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Actual challenges, opportunities, and perspectives of composite materials

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The actual development of technology requires progress in the design and manufacture of new types of materials. The monolithic materials such as ceramics or metals have become insufficient for the needs of the global market. The idea of the combination of several types of materials in one system seems to be the right direction for the progress. Composite materials as multi-phase materials show improved properties compared with individual structural elements and give the opportunity to design the systems with enhanced specific characteristics.

The presented work provides an actual literature review dedicated to composite materials. In this work, the basic terminology, the classification of composite systems, the most commonly used methods for composites preparation, as well as physicochemical characteristics and potential applications of these types of matter are presented.

Keywords: composite materials, biocomposites, nanocomposites, synergism.

1. INTRODUCTION

The composite materials (composites) due to their numerous advantages are the objects of great interest of designers, producers, consumers and scientists from many fields of science and industry. The most important industries are automotive, electronics, astronautics, architecture and medicine. The lightweight, easy-to-design materials with excellent mechanical strength, thermal stability, resistance to cracking, bending, stretching, corrosion, etc. are currently in the request. The development of technology has initiated an increase in demand for new materials with well-defined properties. Individual materials such as ceramics, metals, semiconductors, plastics and natural materials remain very popular, but their application in new technologies can generate some disadvantages. The composite materials have become a solution to the needs of highly specialized markets, which give high freedom in design and allow obtaining systems with the desired characteristics.

In accordance with the requirements of the modern world, in this work the definitions, basic concepts, classification, production methods and application possibilities of composite materials are presented [1].

2. COMPOSITE MATERIALS – BRIEF DEFINITION OF UNIQUE COMBINATION OF MATTER

The composite materials consist of at least two components: matrix and filler phases with different properties. Their composition is the combination of two or more chemically distinct and insoluble phases.

The matrix phase is responsible for the shape and determination the most of the chemical and physical properties of composites. In other words, the matrix phase is the binder for the filler fragments dispersed in the main phase which protects them from external damage. The filler phase improves the properties of a given composite and increases the mechanical strength of the material (reinforcement). The characteristic features of composite materials are anisotropy and inhomogeneity. It means that the properties of composites differ depending on the direction.

The final properties of the composite system are the result of properties of all phases and may not be the same as the properties of the individual, initial components. The composite materials as multiphase compounds show much better properties (thermal, optical, magnetic, electrical, electromagnetic, electrochemical, adsorption, catalytic) than their monolithic equivalents [2-3]. A characteristic feature is synergism, which is defined when cooperation of different elements is more effective than the action of individual elements [4].

3. CLASSIFICATION OF COMPOSITES

The composite materials can be classified into three main groups based on the type of matrix phase as metal matrix composites (MMC), ceramic matrix composites (CMC), and polymer matrix composites (PMC).

The metallic matrix consists mainly of alloys and metal oxides including iron, magnesium, aluminum, copper, titanium, cobalt, and nickel. At high-temperature applications, the cobalt and cobalt-nickel matrices (thermal stability up to 1000°C) are most commonly used. The metal matrix composites have much better thermal and electrical conductivity than polymer or ceramic composites, but their usability is limited due to the difficult production process (application the high temperatures). Difficult conditions of their processing make the production steps more expensive in comparison to the technologies of metals, alloys, and even polymer composites.

The ceramic composites (CMC) are materials based on compounds such as silicon carbide, aluminum oxide, or aluminum nitride. The carbon matrix composites (for example, carbon-based composites reinforced carbon fibers) can also be included in the group of CMC materials, although some literature sources isolate them as an individual group. The ceramic materials are much more resistant to cracking than their monolithic analogs (ceramics). In addition, this type of material is characterized by high thermal resistance at temperature higher than 1500°C. Moreover, the ceramic matrix composites are more resistant to oxidation than carbon-based matrix materials.

The polymer composites are materials made from various types of high-molecular systems such as polyethylene, polypropylene, polyester, polystyrene, polyamide, as well as polymer resins. The polymer composites require lower manufacturing and processing temperatures (100-400°C). They can be easily modified which generates much lower costs than MMC. The polymer matrices are most often reinforced with glass, carbon, aramid, and natural fibers.

The composites can also be classified due to the filler type, into three groups. Among them, the particle-reinforced composites (granular), fiber-reinforced composites and structural (layered) composites are identified. In the particle-reinforced composites (also called granular composites), two subtypes can be distinguished: reinforced with large particles and dispersive type. The dispersive particles are connected to the matrix at the microscopic (atomic or molecular) level. Granular composite suggests the form of powders, including oxides or carbides (mainly silicon, aluminum, or titanium).

The composites can be also filled with different types of fibers. The fibers used can be continuous or discontinuous, long or short, ordered or disordered. The textile materials are also included in this group. Currently, glass, carbon, aramid, and natural fibers are considered the most popular types of fibers filler.

The layered composites consist of alternately arranged layers of individual phases with different properties. In this case, one phase is considered as a matrix and the other phase as reinforcement. The laminates are well known and commonly used examples of layered materials. Another group of the layered composites is a system with a honeycomb core structure. The overall classification of composite materials by type of matrix and filler is presented in Fig. 1 [5-8].

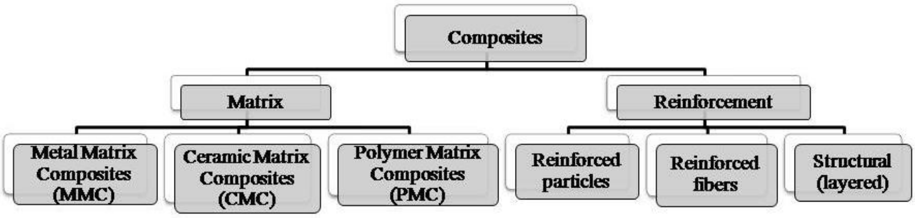

Fig. 1. Classification of composites by type of matrix and reinforcement.

4. DESIGN REQUIREMENTS

There are many requirements during the designing and processing of composites (Fig. 2). The properties of a given material are related to the selection of the appropriate matrix and filler, the right proportions of components, as well as the geometry of the reinforcing phase (particle size, fiber length, and orientation). The important issue is also the bond strength between the two phases (the quality and nature of interactions) and the synthesis conditions (conditions selected individually depending on the ingredients and their proportions).

As an example, the choice of fiber for a particular matrix can be presented. It should be taken into account that not every type of fibers is resistant to high temperatures and some types of fibers (especially organic) are not suitable for use in for combination with metallic or ceramic matrices, where the high thermal stability is necessary [5-6].

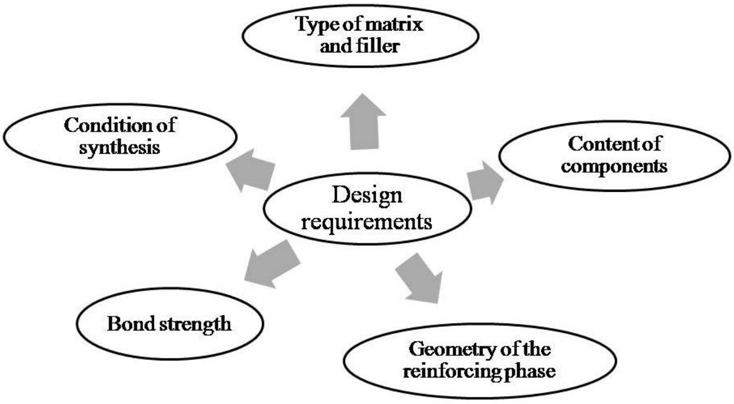

Fig. 2. Factors that affect the properties of the composite material.

5. BIOCOMPOSITES

Biocomposites is a category of biocompatible and/or biodegradable composites. Due to the actual and important trends related to ecology, medicine, biotechnology, and pharmacy, the growing interest in the biocomposites is still observed. Especially, non-toxic, easily recyclable and compatible with human tissue materials are sought. The biocomposites are based on various matrices. The polymer matrices combined with natural fibers are often used in the production of biocomposite materials. Among them, the natural fibers such a sisal, jute, hemp, bamboo, agave, banana, jute, wool, silk, kenaf, wood, corn-components are used. The global trend of obtaining environmentally friendly matrices is also visible. In this case, both natural and synthetic biopolymers are applied. Natural biopolymers include polysaccharides (starch, cellulose, chitin, and chitosan), proteins (collagen/gelatin, casein, albumin, fibrogen, and elastins), polyesters (polyhdroxyalkanoates), and natural rubber. Common used synthetic biopolymers include, among others, poly(amides), poly(anhydrides), poly(vinyl alcohol), poly(vinyl acetate), polyesters (poly(glycolic acid), poly(lactic acid), poly(caprolactone), and poly(ethylene oxide)). Materials, where both matrix and reinforcement are biodegradable, are defined as green composites. The use of natural fibers significantly reduces the cost of material production (they are cheaper than, for example, carbon or aramid composites).

Since, the biocomposites are biodegradable, these materials are extremely important due to the overproduction of rubbish and imbalances in the ecosystem. One of the great examples of applications the biocomposites is food packaging. In addition, the biocomposites, due to their biocompatibility with tissues and non-toxicity, are widely applied in medicine, biotechnology, and pharmacy, for example in tissue engineering, gene therapy, production of therapeutic agents [9-12].

6. NANOCOMPOSITES AND HYBRID COMPOSITES

Nanotechnology remains the driving force behind a new industrial revolution. This is especially visible in the electronics production sector: televisions, computers, Smartphone's, etc. The "nano" trend is also visible in the production of composite materials. The nanocomposites are materials which at least one component has dimensions in the range from 1 nm to 100 nm (10^{-9} m). In the nanocomposites the filler phase is replaced with a "nano" component and defined as nanofiller. The hybrid materials are defined as two constituents with organic and inorganic nature mixed at the nanometer scale. Such combination allows for obtaining a material with improved chemical and physical properties.

The transition from "macro" to "nano" scale allows obtaining the materials with an exceptionally homogeneous structure (the ratio of surface to volume of particles increases (particles are smaller), and thus there are stronger interactions between the components in a given composite), and this translates into their better chemical and physical properties in comparison to the materials obtained from components of larger dimensions. Even small amount of a nanofiller added to the matrix can drastically change the properties of the final material. Various types of nanofillers can be distinguished (Fig. 3), and their classification due to dimensionality and shape can be specified as 1-dimensional (1D), linear, (e.g. carbon nanotubes), 2-dimensional (2D), layered, (e.g. montmorillonite (layered aluminosilicate)), as well as 3-dimensional (3D), powder, (e.g. silver, gold, platinum or other metal nanoparticles).

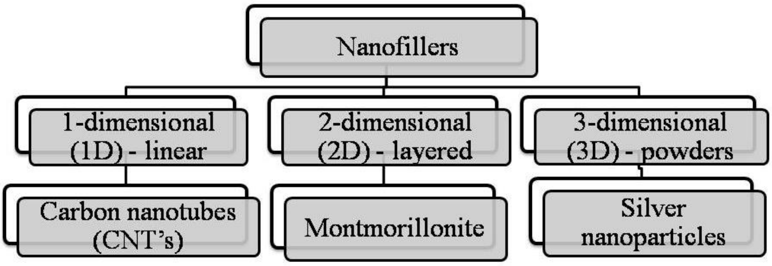

Fig. 3. Classification of nanofillers.

The most commonly used linear nanofillers are carbon nanotubes (CNT's). The structure of carbon nanotubes is similar to graphene layers. The composites containing carbon nanotubes exhibit good mechanical and electrical properties. Aluminosilicates with a layered structure, (montmorillonite), can be also applied as the nanofiller phase. The addition of montmorillonite to the matrix significantly improves the mechanical and thermal properties of the final materials. The addition of metal nanoparticles in the form of silver, gold or copper nanoparticles, are also popular. Such composites are applied in medicine and cosmetology due to the antiseptic properties of metallic nanoparticles. Among powder fillers, polyhedral oligomeric silsesquioxanes (POSS), are also very significant.

In the case of hybrid materials, the systems based on silica nanoparticles with various organic components, such as carbon nanotubes or natural organic nanofibers are commonly used. Silica is often used as a raw material for the synthesis of hybrid materials due to the fact that it is relatively inexpensive features, commercially available, low toxicity and possibility of modification [13-18].

7. MANUFACTURING METHODS

The manufacturing methods of the composites can be adjusted based on the type of matrix (ceramic, metallic and polymer).

Among the preparing procedures of metallic composites, the powder metallurgy, casting, and deposition techniques are the most important. These methods based on powder metallurgy involving mixing the powdered matrix with reinforcement, cold pressing, sintering, and pressing. An example of a composite obtained by the powder metallurgy method is aluminum (Al) reinforced with alumina (Al_2O_3) particles. In the case of casting techniques, the most commonly used procedure based on the simultaneous introduction of particles into the liquid metal phase, however other techniques are also applied (for example the liquid compression technique). Deposition techniques are used when the coating of individual fragments or preparation of reinforcement monolayer is required. Deposition processes can be characterized by low contact of reinforcement with the molten matrix, which is beneficial in the case of reactive metals. The methods for coating reinforcement elements include vapour deposition, spray deposition (e.g. plasma-spraying) or electrodeposition [19, 22].

The ceramic composites are prepared according to pressing and sintering procedures, chemical and physical vapor deposition (CVD and PVD) and self-propagating high-temperature synthesis (SHS). Sintering is a physicochemical treatment, heat-activated where loosely bound powder particles are combined by diffusion into a solid material. Sintering is usually carried out under an inert gas (e.g. argon) atmosphere or in a vacuum, which leads to obtaining a sinter. The chemical vapor deposition (CVD) consists of introducing gaseous substrates into the reaction chamber by means of a carrier gas, where individual chemical reactions take place on a heated substrate. The CVD methods require high temperatures (~1000°C), which are necessary for initiating the expected reactions. The physical vapor deposition (PVD) occurs by vapor deposition using physical phenomena. The formation of the coating is based on the crystallization process. Moreover, PVD is carried out under high vacuum. And the gas of the deposited material crystallizes on the subsoil (base), connecting with adhesion forces. SHS synthesis should be initiated by raising the system temperature to a specific value that initiates the automatic run of the synthesis (exothermic processes determine the spontaneous synthesis). This method allows for saving energy and time compared to conventional synthesis methods [20-22].

The polymer composites can be prepared according to in situ polymerization, solvent and mixing method with the plasticized polymer. In situ polymerization method consists of two stages. The first step involves the penetration of liquid monomer between the filler elements. The second stage is a polymerization process between filler particles or fibers. The solvent method consists of three main stages. The first one consists of preparing a suspension of surface-modified filler in a polar solvent where the solvent penetrates reinforcement components. In the second step, the polymer dissolves in the same solvent and the obtained solution is mixed with the suspension prepared in the first stage. In the third stage, the solvent is evaporated and the obtained composite is dried. This method is applied, for example, during the preparation of polyamide polymers. The method of mixing nanofiller with plasticized polymer is based on the fact that properly cleaned and dried filler (nanofiller) with a plate structure (e.g. montmorillonite) is modified by ion exchange. The filler after modification together with the polymer is fed to the extruder hopper. The polymer is mixed with the modified lamellar filler, heat and treats by granulation. Nowadays is hard to find one universal method for preparing the composite materials, because many times, various methods are connected to each other. The development of technology contributes to the invention of newer techniques and more advanced equipment. Despite this fact, many methods invented many years ago are still effective and widely used [23].

8. METHODS OF PHYSICOCHEMICAL INVESTIGATION OF COMPOSITES

The composite materials are materials with a complex structure. After their design (chosen of appropriate components, proportions, methods, and synthesis conditions) and synthesis, their surface and physicochemical characteristic should be evaluated. Especially, their morphology (sizes, shapes, orientations, distribution of used phases, defects, and general structure) and structural information should be described. The composite materials can be analyzed using various techniques, but some of them are the most significant and widely used. The most important physicochemical methods for characterization and investigation of the composite systems are presented in Fig. 4.

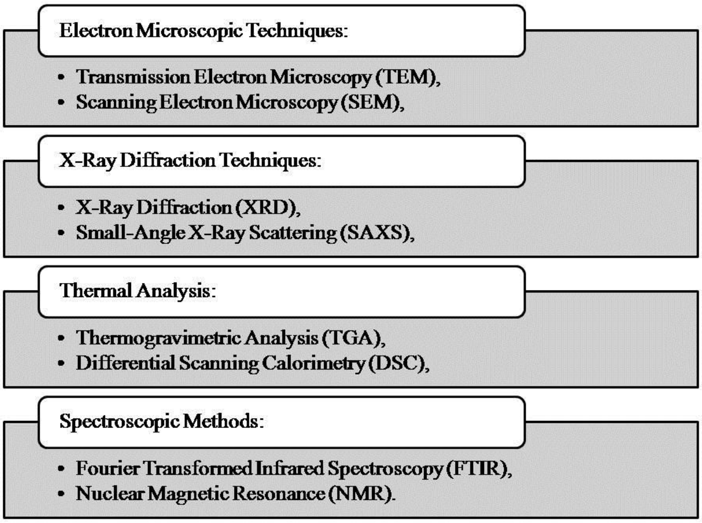

Fig. 4. The most important techniques used in the analysis of composite materials.

The structural information can be clearly obtained by applying X-ray diffraction techniques. There are two mainly used X-ray diffraction techniques for analysis composite materials. X-ray diffraction analysis (XRD which means X-ray analysis in wide angles) is similar to the small-angle X-ray scattering (SAXS). Both techniques are used to supply structural information of the composites. SAXS provides information related to the particle as a whole (gives the distribution of particle, as well as their shape, size, internal structures, crystal lamellar thickness, and surface per volume and/or mass) in the nanometer scale. XRD provides information related to atomic arrangements (dispersion of different types of fillers (or more often nanofillers) dispersed in various matrices) inside the materials. Coupling both SAXS and XRD data is very helpful for analyzing multiphase's systems. The microscopic techniques such as transmission electron microscopy (TEM) or scanning electron microscopy (SEM) are used as complementary with SAXS and XRD (applied to confirm results obtained from diffraction studies). The microscopic techniques give the possibility to study materials both in macroscopic scale (general view at structure) and microscopic scale which allows comparing results from diffraction techniques. Fourier transformed infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR) techniques are used for obtaining more particularly information at the atomic scale. The location of individual bands and their intensity allow identification and also provide some more detailed information about the structure, dynamics, reactions (particularly NMR spectroscopy). The purpose of thermal analysis (thermogravimetric analysis, TGA and differential scanning calorimetry, DSC) is to determine the behavior of the material under the temperature conditions (mass losses, phase changes and thermal effects accompanying them) [23-26].

9. APPLICATION OF COMPOSITE MATERIALS

The composite materials have a wide range of applications. The polymer matrix composites are commonly used in industry due to a low cost of their production. The polymer composites with continuous fiber reinforcement are widely used for lightweight structures (e.g. airframes). The polymer-matrix composites with metal particles (e.g. silver particles) are used for the production of interconnections in electronics. Metal-matrix composites combined with ceramic known as cermets are used to production of drills. The cement-matrix composites in the form of concrete are widely used for constructing roads and buildings [27]. The carbon-matrix composites (particularly with carbon fibers) are commonly used in aerospace, cosmic, ships, military and high-quality sports equipment industry. Rocket nozzles, aircraft brakes, heat exchangers, air-breathing engine, fuselage, wings, skis, and rockets are products involved in carbon components [27-28]. The materials based on glass fibers are commonly used in the building and construction industry as non-load-bearing wall panel, window frames, storage tanks, and processing vessels. The materials based on aramid fiber (Kevlar) are known from the production of bulletproof vests [28]. The biocomposites are used in packaging applications and also in many medical, biotechnology and pharmaceutical applications, such as tissue engineering (composites with a structure similar to human bones based on hydroxyapatite) [29-30]. Many more uses of composite materials can be distinguished and an increase in their number is expected, which is related to the development of technology.

10. CONCLUSIONS

The composite materials are materials with many potential applications and this long list is constantly growing. The development of technology takes place very quickly and thus the growing market needs new materials with precisely specified and improved properties. One of the factors limiting the prevalence of composites is their high price associated with the difficult production and processing technology. The challenge is to create low-cost materials that are mechanically durable with a number of other properties, such as magnetic, optical, flexibility, corrosion, or thermal resistance. Especially the aircraft, shipbuilding, military, space and sports industries need highly specialized equipment or fittings. In these fields, the quality of materials is more important than the costs of their production. The composite materials are more often used in construction (bridge construction, building construction) and automotive (car body elements) areas. Although, the composites are increasingly used in many fields, monolithic materials (such as metals, or ceramics) are still often applied due to the economic aspects. Many methods of obtaining composites are still time consuming and require large financial outlays. With the development of technology there are visible opportunities to improve production technologies and reduction manufacturing costs. In the near future, the materials and nanomaterials are expected to be widely available, not just in industries with highly sophisticated requirements, but also in common life. Due to the rapidly growing "nano" trend, the traditional materials are increasingly being replaced by nanomaterials. Mainly, the nanocomposites and hybrid composites will be obtained in the future. In addition, for ecological reasons, more emphasis will be placed on obtaining "bio" materials that are biodegradable what means safe for environment. This is particularly important in the food packaging industry. There is a huge need to receive materials that are safe in contact with food, as well as being subject to decomposition, which will not pose a threat to the environment overloaded with rubbish. Medicine and biotechnology are also interested in composite materials (especially "bio").

Materials sought to be compatible with human tissues that could be placed in human bodies as implants replacing depleted entities, such as bone implants, arteries, veins, heart valves, and many other [31].

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