to describe the structure of the individual substances that are contained in each phase of the composite.

Specifically cement concrete. This means the structural arrangement of cement concrete as a system is described by a superstructure, which is formed by the infrastructure of the binder, liquid phase (pores) and fillers. The binder is composed of a variety of minerals and each mineral has its own microstructure. The same is obviously true for every grain of the filler. The third infrastructure (pores) may be formed by a gas or liquid.

Cement concrete = **superstructure** - the main determining factor of the composite, which tells us how many distinct phases are there in the system, how are they arranged, etc.

Aggregate, binder and pores = **infrastructure** speaks about the shapes of individual phases, their sizes, and how they touch.

Minerals in the binders, liquids and gases in the pores = **microstructure** says for example, from what the molecules of individual minerals are in phases, what is the nature of those minerals.

❑ **Composites according to the number of stages in a superstructure**

- **single-structured** - systems with one matrix and one or more added phases
- **two or multi-structured** - systems with two or more matrices, where each may contain one or more added stages

A multistructure usually provides the significantly better properties of composites.

❑ **Composites in accordance with the condition of an interphase boundary**

- **conjugated systems** - by chemical and physical forces at the interface the material remains rigid even under external forces; by the phase that reinforces the system are those further divided as:
  - o granular - axial dimensions of the particles are not very different (aggregate)
  - o fibrillar - where there is one dimension prevailing (fiber)
  - o lamellar - one dimension is suppressed compared to the other two (plate)
- **disjugated systems** - bonds between phases are so weak that the system has only limited consistency (loose materials, earth/soil) - not a composite

❑ **Superstructure evaluation according to the reinforcement condition**

- **segregated reinforcement** - reinforcement particles are not in direct contact, they do not create their own infrastructure, reinforcement is a discontinuous phase
- **aggregated reinforcement**- the individual particles are in direct contact, they can create their own infrastructure - they are somehow arranged, reinforcement is a continuous phase

❑ **Dividing composites according to a superstructure**

- composites **Type I** - the space they occupy is completely filled (without the presence of a liquid phase)
- composites **Type II**
- composites **Type III**

❑ **Composites Type I**

A system that does not contain pores. This system is composed of matrices and fillers and their mutual relationship is that the filler particles are segregated, i.e. they do not touch. It is a system where there is not too much of a filler. An example of composite type I is a polymeric matrix with added particles such as ash, without pores. A second common example is the glass matrix composite, non-porous again.

Two-component system: $V_k = V_m + V_f$

❑ **Composites Type II**

A system, that is already three-phase, consisting of a matrix, filler and pores. In such a system there are little pores, less matrix, and it contains mostly filler. As the filler takes up most of the whole system, it is aggregated. And because the system contains little pores, they are segregated. An example of composite type II is concrete.

Three-component system: $V_k = V_m + V_f + V_v$

❑ **Composites Type III**

This system is again a three-phase, therefore it contains a matrix, filler and pores. In this case it is again a little matrix, but a lot of filler and pores. Both the filler and the pores are aggregated. These pores are even and continuous. If the pores are completely continuous, the system is inconsistent. It follows that it is a material with good insulating properties, such as plasterboard.

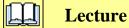Three-component system: $V_k = V_m + V_f + V_v$

3. The choice of materials, production of composites, fiber production

Time to study: 1 hour

Goal After studying this paragraph you will be able to

- assess the suitability of the materials used for the preparation of composites
- describe the basic methods of composites and fibers production
- define composites with metal matrix

Lecture

3.1. Principles and material selection problems

The correct choice of material for a given application is extremely important and in the process of a new product development it is the key.

The correct choice of material affects the utility properties of the future product - whether it will perform the function for which it was designed.

Inappropriately or less suitably selected material can significantly be reflected as:
- technological problems during production
- increase in the cost of production and thus in the price of the final product
- a negative impact on the environment.

❑ **Choice of material**

The choice of material is a complex process where it is necessary to consider such factors as:

- materials costs
- production cost
- energy and raw material demands (material intensity)
- the possible impact of material choice on the environment - production and consumer cycle
- the possibility of material recycling

❑ **The relationship of material, technology and product**

The function of the product (its components), structure (its shape), material and technology interact and therefore the choice of material for the product cannot be carried out independently of the technology.

❑ **Parameters and requirements during designing the product**

- the selection of individual (most suitable) components with regard to their future performance

- determining the compatibility of components - each phase in the composite must maintain its positive qualities, ingredients (components) must not damage each other
- finding an appropriate geometrical form for each phase - stronger parts to be elongated (fibers, strips, belts etc.), while the weaker phase should be wrapping the stronger one and bring individual fibers together into a single structure
- phases in the composite should be distributed so that they can work together
- conditions in which the future composite will function - temperature, abrasion, etc.

❑ **Production Problems**

The less similar associated phases are, the more difficult it is integrating them into a whole. In the opposite case the result is a composite with excellent cooperation between these phases, and therefore with excellent properties.

Production of fiber composites

The main problem is to insert the fibers into the matrix avoiding mechanical damage and to maintain the uniform distribution, directionality and coherence of fibers. Fibers may be relatively easy to break (mechanically) during each manipulation, especially non-metallic fibers (glass, ceramics) are sensitive as their strength depends greatly on the surface integrity. With fiber bundles we need to ensure wetting of each fiber, e.g. by means of wetting agents.

Production of particulate composites

Production of particulate composites is considerably simpler, grains are not as sensitive and therefore intensive manual mixing can be used. It is necessary to ensure complete coating of all grains by a matrix, force out the air and ensure maximum homogeneity of a mixture, and further to prevent particle sedimentation, while the viscosity of the matrix is important (as well). In some cases, sedimentation is used especially when we want to obtain a material with a graduated percentage of filler.

❑ **Components choice**

The basis is selection in accordance to the desired/required mechanical, physical and chemical properties. It is necessary to insure contact of the two components, therefore:

- the matrix must wet the reinforcing phase
- the matrix must withstand a surrounding often aggressive environment
- it must have the ability to deform under load
- it must restrict the development of cracks

3.2. Composites production, fibers production

During production it is necessary to ensure the following conditions in particular:

- the distribution of the reinforcing phase in the volume is even
- the possibility of putting(in) layers with a random orientation of fibers
- a good connection of reinforcement and/with a matrix
- the possibility of changing the volume of the reinforcement
- the possibility of heat treatment after production
- the simplicity and effectiveness of production

❑ **Methods of composite production**

The procedure for the production of composites is divided according to the state of the matrices during its application on the frame in the following way:

- production of composites **with** a **matrix in the solid state**
- production of composites **with a matrix in the liquid state** (melts, solution)

❑ **Production of composites with a matrix in the solid state**

- **pressing/press forming and hot rolling**
- **plasma injection**
- **powder methods**

Pressing or hot-rolling are mainly used for producing composites with metal matrices, single layer or multilayer.

Pressing / press forming

While pressing, the reinforcement (of fibers) is placed between the metal foils and inserted between heated press boards, where due to the action of pressure and temperature both components connect diffusively. Pressing takes place in a vacuum or in a protective (modified) atmosphere. By the compression of several single-layer parts of the multi-layer composite are formed.

Hot rolling

The fibers are inserted between two metal foils which pass between the pressure rollers at elevated temperatures.

Plasma injections

Plasma injections are used for the production of composites with a metal or ceramic matrix. Reinforcing fibers are covered in layers by plasma spraying and the resulting layers are subsequently connected by pressing (ceramic matrix), or hot forming in a vacuum (a metal matrix).

Powder Method

This method is applied in the production of composites with metal, ceramic and polymeric matrices. The base is the application of the powder metal, ceramic or polymer matrix onto reinforced fibers (by electrostatic forces, in water suspension, etc.), compaction into a shape and then the subsequent sintering at high pressures and temperatures. Whiskers (metallic or ceramic) may be mixed into a powder matrix. The most important application of a powder method is in the production of composites with ceramic matrices. It is the basis for the production of composites with a skeletal matrix.

❑ **Production of composites with a matrix in the liquid state**

The methods of producing composites with a liquid matrix are the most commonly used. The basic condition for producing and obtaining the optimal properties of composites are:

- good wettability of reinforcement by a matrix material
- minimum development of chemical reactions at the interface of the matrix - reinforcement

Production/manufacturing methods - the most commonly used

- **impregnation of the reinforcement-matrix liquid**
- **infiltration-gas phase**

and that is in connection with the technology **- forming**, **casting**, **injection moulding** etc.

Impregnation of the reinforcement by a matrix in the liquid state

It is used in the production of composites based on thermoset (polymers), thermoplastic and metal matrices. The principle is based on (comprises) the saturation of a shaped reinforcement (fibers, fabrics, mats) with a corresponding liquid matrix in the form and subsequent solidification (thermosets by hardening, thermoplastics by solvent evaporation and metals by crystallization).

Gas-phase infiltration

At the gas-phase infiltration the reinforcement (of continuous fibers) is saturated by vapours arising from the thermal decomposition of chemical compounds - so-called matrix precursor. There is a condensation of saturated vapour on the reinforcement (fibers) and a solid phase forms.

Casting technology (e.g. pressure) is used mainly in the manufacture of metal composites with short fibers (possibly with whiskers) or polymer composites.

Forming technologies are suitable for the production of shaped parts, profiles, panels, etc. The oldest technology is a hot pressing. More recent technologies include extrusion and injection moulding.

❑ **Production of glass fibers**

The base of glass fibers is carbon SiO_2. In a glass furnace, fresh molten glass is produced from a batch, or rather glass beads or frits are melted. The glass is then drawn (becoming fibrous) by nozzles located in the bottom of the furnace. The fiber diameter is typically 1 mm, but it can be regulated by stretching the glass stream flowing from the furnace. The final diameter of the fiber is given by the difference between the flow speed of molten glass and the speed of extracting the individual fibers. After removal from the furnaces, monofilaments are surface-treated with lubricants, grouped into strands and wound onto a coil. Before use, they are usually spun using one of textile technologies into the desired shape.

❑ **Production of graphite and carbon fiber**

Graphite and carbon fiber are mainly made of fibers of PAN (polyacrylonitrile fibers), and from novoloid fibers (phenol-aldehyde fibers). The production of PAN fibers has three basic steps:

- **stabilization** - 200-300 °C, an oxidizing atmosphere, and the fiber is under mechanical stress, it will cross-link macromolecules with oxygen bridges; fiber turns black and becomes infusible.
- **carbonization** - 1200-1500 °C, an inert atmosphere N_2, the decomposition of macromolecules, hydrogen removal, the reduction of oxygen and nitrogen, 80-95% mass is carbon; fiber achieves the highest strength
- **graphitization** - 1800-3000 °C, an inert atmosphere of N_2 and Ar, a further increase of the carbon content, the similar conversion of the recrystallization of a given graphite is taking place; the increase of fiber stiffness; due to the growth of the graphite crystals and the increase of defectiveness, fiber strength decreases

Carbon fibers are protected against abrasion (they are more fragile than glass, and in order to reduce adsorption of the gases on their surfaces) by using polymeric coatings. It is also necessary to increase surface reactivity towards binding agents, of the matrix and therefore it is necessary to roughen the surface of the fibers by etching for example.

❑ **Production of boron fibers**

Boron fibers are prepared by the CVD method (Chemical Vapor Deposition). This method is based on reducing the gas mixture (H_2 a BCl_3) that is fed into the reactor due to high temperature. The substrate is a thin tungsten filament. Boron trichloride is reduced with a hydrogen forming elemental boron, which is deposited on the substrate surface.

❑ **Production of SiC fibers**

Continuous SiC fibers are produced, like boron fibers using the CVD method. The source of silicon and carbon are gaseous alkylsilanes (CH_3SiCl_3), which are reduced in the reactor with hydrogen. Silicon carbide settles on the carbon substrate. Short fibers of SiC - whiskers are produced for example from rice hulls, which are annealed in an inert atmosphere, wherein there is the decomposition of organic substances and the conversion of SiO2 present in the shells into SiC.

3.3. Metal matrix composites (MMC)

The preparation of each of the composite materials is based on the nature of its components. All materials have their positive and negative properties, but by preparing composites (from them), we usually try to change them. The assessment of the advantages and disadvantages of these materials are always presented in the context of other used materials, resp. composites.

❑ **The advantages of the metal matrix**

- high strength and toughness
- usability at higher temperatures
- non-absorbability
- improved/higher radiation resistance
- they do not absorb or release gases into the surrounding area
- mostly non-flammable
- they conduct electricity and heat well
- the possibility of welding (them) to each other and with other metals
- higher hardness and wear resistance
- resistance to surface damage, and more

❑ **Disadvantages of the metal matrix**

- more complex production
- relatively underdeveloped technology of production
- high specific weight, density
- typically a higher price
- little experience with maintenance and disposal
- worse formability
- some are subject to corrosion

❑ **Basic requirements**

In metal matrix composites we are not generally concerned about the increase of the firmness or the strength. The basic purpose of manufacturing these composites is:

- the extension of the temperature range to which the metal is usable
- suppression of creep at higher temperatures
- to reduce the temperature dependence of mechanical properties on the temperature
- to increase the abrasion resistance
- to reduce specific weight (density) against a pure metal
- to improve dimensional stability (the reduction of thermal expansion)

❑ **Metals used for the matrix**

Aluminum and aluminum based composites

They are the most widely used metal matrices, mainly for their price and variability. Aluminum is lightweight, does not corrode, malleable at low temperatures and affordable. There are many modifying alloys, (with) resistance up to 600 °C. The resulting composites have a good strength to density ratio, therefore, they are often used in aeronautics and the automotive industry and also have a good thermal and electrical conductivity. Due to the high activity of aluminum to oxygen the reinforcing phases mainly are oxides Al_2O_3, carbides Al_4C_3 and SiC.

Titanium and (titanium) based composites

They are used mostly for fiber composites. Among the features are the variability of the alloys, a strength similar to steel, low corrosion and a higher price. Such composites have about twice the density of aluminum, but the ratio of strength to density for titanium composites is even higher than for aluminum, and moreover they can withstand much higher temperatures. They are usable up to 1000 – 1200 °C, compared to aluminum. Titanium alloys are very reactive at increased temperatures and therefore prone to react with fibers or other fillers during production. As a reaction, a brittle interfacial zone occurs that reduces the material strength. The most frequently used alloys are $Ti_6Al_{14}V$, $Ti_3Al_{25}V$ or pure titanium.

Silver and silver based composites

They are characterized by good electrical conductivity, have a high melting point and therefore are used primarily in electronics for electrical contacts of different relays, switches and circuit breakers. These composites are reinforced by dispersion strengthening with the particles of refractory compounds, particularly Al_2O_3, CdO, SnO_2 and others.

Copper and copper based composites

They are strengthen with oxides Al_2O_3, BeO, ThO_2, SiO_2 and TiO_2, which increase heat resistance and thermal stability while maintaining high electrical conductivity. For the reinforcement, particles of carbides, nitrides and refractory compounds are used. Dispersion strengthened copper-based materials are used in electrical engineering and electronics as electrical contacts, motor forces, and in the welding technology for manufacturing electrodes (spot welding galvanized sheet metal), etc.

Iron and iron based composites

They are most often reinforced with oxide particles, but normally ferrous alloys are not strengthened since most of the produced steel alloys are (already) sufficiently resistant to

stress at higher temperatures. Dispersion strengthening in materials based on iron oxides is done by admixing oxides in terms of resistance to embrittlement in the field of neutron devices.

Nickel and nickel based composites

Dispersion strengthening is done by oxides ThO_2, HfO_2, ZrO_2. Dispersion strengthened nickel alloys are stronger and more stable to higher temperatures. It is a refractory material for operation in a temperature range 650-1650 °C. They are mainly used in aviation and space technology.

The reinforcement should be selected so as to avoid chemical reactions.

❑ **Production of metal matrix composites**

Manufacture from melt
- particulate composites
- fibrous composites

Powder metallurgy
- cermets
- sintered carbide as composites

Directional crystallization

Special systems
- bearing composite materials
- glass-metal composites
- complex composite systems

❑ **Particulate composites**

More than three quarters of all composites with a metal matrix are particulate composites. Although it is possible to use any metal as the matrix and as a dispersion any ceramic or metal particles, (nowadays) the most typical is a composite with an aluminium matrix and a dispersion of SiC or Al_2O_3.

❑ **Fibrous composites**

The most common is again a matrix of aluminium or titanium alloys, where various types of fibers, continuous or discontinuous in length, are usually arranged in one direction or a plane are used.

The most common types of fibers are BORSIC fibers with the designation B/W, meaning boron fiber on a tungsten medium, further SiC/C which is a carborundum fiber on a carbon medium (it can be prepared by vacuum sputtering on the bearing carbon fiber), SiC (whiskers), C (PAN) or Al_2O_3.

If the fibers are arranged in one direction, the MMC composite has very strong anisotropy (of) properties Fibers also strongly reduce the dependence of mechanical properties on the temperature and broaden the range of the application of metal alloys. They can increase the fracture toughness, improve fatigue properties and suppress creep.

❑ **Powder metallurgy**

Powder metallurgy is widely used for materials where the dispersion can be efficiently pre-sintered and then infiltrate the matrix into it. The condition is good wetting dispersion of the molten matrix. Therefore it is often a mixture of the particles of two metals.

❑ **Cermets**

Cermet is a term for composites produced by powder metallurgy with the matrix of moderate or refractory metals and a refractory dispersion of compounds (often oxides). The quantity of dispersion usually exceeds 50%, so there are often pores within the structure in large quantities. Conventional cermets and special cermets A+W are used primarily where there is the requirement for high abrasion resistance, corrosion resistance, changes in temperature and high mechanical strength.

❑ **Sintered carbides as composites**

So-called sintered metal carbides have a similar composition and method of making powder metallurgy. It is a composite with a very small amount of a cobalt matrix (15-25 %). As a dispersion there are used carbides, especially WC and TiC. This system is interesting in that the WC in a cobalt matrix is partially soluble and creates a very solid interface.

❑ **Directional crystallization**

For many systems of metal alloys, there are one or more eutectics. In the context of composites there is important the following properties of eutectics.

- One (usually a minor part) of eutectic is often excluded as an individual unit that has a particular shape: thread/fiber, needle, plate, small ball.
- The size of these units at constant conditions for crystallization is constant.
- The mutual distance between these units is also constant, and their distribution within the eutectic cell is even.
- The orientation of these units is bound to the orientation of the interface of the solid phase melt - e.g. fibers grow perpendicularly to the interfaces and others.
- It is then possible to utilize the properties of eutectics to so-called directional crystallization, during which a very perfect composite system is formed directly from the melt.

❑ **Bearing composite materials**

Some composite materials are promising as materials for friction pairs, especially where you cannot use a lubricant (dry friction - vacuum, rocketry). One type of such materials forms a worse fusible metal matrix and fusible dispersion which during partial melting may represent a lubricant.

❑ **Glass-metal composites**

Metal composites with the dispersion of glass powder also have very good friction properties. However, they also have very good corrosion and abrasion resistance. They are produced either by the sintering of metal and glass powder (i.e. powder metallurgy), or the infiltration of molten glass into a pre-sintered metallic matrix.
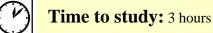
❑ **Complex composite systems**

Primarily for the aviation industry, metal matrix composites made of lightweight metal are a very common material. In a number of cases there are even more complex composite systems made e.g. GLARE laminates, developed and used in the Airbus aircraft. It is actually a composite plate with plates of aluminium and plates of a plastic composite with an epoxy matrix and continuous glass fibers. Such composites resist fatigue cracks very well.

The manufacturing process for **fiber composites** is chosen to reach a perfect blending of the matrix with the fibers, without mechanical damage and without the degradation of the fibers. We must ensure the coherence of the matrix with fibers and avoid embrittlement of the matrix.

In most cases, two-stage procedures are selected where first a simple design - (a single-layer tape) is made, and then (from which) the desired structure is created.

The particles are introduced into the metal matrix usually in powder form, which forms a fine dispersion. The shape of the particles can be spherical or irregular. The function of the dispersed particles in the metallic matrix is to strengthen it by preventing the movement of dislocations. They also increase wear resistance.

4. Polymeric matrix composites (PMC)

Time to study: 3 hours

Goal After studying this paragraph you will be able to

- be oriented in the types of plastics used for the preparation of composites
- describe polymerization, polycondensation and polyaddition
- characterize fiber composites with a polymeric matrix

Composite materials with a polymer matrix can be divided into several basic groups. We distinguish composites based on:

- **plastics**
- **bitumen**
- asphalts
- tar

Plastics

Plastics (polymers) are the most widely used group of composite materials. Plastics are materials based on macromolecular compounds (substances), which can be shaped for example by heat or pressure. Macromolecules are generated by combining simple molecules, called monomers into various chains - linear or cyclic. Such macromolecules vary from other organic compounds by relative molecular weight of 10,000 and an average degree of polymerization of 100 (more than 100 monomer individuals are connected). Organic macromolecules arise due to the ability of some elements to form chains (Si, C). The atoms of these elements can be easily combined in a linear chain and with a network or spatial structure they create a macromolecule.

The characteristics of the polymers are determined by the type of bonds that prevail in the structure. Primary bonds between components determine the size of the molecule and its layout. In addition, there are further secondary links in the structure that connect other atoms. These are bindings of a different nature, Van der Waals forces, hydrogen bridges and others. Both types of links, primary and secondary, together determine the chemical and physical properties of the polymer.

4.1. Categories of plastics according to the behaviour at higher temperature

- **thermoplastics**
- **thermosets**
- **elastomers**

Thermoplastics

Thermoplastics account for about 90% of polymer composites. These are polymers of macromolecules with linear chains in which the macromolecules are bound by random intermolecular forces. These are very long molecules (macromolecules) formed by repeating

the same structural units (several thousand to millions). This type of molecule is known as a polymer.

Very weak secondary bonds (Van der Waals forces, hydrogen bridges) could break with thermal vibrations, therefore these substances soften from a certain temperature, or may transform at a high temperature, and after cooling they get their original characteristics.

Their basic characteristic is the ability of repeated heat treatment.

Thermosets

Thermosets are densely crosslinked polymers. In the case of thermosets the crosslinking in three directions (3-D structure) is formed by primary bonds.

These substances are solid but brittle until the temperature of their decomposition. The method of crosslinking is referred to as curing (at normal or an elevated temperature). They are non-renewable - an irreversible change by heat exposure

Elastomers

In the case of elastomers, the crosslinking is formed by secondary bonds and is called vulcanization. Elastomers are natural and synthetic types of rubber.

Natural rubber is obtained from the rubber milk (latex) of certain tropical trees (rubber trees). Crude rubber is plastic and has a very low tensile strength. It softens when heated in the air and it melts at about 220 °C. Light, especially UV, causes its aging (photochemical oxidation) - rubber loses its elasticity, it becomes brittle. These inappropriate characteristics are lost to vulcanization - a process of crosslinking a linear polymer (elastomer), in which the action of the vulcanizing agent (S, polysulfides, peroxides ...) forms structural changes. This creates a modified product - from plastic rubber there is elastic rubber. The curing process (vulcanization) increases the mechanical strength of the rubber, resistance to temperature changes, the effects of light and various chemicals.

Synthetic rubbers can be vulcanized just naturally and are divided into rubbers for general use and special rubbers. Rubbers for general use have similar properties to natural rubber and are generally used as its substitute. Most important is the polybutadiene. Special rubbers are produced in smaller quantities, and some properties are superior to natural rubber. Gum (rubber) is a vulcanised rubber mixture.

- **Soft rubber** (sulphur content up to 3 %) has low hardness and high elasticity. It is used in tires, seals, and the insulation of electrical equipment, for the production of conveyor belts and in the consumer goods industry (toys).
- **Hard rubber** (sulphur content of 3-3.6 %, ebonite) has a higher hardness, good mechanical and electrical properties and excellent chemical resistance. It is used for fittings, tanks and surgical instruments.

As the basic raw material for making elastomers there is rubber, for the preparation of thermoplastics and thermosets essential raw materials are mainly from coal, oil, natural gas and biomass. By the cracking of crude oil there are (also) obtained, among other things, fractions such as ethylene, propylene, aromatic hydrocarbons as benzene, xylene and toluene. Their further treatment is carried out through the processes of polymerization, polyaddition or polycondensation.

4.2. Plastics by production (formation of macromolecules)

Polymerisation

It is a chain polyreaction at which macromolecules arise from a monomer.

- The principle - one type of monomer plus an initiator (for chaining) - forms polymer and heat (warmth).
- Description - polymerization is such reaction, when no component (hardener, initiator, etc.) enters the macromolecules. The initiator only causes a reaction in hardening and it does not particularly affect the resulting properties of the final product. A small addition of certain substances (the accelerator) can speed up the whole process. To activate polymerisation we can use the temperature, light, or radiation however, it is not possible in construction engineering. It is an exothermic reaction.
- Plastics obtained by polymerisation

    ethylene - polyethylene PE

    isobutylene - PIB, vinyl chloride - PVC

    styrene - PS, vinyl acetate - PVAC

Polycondensation

It is a polyreaction at which (in addition to the macromolecule) a simple low-molecular compound also forms (H_2O, HCl, CH_3 OH …).

- Principle - by linking monomer 1, monomer 2 and a catalytic converter, polymer, water and heat are formed
- Description - polycondensation is a polyreaction which generates in addition to macromolecular compounds an even low-molecular compound
- Plastics obtained by polycondensation

    dicarboxylic acid + diamine produces polyamides

    dicarboxylic acid + dialcohol produces polyesters

    formaldehyde + phenol produces phenol-formaldehyde resin

    Similar or the same for polyester, phenolic and furan resins

Polyaddition

It is a polyreaction method generating macromolecules by gradually adding at least two different compounds associated with the site exchange of hydrogen atoms in functional groups without creating degradation products.

- Principle - by linking monomer 1, monomer 2 and a catalytic converter, polymer and heat are formed
- Description - the addition of the hardener forms macromolecules by connecting gradually all components on the functional groups
- Plastics obtained polyaddition

    diepoxide + diamine produces epoxy resin

    diisocryl + dialcohol produces polyisocryl (polyurethanes)

The five most important plastics which account for around 60 % of the total production of plastics are: PE (low and high pressure, bags and bottles), PP, PVC and PS.

Thermoplastics are prepared by polymerization and polycondensation. Thermosets are prepared by polyaddition.

4.3. Plastics by chemical composition

Name	Atoms included in the main chain	Example
C Plastics - Carbon plastics	atoms: C and H (only)	**polyethylene**
C-O plastics - carbon-oxide plastics	atoms: C, H, O	**polyester**
C-N plastics - carbon-nylon plastics	atoms: C, N, H , possibly O	**phenoplast, aminoplast**
C-S plastics - carbon-thioplastics	atoms: C, S, H , possibly O and N	**polyurethane**
Si-O plastics - (silicone plastics)	atoms: H, Si and O	**Silicones**

4.4. Plastics by feedstock (raw material)

Semi-synthetic plastics

Semi-synthetic plastics are produced by the chemical or physical transformation of natural polymers. Starting materials for their preparation are natural rubber, cellulose, casein, etc. Natural rubber is a product of the rubber latex milk and is the starting material for the production of rubber mixture. Cellulose is a structural (building) element of plant tissues (spruce, poplar). Casein (curd) is a protein from milk, the feedstock (starting material) for the production of adhesives.

Fully synthetic plastics

These are plastics manufactured by the polymerization synthesis of low-molecular weight organic compounds. Low-molecular organic weight compounds are derived from crude oil, natural gas and coal. Production of plastic from those materials is done by using chemical polyreaction such as polymerisation, polycondensation and polyaddition.

4.5. The properties of plastics

All properties are here again placed in the context of other materials that are used to prepare the composites.

❑ **The benefits of plastics**

- low weight (0.8 to 2.2 g.cm^3), density (1600-2000 kg.m^3) compared to steel (7800 kg.m^3) or aluminium (2700 kg.m^3), it means they are lightweight (foamed/cellular/expanded plastics may be up to 0.01 g.cm^3, i.e. density, which is naturally not present at all)
- advantageous mechanical properties that can be modified as required to obtain substances that are hard, soft, porous, abrasion resistant, elastic and more

- insulation properties (low thermal conductivity - 300 times lower than aluminum), thermal insulation, electrical insulation (not current) and sound insulation properties
- easy workability, formability
- good tolerance of different fillers, can hold a large amount of filler
- good chemical resistance
- the possibility of colouring, high durability/lifetime and easy maintenance

❑ **Disadvantages of plastics**

- low resistance to high temperatures (thermoplastics can be used up to 100 °C, thermosets withstand slightly more)
- high coefficient of volume expansion (3 to 15 times larger than metals, and 20 times greater than ceramics)
- low strength that decreases with the temperature and low modulus of elasticity (tensile modulus)
- easily flammable (low ignition point, the production of dense smoke, toxicity), electrostatic charging
- ease reaction with atmospheric oxygen which causes aging and aging due to solar radiation
- swelling with water and associated change of volume

Not all plastics are the same (have the same properties to the same extent) it is only a general overview.

Plastics are materials that due to weather conditions, sooner or later age (get old) and thus lose its favourable mechanical properties. Aging can be slowed down by using various stabilizers (antioxidants, softeners, pigments). Well-resistant to the weather are for example various types of formaldehyde resins, on the contrary with little resistance to the weather (weathering) there are PA, PS, PE and PVC.

The oldest manufactured plastic is Bakelite (1909) - formaldehyde resin reinforced with wood floor.

4.6. Composites with a polymeric matrix and particulate composites

Particulate composites

- particles in elastomers
- particles in thermoplastics
- particles in thermosets

Fibrous composites

- fibers in thermoplastics
- fibers in thermosets

Combined composites

❑ **Particulate composites with a polymeric matrix**

Polymeric matrices have low strength (themselves) and have low heat resistance, in particular. Adding a mixture of dispersion particles to a polymeric matrix increases the modulus of elasticity, thermal (dimensional) stability, reduces shrinkage and improves other properties.

To reinforce the material we mostly use powders of micronized minerals, particularly kaolin, talc, mica, limestone. To improve the sliding properties and abrasion resistance we use for example particles of bronze with a graphite or molybdenum sulphide. To achieve electrical conductivity metal powders (Al, Cu, and Ag) of high concentration are added. To increase stiffness particles of larger dimension (1 mm and more) are used.

Particles in elastomers

Elastomers are generally very homogeneous, therefore we can use very small particles to depressively solidify the elastomers.

A specific example are conveyor belts or tires, where we use from 10 to 20 % of silica powder, talc or carbon black for the base rubber. It often also combines several kinds of dispersion.

Particles in thermoplastics

For thermoplastics there are usually used larger particles with a diameter of 10 μm. They reduce the shrinkage (or final shrinkage), increase the toughness, suppress the viscoelastic behaviour, increase the attenuation and suppress vibrations

Typical examples:

Polystyrene and cellulose particles (sawdust) - anti-vibration material

Polyethylene and 70-80 % of lead powder - protection against radiation (X-ray, gamma-ray) etc.

Particles in thermosets

For thermosets there are also used larger particles with a diameter of at least 10 μm. The effects are: an increase of firmness, moderation of crack growth, an increase of electrical insulation - quartz/silica sand, reduction of flammability - hydrated Al_2O_3 powder.

4.7. Fibrous composites with a polymeric matrix

Fibrous (Fiber) composites with a polymeric matrix are the most common and most traditional composite materials. Reinforcement fibers are used mainly in thermoplastics and in thermosets as well. (Thermoplastics as well as thermosets are mainly used for reinforcing fibers) The most frequently used fibers are glass, carbon, boron and others. The reinforcement is usually made in the form of continuous fibers, nonwoven fabrics, mats, etc.

As thermoset matrices the most commonly used are epoxy, formaldehyde, polyurethane and other resins. Carbon, aramid and glass fibers are preferably used with epoxy resins for laminates.

The thermoplastic matrices are the most common type. A low-cost representative is polypropylene. More expensive and chemically and thermally more resistant are polyamides.

In the case of composites with short fibers, again, thermoplastic matrices are used in the first place and followed by thermoset matrices as well. As reinforcement there are used predominantly chopped glass fibers, but also carbon and other types.

Glass fibers can also be used in the form non-woven fabrics, mats or cloths. Mixtures of polymers with a short fiber provide composite materials with isotropic properties and enable preferable production methods such as injection moulding or extrusion to take place.

❑ **Laminates - laminated materials**

Laminates (laminar composites) are formed by combining multiple layers of polymer and reinforcement. They differ from the composites with a fibrous filler in that the reinforcement is not loose in the matrix, but the individual fibers are spun together in the form of fabrics or mats.

Products from a laminate are manufactured by layering fabrics or mats in order to achieve the desired strength and rigidity of a product. The individual layers are saturated with bitumen, which is then cured. They withstand a bending load well.

The most common laminates:

Fibreglass - glass reinforcement and for example phenol-formaldehyde resin

Formica laminate - tempered paper

Hardened fabrics - (textgumoid)

Fibers for polymeric composites

The most commonly used fibers for polymeric composites are glass, carbon, aramid fibers; boron fibers due to the high price are tended only for special applications in aviation.

❑ **Fibers in thermoplastics**

As the matrix is used: polyamide, polyethylene, polypropylene and polycarbonate. The optimum amount of fibers is about 40-50 %.

For glass fibers in the thermoplastic the critical fiber length is about 0.2 mm. This allows preferably to produce granules of thermoplastics, where the individual granules already contain glass fibers of a sufficient length. As for thermoset composites, the properties are highly anisotropic and depend on the loading specifications.

❑ **Fibers in thermosets**

The classic and the oldest type of mass-produced composites are polymer and glass fiber. Around 90 % of all thermoset composites contain glass fibers. Typically used fibers are continuous or at least long.

The optimum amount of fibers is 60-75 %, a higher amount in the composite has a larger number of pores.

Basic matrices that are used are:

Polyester - is the most common matrix because polyester resins generally have good mechanical, electrical and chemical properties. Polyesters are suitable in a slightly alkaline medium and excellent in a mildly acidic medium.

Polyvinyl esters have good resistance to an acidic and alkaline medium, particularly at high temperatures. PVE profiles with glass fibers have good thermal and electrical insulating properties.

Epoxy - epoxies have excellent mechanical and electrical properties and are commonly used with carbon or glass fibers. (They also have) good electrical insulation properties in a wide range of temperatures, considerable resistance to water, alkali solutions and acids and some solvents.

Phenol - phenolic resins are used for the requirement of high fire resistance, high heat resistance, have low smoke generation and limit flames during combustion, specifically, on various designs of electrical appliances.

So-called Pyrrons - belong to the best thermoset composites, have a heat resistance up to 550 °C, tensile strength 76 MPa, and E 5 GPa.

❑ **Combined composites**

It is often not only one single composite material, but the component is composed of several different materials being appropriately combined. An example is the construction of modern fibreglass skis or tire construction. It also often combines several kinds of dispersion.

4.8.   The production of fiber composites with a polymeric matrix

The properties of the composite are significantly affected by the production process, by the properties of the fibers and their surface treatment.

❑ **The manual laying (using a fabric)**

It is the most traditional method of production, where the glass reinforcement is placed into a mould and subsequently saturated with a binder. The desired thickness is gradually built up from layers (lamination), then the binder is cured and the segment (the workpiece) is removed from the mould. It is the least demanding technology. The fabric provides (ensures) approximately the same orientation of all the fibers and at the same time allows to partially suppress anisotropy, because the fibers are in the two main directions. The fibers are generally continuous. There are various manual or semi-automatic production methods. Specifically, there is for example the manual production of embedding the fabric in the form and over rolling, semi-automatic production by embedding the fabric in a form and over pressing, semi-automatic production by embedding the fabric in the form using overpressure or automated production by embedding the fabric in the form using a vacuum.

❑ **Winding (using continuous fibers)**

It is a technology based on a continuous winding of a fiber bundle or otherwise modified reinforcement to the circular form. The fibers are wound either already moistened with resin, or are moistened after winding. The method of winding continuous fibers onto an appropriate form and the simultaneous or following pouring of polymer is mainly used for hollow, rotary symmetrical parts. It is thus possible to produce even very large parts. Example: winding the wind turbine tower with a height of 55 m and a diameter of 8 m, it is a composite with 50 % of the graphite fibers in an epoxy matrix, the resulting composite has a density of 1.7 g.cm^3, tensile stress of 1150 MPa and E 115 GPa.

For the production of various profiles of plastic composites with continuous fibers there has been developed a production method called pultrusion. The continuous fibers are pulled through a forming nozzle (or slot) in which they are simultaneously saturated with a polymer. It is possible to use both thermoplastics and thermosets. The method is fully automatic and very productive.

❑ **Drawing (fiber drawing)**

Technology based on drawing fiber bundles, mats and fabrics in a resin bath, where the reinforcement is saturated. Then the (saturated) reinforcement is formed into a desired shape and cured.

❑ **The injection and blowing method (using discontinuous fibers)**

It is used for preparation of composites from granular material which already contains the fibers. You can use slightly modified equipment for the injection, blowing or pressing of conventional plastics. The method can be used for thermoplastics and thermosets as well. The plastic melt has during the processing (e.g. injection) usually relatively high viscosity. This causes the individual fibers to orient in the direction of the melt flow, therefore it is possible to achieve a partial orientation of the fibers of the product.

5.   Ceramic or glass matrix composites (CMC)

Time to study: 1 hour

Goal After studying this chapter you will be able to

- define the basic methods of ceramic applications for composite materials
- distinguish the technologies of preparing substrate for glass matrix composites
- describe the difference between the partially crystalline glass and glass ceramics with dispersion

5.1.   Ceramic matrix composites

Ceramics are inorganic non-metallic materials with a heterogeneous structure. They consist of glass, pores and minerals of different compositions. Material based ceramics have high strength at elevated temperatures and are resistant to oxidation. Their main disadvantage is their brittleness.

❑ **Advantages of ceramic composites (compared with metals)**

- low density
- low coefficient of thermal expansion
- higher hardness
- higher temperature and corrosion resistance and even wear resistance
- higher melting point and the stability of mechanical properties in a wide temperature range

❑ **Disadvantages of ceramic composites**

- the final product of ceramics cannot be subsequently modified by any thermal or mechanical processing
- low fracture toughness
- brittleness
- difficult reproducibility of complex shapes
- difficult bonding of ceramics with each other and with other materials as well

❑ **Ceramic matrix composite requirements**

- to increase the toughness of the ceramic matrix
- to even the strength - especially tensile strength, to suppress the dependence of the ceramic matrix strength on the type of stress and the dimensions of the components
- to increase the abrasion resistance in extreme conditions
- to increase heat resistance in extreme conditions
- to improve the machinability of the ceramic matrix

5.2. Particulate ceramic matrix composites

For the reinforcement of the ceramic matrix there are suitable only synthetically prepared ceramic powders based on oxides, nitrides, or carbides respectively borides. Matrices have a similar base; oxides, carbides, nitrides, borides, or graphite as well.

These include the composites systems:

Ceramics - ceramics

Ceramics - metal

Composites based on graphite

Ceramics - ceramics

In ceramics - the ceramic system there is a secondary ceramic phase dispersed in the base of a ceramic matrix. For example in the Si_3N_4 matrix there are dispersed particles of SiC or B_4C. Both phases shall contribute to the improvement of properties for use on the component in the course of applications in aircraft and rocket technology.

Ceramics - metal

These systems are generally referred to as **cermets**. They are oxide or carbide-based (Al_2O_3, WC, TiC). As cermet is considered a composite material with the content of a ceramic component of more than 50 %, the rest is metal.

Their properties are a combination of both materials, i.e. good thermal and electrical conductivity, heat resistance, chemical stability. The main areas of their use are the rocketry and aviation industry, electronics, nuclear engineering, mechanical engineering and metallurgy.

Oxide-based cermets (Al_2O_3-Cr, Al_2O_3-Fe, Al_2O_3-W) are used for cutting tools, the thermocouple sleeves etc.

Carbide-based cermets (WC-Co) are used for components with a very high surface hardness, valves, nozzles, accurate gauges.

The systems of ceramics - metal and composites based on graphite are prepared via processes such as sintering or skeletal type of systems where the matrix and the secondary phase are mechanically penetrated and create a so-called skeletal structure.

Graphite-based composites

Composites based on graphite are represented by a graphite skeleton impregnated with metal. Currently, it is the most widely used composite. They have very good mechanical properties and are chemically resistant. They are used for sliding bearings, sealing rings, (the slides of pantographs) on trolleybuses, trams or trains.

5.3. Fiber ceramic matrix composites

Ceramic matrices are brittle, have poor fracture toughness, but on the other hand, they have excellent high temperature properties and chemical resistance. To increase the fracture toughness there are fibers with a higher modulus of elasticity than that of ceramics introduced into the ceramic matrix. Fibers that are used are metal (tungsten, molybdenum), ceramic (SiC) and carbon. The strongest types are metallic and ceramic whiskers.

When using whiskers, the matrix is formed by ceramics based on Al_2O_3 or ZrO_2 and dispersion is formed by whiskers, mostly SiC. There are newly used also Al_2O_3 whiskers. The

composite has high tensile and compressive strength at both normal and high temperatures. Whiskers increase resistance to creep and erosion, and reduce the coefficient of friction.

Short fibers are prepared for example from SiC, Si-Ti-O-C, Al_2O_3, Si_3N_4 and other materials. They are used to increase the fracture toughness and reduce the creep of conventional ceramic matrices from oxide or non-oxide ceramics.

Carbon or graphite fibers can be incorporated into a matrix of a suitable polymer which is subsequently graphitized. A basic semi-finished product with a plastic matrix is produced by conventional methods for the preparation of PMC and further graphitized. Graphitization is a relatively difficult process because fibers must not be degraded during the course. These composites are used for example in the most demanding parts of space shuttles (the leading edge). A carbon fiber must be (also) often protected against oxidation by SiC coating.

5.4. Ceramic coatings

Ceramic coatings are applied in difficult operating stress, in an aggressive environment and while working at increased or high temperatures. They provide higher wear resistance, avoid fatigue failure and also serve as an effective heat and corrosion barrier. Commonly used technological processes for their preparation include CVD and thermal spraying.

Typical compounds - nitrides (TiN, Si_3N_4), carbides (TiC, WC, and SiC) and oxides (Al_2O_3, TiO_2, ZrO_2, and MgO).

5.5. Glass matrix composites

As a substrate for glass matrix composites there is used in most cases flat glass, which is either surface treated, layered or the composition of the glass is modified from which it arises.

❑ **Composites substrate production**

Flat glass drawing - Fourcault method

Molten glass is a melt of silica sand, dolomite, limestone, soda and other components. Its specific composition can be modified as needed. The types of used glass can be found in the Chapter 3.2 Composites production, fibers production. The principle of this method is based on melting the charge in the melting aggregate, a fire-clay discharge is lowered into the bath of molten glass, where its slot creates the base of a glass sheet due to buoyancy. A sheet of glass is constantly drawn in a shaft, which serves as a lehr (for cooling), the glass strip is pulled upwardly and subsequently cut off according to the requirements.

Float glass production - Float method

The molten glass of the same composition is melted from a batch in the melting aggregate similarly as in the previous case. The principle of this method is then based on molten glass which is gradually passed from the melting furnace into the area of shaping, which takes place on the surface of the molten tin. Tin guarantees the quality surface of the bottom side of the strip-shaped flat glass, the top layer is in contact with the furnace atmosphere only, and its quality depends on the surface tension of the molten glass. After passing through the cooling furnace the glass strip is cut and modified as required.

5.6. Particulate composites with a glass matrix

❑ **Turbid glass**

- opaline glass
- opal glass
- opaque glass

There are dispersed foreign particles in the glass (crystalline, vitreous, and gaseous). These particles have a different refractive index from other glass, they scatter light and the isotropy of the glass changes. Particles cause turbidity whose level depends on the difference between refractive indexes, on the size of the particles and their quantity.

A slight turbidity provides **opaline glasses** (phosphates) a yellow, blue. More turbidity give **opal** glasses (fluorides) milk glass. Non-transparent or **opaque** glasses are produced by the exclusion of borides from the molten glass (larger particles), in which they are initially dissolved.

This type of glass is primarily used for aesthetic purposes-chandeliers, furniture glass, ovenproof glass (Pyrex) or jewellery.

❑ **Coloured glass**

- photosensitive
- photochemical
- anti-sun glass

These are generally sun glasses and welding goggles-eye protection, colour filters or signal glass in transportation. The homogeneous ionic colours are ions of transition elements and rare earth elements that provide colouration independently of the composition of the glass. Heterogeneous colloidal colours are the respective oxides and their compounds, metal particles of Cu, Ag, Au, Pt, which when introduced into the glass mixture reduce and cause colouration.

Photosensitive glass

This glass is used for eye protection glasses and goggles having iron oxides as the active colouring ingredient , which absorbs UV (Fe^{3+}) and IČ (Fe^{2+}) radiation, but other colouring oxides (Mn, Bi, Cr, Ti) are also introduced.
These glasses absorb 50-90 % of the light in the visible area. Welding goggles should have a green tint due to the high content of iron oxide; the blue tint is caused by Fe^{3+} and Cu^{2+} ions for lower temperatures.

Photochromic glass

It is used for eyeglasses and instrument glass in measurements (dosimetry). Photochemically active glass (Ag halides) becomes for example darker when exposed to a visible light, because it does not allow the full range of colours to pass through.

Anti-sun glass

This glass is used for the windows of vehicles, the glass is coloured by iron oxides with a predominance of Fe^{2+} and captures the thermal component of the solar radiation.

5.7. Partially crystalline glass

Sitalls or glass ceramics are glass-formed materials which can be easily forced to partially crystallize. Therefore the basic glass matrix creates a dispersion from microcrystals of certain ingredients. The volume amount of the dispersion is usually 40-50 % and the size of crystals is in tenths of micrometers.

There are three basic methods for preparing these composites:

- The heat treatment of the glass - glass is heated for long time to a temperature above the devitrification point (the temperature at which transition of amorphous structure to a crystalline structure by diffusion of individual particles occurs, without melting) so that the formation of small crystals inside the glass emerge.
- The controlled cooling of the glass - the molten glass is cooled so slowly that during cooling it partially crystallizes.
- Glass frit sintering (glass powder) - where the frit partially crystallizes

The most frequent types of composites contain, besides the conventional nitrogen in glass, also Li_2O which makes the spodumene ($LiAlSi_2O_6$) preferentially crystallize and it has a negative coefficient of thermal expansion, so the entire composite has a thermal expansion close to zero. With a content of about 80% of crystals the composite can withstand thermal shocks up to 800 K and still transmit over 80% of IR radiation. This type of composite is often used for the glass-ceramic cooktop of kitchen stoves. Similar composites are due to a minimum dimension change of temperature and are also used for astronomical mirrors.

5.8. Dispersion glass with ceramics

A particle composite can be obtained by adding particles of a substance with a higher melting point into the molten glass.

A composite with a Pyrex matrix and about 30% of the dispersion of either particles of yttrium-stabilized ZrO_2 or Al_2O_3 platelets is used for example in fuel cells for the direct conversion of thermal energy into electrical energy.

A composite with a matrix of borosilicate glass with a dispersion of 55% of the oriented mica platelets (e.g. MACOR by FiberOptic) is a highly versatile material. Because of its low brittleness, excellent electrical insulation and applicability up to 1000°C, it is used in a high-vacuum technology, satellites and medical science as well. Despite the glass matrix and the particle dispersion it is relatively easily machinable.
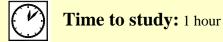
5.9. Fiber composites with a glass matrix

As a replacement of special types of steel in many applications, the composite of a mat of continuous fibers, in which the molten glass is infiltrated, can be used. When borosilicate glass is used, the composite is applicable at temperatures up to 500 °C; silicon carbide or graphite fibers can be used. A composite with graphite fibers in the plane of the fibers is electrically conductive and has high thermal conductivity.

Superkanthal

This is a branded composite with a matrix of pure silica glass with a dispersion of 80 % of $MoSi_2$ particles, oxidation resistance of this material is almost equal to the platinum, yet it has considerable electrical conductivity and thermal shock resistance. It is stable up to 1400 °C, and is therefore an ideal resistive material for high-temperature applications.

6. Foam and fiber boards

Time to study: 1 hour

Goal After studying this chapter you will be able to

- distinguish metal foams, polystyrene foams and ceramics foams
- describe the principle of the foam materials
- define the composition and the applications of fiber boards

Foams and fibers with a small amount of matrix (the gaps between them predominate) belong to third type composites - composites with a gas dispersion. This dispersion is usually ordinary air, it can also be (with closed pores) hydrogen, nitrogen or water vapour. These composites are generally not being prepared to improve the mechanical properties of materials, but above all for other synergy effects. It often deals with about reducing the thermal conductivity, or increasing the vibration control or sound.

Foam materials

Foam materials are formed as artificial microcavites in the matrix filled with a gas. These microcavities are usually approximately spherical, closed in small quantities and can include any gas; in the case of large quantities they are linked together and open micropores are formed into the outer space. This group of composite materials includes:

- Polystyrene foams (Polyfoams)
- Metal foams
- Ceramics foams

6.1. Polystyrene foams (Polyfoams)

Polyfoams represent the most known foam materials, particularly a polystyrene foam is often used. Basically any plastic material can be frothed up. Besides polystyrene, other widely used foamed materials are polyethylene, polypropylene, polyvinyl chloride and polyurethane.

Foamed (expanded) polystyrene is very often used as heat insulating material, where its thermal conductivity depends primarily on its density. It prevents the passage of the heat by conduction and convection very well, but transfers a relatively large amount of infrared (heat) radiation. Therefore, its characteristics can be improved by adding a small amount of graphite, which absorbs the penetrating radiation. Polystyrene is very fragile and the bulk of its deformation under stress is irreversible.

Foam polyethylene and polypropylene are therefore more suitable for construction purposes, (foamed polypropylene-significant portion of the deformation that occurs during repeated pressure is reversible). Therefore, polyethylene and polypropylene foams are increasingly used in the automotive industry.

Polyurethane as a plastic material with a lower stiffness especially is suitable as a soundproof material.

In principle, it is possible to distinguish three types of polyfoams:

- rigid and brittle - expanded polystyrene
- rigid and tough - polyethylene foam and polypropylene foam
- flexible and tough - polyurethane foam

6.2. Metal foams

Metal foams are one of the promising materials of the future. Currently they are primarily being prepared from aluminium and its alloys or titanium and its alloys. Compared to dense metals the behaviour of metal foams differs in many details.

- The behaviour at the loading point - while massive metal plastic deformation in a relatively large radius of a tip occurs, in metal foam mainly compaction under the tip immediately occurs.
- The insensitivity of metal foams to notches - they are due to its structure completely insensitive to notches (unlike massive metals)
- The energy absorbed during compression - metal foams, unlike the massive metals, absorb during loading significantly more energy, and therefore are suitable as part of various body armour or shock absorbing systems, this property depends on the amount of pores in the composite.
- The electrical conductivity of metal foams decreases with increasing number of pores, especially open pores.
- There are also differences under loading pressure and it also strongly differ during the flow of massive metal at a pressure or tensile stress

6.3. Ceramics foams

An example of a ceramics foam can be a composite with a matrix of SiC, which has 90 % of the pores at a density of 0.3 g.cm^{-3} and is applicable to 1500 °C. It is used for heat exchangers (it has thermal conductivity about the same as steel), noise silencers, vibration absorbers, rocket nozzles, and turbine blades. It comes under the name DUOCEL.

Carbon foam is so-called net glassy carbon which is applicable up to 350 °C in the air and up to 3500 °C in a non-oxidizing atmosphere. It is especially useful for high temperature filters, vibration dampers, porous electrodes for galvanic processes, and advanced batteries.

6.4. Fiber boards

Fiber boards with a binder

When we reduce the quantity of the matrix below about 20 % in the fiber composite, it is no longer enough to fill all the gaps between the fibers and we receive a composite with small quantities of the matrix (usually only a few percent) and a double dispersion - fiber dispersion, which is usually 10 to 30 % and pores between the fibers, which are typically 70-90 %.

Especially ceramic fiber boards are often formed for high temperatures. The binder - matrix may be either organic (starch etc.) or inorganic (heat-resistant cement). The organic matrix when first used at high temperature carbonizes and changes to a carbon and its compounds.

A good example is the Fiberfrax, a fiber with a diameter of $3 - 4$ μm from mullite for manufacturing boards and simple construction components applicable up to 1250 °C. These products are highly suitable for thermal insulation.
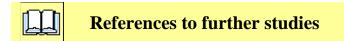
Similar composites are made of fibers labelled as IsoFrax containing more SiO_2 and MgO instead of mullite.

Fiber boards without binders

For very demanding applications, especially in space technology, it is a block of ceramic fibers without binding or with a minimum of binding identical to the material of fibers that is sintered at a high temperature so that a block of fibers bound together by diffusion bridges occurs.

The current structure (design) of space shuttles uses as a thermal insulation of the surface blocks such composites with 10 % silica fibers and 90 % of the pores in two versions. For temperatures above 700 °C, the blocks are covered with a borosilicate layer (black, for good heat radiation) and for a temperatures below 700 °C, the blocks are covered with a layer of aluminium oxide (white).

As a newly developed material, graphite fibers are sintered in a similar way.

References to further studies

- IMANAKA, Y. et al. *Advanced Ceramic Technologies & Products*. Tokyo: Springer, 2012. ISBN-431-53913 978-4-1, ISBN-431-54108 978-4-0 (eBook).