Problem State of Obtaining, Structure Modification and Application of Polymer Nanocomposites: A Review

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(Received on 13th May 2024, accepted in revised form 19th September 2024)

Summary: This article is a review of minerals that are used to modify the physical and mechanical properties of polymers and obtain composites with improved performance characteristics. A general classification of fillers is presented, taking into account their division into dispersed and reinforcing ones. General characteristics of fillers are given and their division into groups is considered: mineral, organic, and other subgroups depending on the type of polymer matrix used. To obtain polymer nanocomposite materials with an improved set of properties, information is provided on the features of selecting substances and materials for the purpose of their use as fillers. A unique possibility of modifying the surface of the fillers themselves by dressing and with organosilicon compounds is demonstrated, which makes it possible to obtain hybrid composite materials with improved physical and mechanical characteristics on their basis. The probable mechanism of the formation of organic-inorganic hybrid nanocomposites based on polyolefins and mineral fillers is considered. Unique characteristics and features of the structure and properties of nanostructured materials are presented. The results of their implementation in various fields of technology are described. Technological features of obtaining and processing structural nanomaterials are presented. The main technological factors influencing the properties of polymer composite materials during their processing by injection molding and extrusion methods are indicated. The main types of polymer matrices and nanofillers intended for obtaining composite materials with specified performance properties are listed. The main promising directions of mechanical-chemical synthesis and practical use of nanocomposites are noted.

Keywords: Polymer composite material, Dispersed filler, Fibrous filler, Sheet filler, Reinforcing filler, Dressing, nanostructure impregnation, Composites, Carbon nanotubes, Polymer, Fiber.

Introduction

The tasks of comprehensive modernization and improvement of the polymer materials industry can be solved in two main directions: the synthesis of new polymers and structure modification of polymers already existing in the industry. The first direction is less promising, since in one polymer, by varying the technological parameters of synthesis alone, it is not always possible to reproduce the complex of properties that would satisfy the ever-increasing needs of modern industry. The second direction is the most universal method of modifying the structure of polymers. This circumstance is due to the fact that there is a whole range of methods for modifying the structure of polymers, which can significantly affect the improvement of the range of their properties. These methods include physical and chemical modification of the polymer structure, targeted introduction of various types of fillers, stabilizers, plasticizers, graft copolymerization with polar monomers, vulcanization, mechanical-chemical synthesis in the process of reactive extrusion, etc. Each of these methods has its own advantages and disadvantages. Depending on the task at hand, each specialist selects a modification method that achieves the maximum effect in improving the performance characteristics of the composite polymer material. Of the existing methods for modifying the structure of polymers, the most promising and accessible is the use of mineral dispersed and fibrous fillers. The availability of this modification method is demonstrated by the fact that filled composites can be obtained directly at polymer processing plants [1].

In this regard, in recent years there has been a sharp increase in interest in the use of composite materials for the production of structural products. This is due to two main reasons: firstly, the introduction of mineral and organic fillers into polymers leads to the creation of materials with a new set of properties; secondly, the presence of a filler leads to a decrease in the relative proportion of polymer in the final product, which ensures savings in organic raw materials or an increase in the production of the total product at the same polymer consumption. It is noted [1–5] that the growth rate of the production of fillers for polymers is several times higher than the

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rate of development of the production of polymer materials. Among the plastics currently produced, the most large-scale ones are polyolefins (polyethylene of various types, polypropylene, ethylene/α-olefin copolymers, polypropylene random copolymer, ethylene/propylene block copolymer, etc.), polyvinyl chloride, polyamide, and polystyrene plastics. Therefore, in order to obtain structural materials for various purposes on their basis, the development of effective methods for introducing fillers into these polymers is a practically important task. Traditional methods for producing filled thermoplastics consist mainly of mechanical mixing of the polymer and filler in powder form or by combining the components in a polymer melt. Currently, abroad, the number of fillers that are treated with special substances - dressings, i.e. organosilicon compounds, for example silanes, titanates [2, 4, 5], which contribute to the improvement of adhesive interactions of macrochains with a modified solid surface, has increased.

In the development of special-purpose materials, research aimed at developing methods for synthesizing composite materials *in situ* has begun to gain significant attention. In this case, uniform dispersion of filler particles throughout the entire volume of the polymer matrix is ensured. Of course, the very fact of uniform dispersion of the filler in the polymer always has a positive effect on improving the physical and mechanical properties of composites and nanocomposites. The only drawback is that the highly filled compositions synthesized by this method are characterized by low melt flow index values. Therefore, there is a need to introduce plasticizing additives at the final stage of extrusion mixing and granulation. All these problems and methods of modifying the structure of industrially synthesized polymers are discussed in more detail in the sections below.

Fillers for modifying the structure and properties of polymer materials

Homo- and copolymers synthesized in industry have the necessary set of properties allowing them to be used in various fields of engineering and technology. However, further improvement of technology and increase in operational requirements for product quality puts forward increasingly stringent requirements for improving properties. In this regard, there has been an increasing interest in developing new types of polymeric materials through the use of various fillers, plasticizers, stabilizers, and coupling agents that can significantly improve their range of physical-mechanical, and physical-chemical characteristics. Of greatest interest are studies related to the use of various mineral fillers, which make it possible to obtain polymer composite materials (PCM) with predetermined properties [6]. The basis of PCMs is polymeric matrices, in order to modify the structure of which various additives are introduced into their composition, facilitating their processing, increasing heat resistance, thermal stability, and combustion resistance. However, the most effective additives that have the greatest impact on the quality characteristics of the polymeric binder are various mineral fillers. In addition, fillers, unlike other additives, do not form a single homogeneous mass with the binder, but as a result of segregation are distributed in it in the form of isolated parts concentrated in the interspherulitic amorphous region. It is known that solid, liquid and gaseous fillers can be used in the process of production and research of composites. Gaseous fillers are used, as a rule, to produce materials with open, interconnected, or closed pores: foam plastics, ion exchange resins, rubber sponges, etc. Liquid fillers are used in the obtain of solid porous materials from liquid emulsions [6, 7].

In most cases, solid inorganic or organic fillers are used, which are divided into three groups: powdery (dispersed), fibrous and sheet. Volume fillers are also sometimes isolated, which include bulk fabrics and frame systems: natural wood or systems obtained by foaming or sintering ceramic, metal or polymer powders [7]. It is worth mentioning that dispersed, fibrous, and sheet fillers can be obtained from the same material, for example, glass. Dispersed fillers are the most common. The particle size of the dispersed filler varies widely from 2 to 300 µm, but usually does not exceed 40 µm, and for nanocomposites particles smaller than 100 nm are used. The content of dispersed fillers varies in the range from several percent to 70–80% [8, 9]. At higher filler concentrations, its particles begin to contact each other, which leads to their uneven redistribution in the polymer matrix and, as a consequence, contributes to the deterioration of the main physical and mechanical characteristics of the composite [8].

Therefore, dispersed fillers must be compatible with the polymer and uniformly dispersed in volume, i.e., well wetted with a solution or melt of the polymer, be non-agglomerative, and have predominantly the same particle size and low humidity [8, 9].

Dispersed fillers can be of two types: inert and active (reinforcing). The former is introduced into the polymer composition in order to reduce the cost of the composite, and the active ones are used to strengthen the polymer composite. It should be noted that the activity of the filler is determined by three main factors:

- the ratio between the energy of adhesion and cohesion of the polymer to the filler, which can be increased by introducing polar groups into the polymer matrix;
- the degree of dispersion of filler particles, which is determined by the specific surface area of the filler, ensuring a high level of contact with the polymer matrix [10];

The use of a compatibilizer to improve the compatibility of mixture components or the modification of the filler surface with organosilicon compounds have opened up new promising possibilities for improving the adhesive contact of polymer matrix macrochains with the filler surface. As an example, we can cite the very fact of improving the rheological properties of the composite by wetting the surface of chalk with stearic acid, calcium stearate or dressings. In this case, an excellent opportunity for uniform dispersion of chalk particles in the volume of the polymer matrix of the composite is achieved [1, 8].

Thus, under certain conditions of preparation and processing, almost any dispersed filler can become active. At the same time, the possibility of obtaining composite polymer materials that simultaneously contain inert and active fillers is not excluded. The most common dispersed fillers include mineral, organic, and metallic ones [7].

Mineral fillers are used primarily to reduce shrinkage, residual stresses, and susceptibility to cracking, as well as to increase strength characteristics. They also provide rigidity and fire resistance. Each of these fillers has its own characteristics. Chalk is one of the cheapest mineral fillers, has low hardness (easy to process), and is used in materials based on polyvinyl chloride, polypropylene, polystyrene, and its copolymers for the production of pipes, as well as in polyester fiberglass. Kaolin contributes to a significant increase in the effective melt viscosity and elastic modulus and improves the electrical properties and moisture resistance of the polymer composite. Kaolin is poorly dispersed in most polymers and is primarily used in composition of fiber-reinforced polyester binders [7, 10].

Talc is characterized by low abrasiveness, gives composites increased rigidity and, unlike other dispersed fillers, does not reduce impact strength. Talc is most often used to fill polypropylene. Quartz is used in different modifications (quartz flour, aerosil, fused quartz, microcrystalline quartz and precipitated silicon dioxide), which differ in the degree of crystallinity, abrasiveness, specific surface area, and dispersibility in polymers. Along with reducing shrinkage, all quartz fillers contribute to increasing the strength properties of composites and are therefore widely used for filling thermoplastics and thermosets. Feldspar and nepheline are well dispersed in polymers and are wetted by them, provide low viscosity of filled compositions even at high degrees of filling, increase thermal conductivity, and refractive indices close to polymers allow obtainig transparent and translucent products. They are effectively used when filling polar polymers (ABS plastics, polyamides, polyurethanes), where an increase in rigidity, flexural strength, and heat resistance has been noted [7, 9]. Ground mica is used to improve the strength, fire resistance, chemical resistance, and dielectric properties of composites. Recently, shungite has also been widely used due to its unique fullerene-like structure and adsorption properties. This mineral imparts electrically conductive properties to PCMs and reduces their radio transparency [11]. The most common organic origin filler is wood flour, which is obtained from softwood (mainly pine and Canadian fir) or hardwood (ash or maple) when the presence of wood resin is undesirable [9]. Wood flour is combined with mineral fillers. It is characterized by low abrasiveness and increases the flexural modulus of elasticity. Along with wood flour, organic dispersed fillers such as ground nut shells, crushed sunflower husks, rice husks, corn cobs, sugar cane stalks and other types of agricultural waste are used. Their use is primarily due to their low cost and the possibility of obtaining biodegradable polymer materials [8]. Starch (the most important component of potatoes and grain crops), as well as chitin and chitosan obtained from it, which are close to cellulose in structure and properties, are widely used [9].

Organic dispersed fillers are also carbon materials, which include the commonly used soot, carbon black (CB), and graphite. In some sources, soot and carbon black are synonymous, but soot is a by-product of hydrocarbon combustion processes, and carbon black is an industrial product obtained by thermal decomposition under controlled conditions. Coarse-grained soot is mainly used as a filler, which does not significantly increase the viscosity of the compositions [1, 7]. Soot and carbon black act as light stabilizers and impart electrically conductive properties to the material, facilitating the flow of static electrical discharge. CB has been in demand worldwide for many decades, and the need for it is increasing every year. The applications of carbon black are varied. The main consuming sector is invariably the tyre industry. For the development of modern technology, it is necessary to create and introduce elastomeric materials that are superior in quality to those that currently exist. One of the known methods to solve this problem is the use of various grades of CB when developing formulations of rubber mixtures for the manufacture of products based in them. The undoubted advantage of using CB in rubber compounds is its low cost and complex effect on performance properties. It is well known that the introduction of CB into rubber compounds contributes to a significant increase in their elastic modulus, hardness, strength, wear resistance, and other characteristics [12]. A significant amount of research has been carried out to study the influence of CB on the properties of elastomers. For example, in work [13], a large place is devoted to the study of the influence of butadiene-styrene elastomer content on the nature of changes in strength properties, elongation at break, heat resistance, and melt flow index polymer compositions based on polyolefins: high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), ethylene-1-hexene copolymer (EHC), polypropylene random copolymer (RPP) and ethylene-propylene block copolymer (EPBC). Nanoparticles of carbon black, aluminum and calcium stearate were used as fillers. Also in the work [14] the results of a study of the influence of the CB content on the thermal deformation properties of nanocomposites based on compatibilizer-modified polyolefins are presented. The CB was a highly structured amorphous soot of the Printex XE 2B brand with a nanoparticle size of 20 nm. HDPE, LDPE and PP were used as polyolefins. The concentration of CB in the composite composition varied within the range of 1.0 - 20 wt %. It has been shown that an increase in the CB content in the composite within the range of 1.0, 5.0, 10, 20 wt % significantly affects the regularity of changes in thermomechanical curves. The introduction of 10 and 20% CB into the polyolefin composition causes a “plateau” or bend to appear on the thermomechanical curves in the region of the viscous-flow state. The introduction of 20 wt % TC into the composition of compatibilized LDPE* and PP* promotes the formation of a heat-resistant plateau. To interpret the discovered regularities, new scientific approaches have been developed, based on modern theoretical concepts in general about the mechanism of formation of the supramolecular structure of nanocomposites and the interphase amorphous region. In article [15], using the method of stepwise dilatometry, the results of studying the temperature dependence of the specific volume and free specific volume of nanocomposites depending on the CB content in their composition are considered for the first time. In accordance with Avrami theory, the results of a study of crystallization isotherms of nanocomposites are presented. As a result of the data obtained, a unique opportunity presented itself, based on the results of the analysis of the kinetic regularities of crystallization of nanocomposites based on HDPE and CB, to study the crystallization process and the growth mechanism of crystalline formations. For example, it was established that for nanocomposites with 1.0 – 10 wt % CB content, the process mechanism is characterized by the formation of a three-dimensional spherulite structure with the continuous formation of homogeneous and heterogeneous nucleation centers. In nanocomposites with a 20 wt % CB content, the process of isothermal crystallization in the region of a first-order phase transition occurs at 115°C, as a result of which a two-dimensional disk-shaped crystal structure is formed, with homogeneous and heterogeneous nucleation centers being continuously formed. At the same time, a fairly well-founded theoretical analysis of the process of isothermal crystallization process is provided, taking into account modern trends in this scientific direction. Based on the obtained data, it can be stated that the appearance of a bend in the thermomechanical curve in the region of the viscous flow state is the result of a change in the growth mechanism of crystalline formations [14, 15].

The results of the derivatographic method for analyzing the thermal properties of nanocomposites depending on the CB content are considered. Based on the derivatograms, it was established that with an increase in the CB content in the polymer matrix from 1.0 to 10 wt %, a slight increase in the melting temperature and thermal destruction of nanocomposites is observed. However, in a nanocomposite with a 20 wt % CB content, on the contrary, a decrease in the melting temperature and thermal destruction occurs. This circumstance, as shown above, is apparently associated with the formation of a more simplified crystal structure in the nanocomposite [15].

It is known that graphite helps reduce the coefficient of friction, while having good thermal and electrical conductivity. The results of a system analysis of the electrical conductivity of nanocomposites based on HDPE and carbon fillers such as CB and graphite are presented in some detail in [16]. For comparative analysis, 13 nanoscale carbon fillers are presented. It was necessary to select the most effective ones from among the different types of nanofillers used. It was important to evaluate the effectiveness of using graphite nanoparticles and CB based on electrical conductivity data and the results of studying the basic physical and mechanical properties. The properties of nanocomposites such as electrical conductivity, strength characteristics, and melt flow were studied. As a result, the most effective grades of CB and graphite were selected, providing the highest values of electrical conductivity [16].

Nanofiller types and compatibilization of nanocomposites

For polymer composite materials, there are the following types of nanosized fillers, which are illustrated in Fig. 1 [17]. This Fig shows a schematic representation of several types of nanofillers, indicating their particle sizes. Let's consider some of them:

- carbon nanotubes and nanofibers, including single, double and multi-walled nanotubes; single and graphitized nanofibers and whiskers, as well as nanotubes with grafted layers and functional groups;
- inorganic nanotubes with the composition: B_4C, BN, LaF_3, SiC, TiS_2, MoS_2, ZrS_2, their length is 3–30 µm, outer diameter – 25–100 nm, inner diameter – 10–80 nm;
- short nanofibers and nanorods, including metal (Ag, Bi, In, Si), semiconductor (GaP, InP), nitride (Si_3N_4) and oxide (TiO_2);
- nanoparticles of spherical or irregular shape, particles of metals and alloys, non-metals (B, Si), particles of nanodiamond and nanographite (C), nitrides (AlN, BN, CrN, Si_3N_4, TiN, ZrN), carbides (B_4C, Mo_2C, SiC, TiC), borides (TiB_2, NbB_2), various simple and complex oxides; particle size varies from 5–30 to 400–600 nm [18-22].

Based on the above, it can be established that fillers differ not only in composition, but also in their crystallographic structure, which, as will be shown below, have a significant impact on the overall structural features and basic physical-mechanical and physical-chemical properties of polymer composite materials.

Carbon nanotubes (CNTs)

An allotropic modification of cylindrical carbon is carbon nanotubes (CNTs) with a length from one micrometer to several centimeters, consisting of one or more rolled graphene planes. There are different types of nanotubes: single-walled and multi-walled, straight and spiral, long and short. The unique emissive properties of CNTs allow them to be used in displays and cathodes [23].

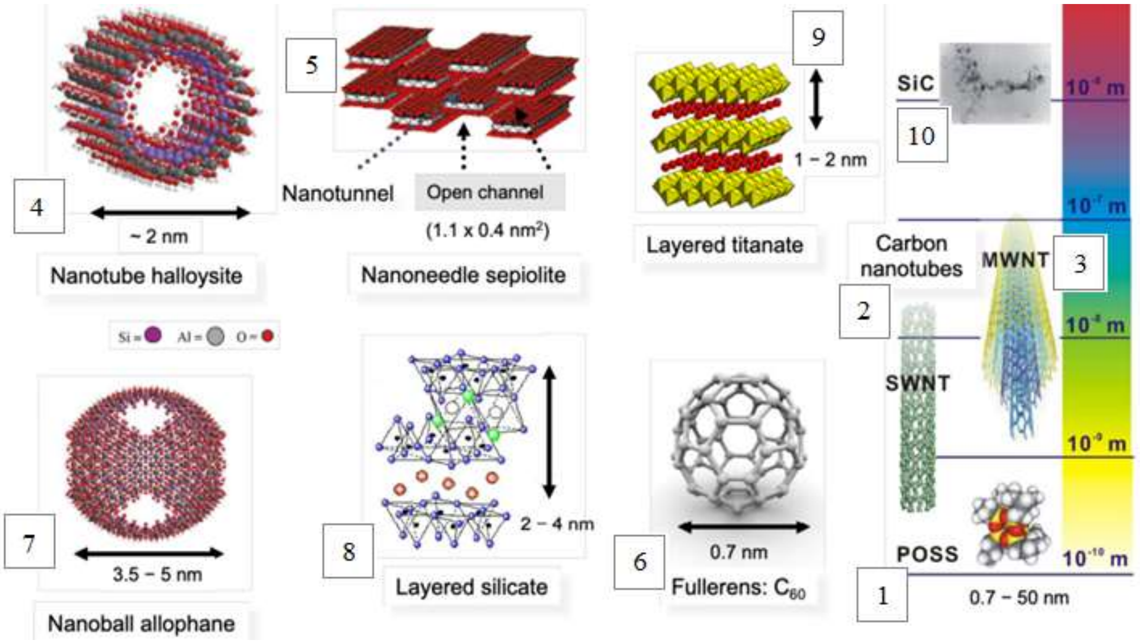

Fig. 1: Schematic representation of the structure of various nanofillers with the given sizes of nanoparticles. Polyhedral oligomeric silsequioxanes (POSS (1)), carbon nanotubes (single-wall nanotube (SWNT (2)) and multi-wall nanotube (MWNT (3)), nanofiber (halloysite (4)), nanoneedle (sepiolite (5)), nanoballs (fullerens (6), allophane (7)), layered nanomaterials (layered silicate (8), layered titanate (9)), and silicon carbide (SiC (10)) [18-22].

The characteristic features of the CNT structure open up promising possibilities for their practical use in nanocomposites based on polyolefins [24]. The introduction of CNTs into polymer matrices made it possible to develop a unified strategy for the preparation and study of nanocomposites with electrically conductive, mechanical and thermal-physical characteristics. However, despite the targeted improvement of the properties of CNT nanocomposites, the use of these fillers is very limited due to the high cost and lack of technology for their industrial production. Along with this, certain difficulties arise with their uniform dispersion in the polymer matrix in the melt mode. In addition, there is a problem with their agglomeration in a viscous-flow state, as it is characterized by the existence of weak adhesion between the polymer matrix and the surface of the filler [25]. In the process of intensive processing, to a certain extent, it is possible to influence the dispersion process in the polymer matrix to a certain extent. To improve the interphase interaction, it seems possible to preliminarily chemically modify the surface of CNTs [26].

The presence of functional groups on the side walls of CNTs, an increase in the chemical reactivity between the filler and the matrix, as well as the presence of functional groups on its walls ensures more efficient load transfer from the matrix to the reinforcement [27].

It should be noted that chemical treatment of CNTs with a mixture of nitric and sulfuric acids (HNO_3/H_2SO_4) leads to the formation of carboxylic acid groups (-COOH) on their surface [28]. A method for chemical surface treatment of CNTs was developed by Gojans *et al*. [29]. This method contributed to a significant change in the nature of the CNT surface, as a result of which high compatibility with the polymer matrix was achieved. Along with the use of the acid treatment method, the possibility of using clay nanoparticles was considered, which would provide a high dispersion of carbon nanotubes in the polymer matrix while simultaneously improving the electrical characteristics of nanocomposites [26]. Simultaneously with the production of nanocomposites based on a monopolymer matrix, in recent years the attention of scientists has been attracted by research aimed at using a binary polymer base, i.e. mixtures of polymers. It has been shown that nanocomposites based on polymer mixtures and CNTs have high electrical and thermal-physical characteristics. Research has also shown that the electrical conductivity and strength of nanocomposites increase due to the fact that CNTs promote the formation of a three-dimensional physical mesh within the polymer matrix. With increasing CNT content and reaching a critical value corresponding to electrical percolation, the electrical conductivity of nanocomposites increases sharply. With a further increase in the CNT content, the increase in the electrical conductivity of the nanocomposite slows down significantly [24, 27]. It should be noted that in nanocomposites obtained on the basis of a binary polymer mixture, to achieve the maximum value of electrical conductivity, a relatively smaller amount of CNTs is required than in the case of a monopolymer base. At the same time, one important condition must remain, according to which the selective arrangement of CNTs occurs in the matrix phase or interfacial region of the polymer mixture [30]. To achieve a relatively greater effect, the polymer mixtures used must be characterized by identical morphology, as a result of which the double phenomenon of electrical percolation can be recorded.

Based on the above, it can be established that in binary polymer mixtures the electrical conductivity of nanocomposites is influenced by the concentration of CNTs and the final morphology of the mixtures. The formation of the morphology of binary mixtures is largely determined by the ratio of polymer components in the mixture and their ability to be combined during the mixing process [13, 24]. It was shown in [31] that high-quality nanocomposites were obtained by mechanical mixing of multi-walled carbon nanotubes (MWCNTs) in a polyetherimide (PEI) melt. When introducing dispersed MWCNT into the polymer matrix (PEI), it was pre-mixed with a poly(butylene terephthalate) (PBT)/MWCNT masterbatch. This approach ensured the production of a homogeneous dispersion of MWCNTs in the polymer volume of PEI. For this mixture, the electrical percolation threshold (pc) was reached at 1.0 wt % MWCNTs. It is characteristic that (pc) showed a power-law dependence of electrical conductivity depending on the MWCNT content with a critical index of 1.92. The value of this indicator indicates that a three-dimensional percolation structure has been formed. The very fact of a decrease in the glass transition temperature and pressure in the extruder head with the introduction of a masterbatch indicated a decrease in the viscosity of the melt and, accordingly, an improvement in the PEI processing technology.

Obtaining graphene

Back in 2004, British scientists Andre Geim and Konstantin Novoselov were the discoverers of graphene. Working at the University of Manchester, they investigated the properties of carbon materials, including graphite. By experimenting with graphite, they were able to isolate a monatomic layer of carbon, which was called graphene.

Graphene combines a whole range of properties. This attracts thousands of scientists around the world for research in various fields (physics, chemistry, biology). No other material, except graphene, can simultaneously combine high electrical conductivity, thermal conductivity, strength, flexibility, elasticity, chemical resistance, and high optical absorption coefficient. However, it is always necessary to remember that the listed properties are inherent in ideal single-layer graphene. When graphene is given a superior comparative form, saying that it is "the very best," what they mean is that there is no material in the world of the same thickness (that is, the size of one atom or 3.35 Angstroms) with comparable properties. This also applies to other properties of this material. When conducting certain experiments confirming the uniqueness of its properties, it is necessary to take into account the "uniqueness" of graphene, making adjustments for size and scale [32-37].

A key factor in the successful use of graphene in various fields of engineering and technology is the ability to split graphite into separate sheets. In this regard, several mechanochemical methods have been developed for breaking graphite into individual sheets, which included mechanical or chemical exfoliation, as well as chemical vapor deposition [32, 33]. It is quite obvious that all of the listed methods for splitting graphite have their advantages and disadvantages, which depend on the purity and the presence of defects (oxygen and other functional groups on its surface).

One of the first chemical methods for the formation of graphene is considered to be the production of graphene by reduction of graphite oxide [34–37]. This very effective approach to the problem of separating graphite layers is based on the use of chemical oxidizing agents (Fig. 2). The use of strong gaseous oxidizers such as oxygen or halogen promotes oxidation of the interlayer space of graphite. The latter circumstance leads to the expansion of the interlayer space and, accordingly, a decrease in the energy of interaction between the layers. As a result, the possibility of separating graphene layers in the liquid phase is facilitated, which makes it possible to produce graphene oxide samples with transverse dimensions of several hundred micrometers [36, 37].

It should be noted that graphene is a unique material of the 21st century, which is hundreds of times lighter and stronger than steel. Taking into account that industrial production of graphene has been established, it will become the most popular and accessible promising material.

Despite the unique characteristics and potential for using graphene as a flexible, durable and electrically conductive material, its only drawback is its high cost. Despite this, intensive research is being conducted in the world's leading scientific organizations in the direction of improving its production technology.

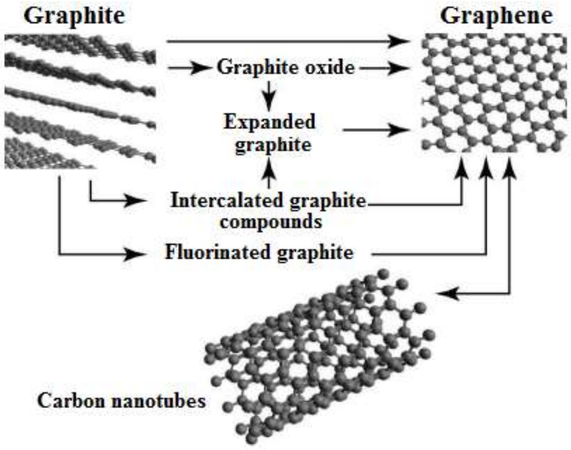

Fig. 2: The mechanism of the process of synthesis of graphene and carbon nanotubes in the process of graphite splitting by various methods.

Compatibility of mixture components in polymer nanocomposites.

Compatibility of the mixture components is an essential condition for obtaining nanocomposites with predetermined characteristics. This circumstance is explained by the fact that the difference in the chemical nature of the components of the mixture contributes to the production of nanocomposites with poor performance properties [1, 38-40]. Therefore, ensuring the necessary compatibility becomes important for improving the basic physical-mechanical properties and processability of nanocomposites. Thermal destruction of the organomodifier and the interaction of the decomposition products with the polymer matrix together can significantly affect the morphology and final properties of the composite material (Fig. 3).

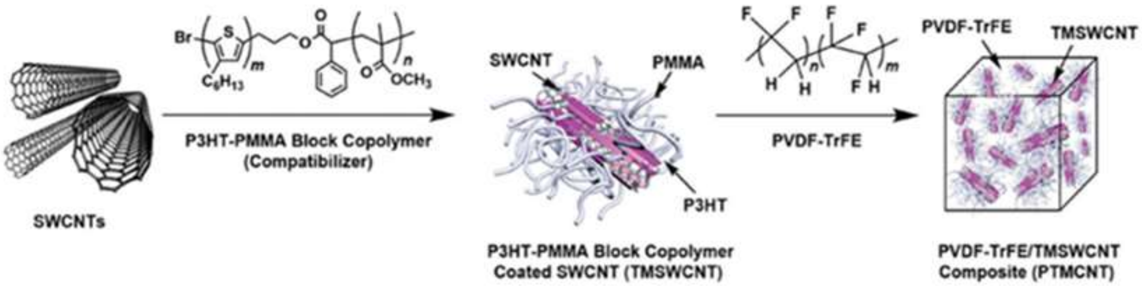

Fig. 3: Schematic representation of the preparation of compatibilised PVDF/SWCNT nanocomposite [40].

The most effective modifiers that improve the compatibility of the polymer matrix with the filler surface are compatibilizers, which are graft copolymers of polyolefins with polar monomers. These include graft copolymers based on polyolefins and maleic monomer, polyolefins with polar monomers such as acrylonitrile, acrylic and methacrylic acid, methyl methacrylate, vinyl acetate, etc. [13-16]. The mechanism of action of graft copolymers is based on the fact that the main polyolefin macrochain participates in the formation of the crystalline structure of the polymer matrix [39]. The lateral polar grafted chain and filler particles are pushed into the amorphous interspherolitic space during the growth of polymer matrix crystals, where, as a result of adhesive contact, the compatibility of the mixture components improves. It is this feature of the compatibilizer-graft copolymer that is a necessary condition for improving the quality of products based on nanocomposites [13-16, 39].

Polymer nanocomposites.

Polymer nanocomposites are polymers or copolymers containing nanoparticles. A nanoparticle, sometimes called a nanoobject, is usually considered to be a conglomerate or aggregate particle consisting of approximately a thousand atoms and being part of a bulk material. Nanoparticles can be of different shapes, but at least the main requirement is that the size of its particles should be in the range from 1 to 100 nm.

Nanoparticles differ from conventional dispersed filler particles in that they have a more developed specific surface area (an order of magnitude or more). In this case, the surface/volume ratio for the filler phase has very high values. In this regard, the properties of nanocomposites, compared to conventional composite materials, depend to a much greater extent on the morphology of filler particles and the nature of the interaction of components at the phase interface. In nanocomposites, the filler must be dispersed in such a way that the resulting particles are crushed in only one direction and have sizes in the nanometric range (1-100 nm). If the filler is crushed only in height, then the dispersed phase is formed by films, plates and other similar particles. If the filler is crushed both in height and width, then the dispersed phase will be distributed in the form of fibers, threads, and capillaries. Finally, if the filler substance is crushed in all three directions (height, width and length), the dispersed phase will consist of discrete (individual) particles, the shape of which can be very diverse.

It is well known that polymers have a wide range of applications due to their unique combination of properties, durability, light weight, efficiency and high productivity of equipment for processing them into various types of structural products [41]. Compared to metals and ceramics, polymers are still characterized by comparatively low values of heat resistance, electrical conductivity, and thermal degradation and, therefore, it is not possible to solve this problem by any methods of modifying their structure. Reinforcement of fibers, nanoparticles and whiskers are alternative ways to achieve the required properties [42].

Thus, it can be concluded that nanocomposites are a relatively new class of composite materials, in which the used nanoparticles of inorganic origin are uniformly dispersed in a polymer matrix. Thanks to this, it is possible to obtain materials with improved performance properties. Nanocomposites are among the multiphase systems in which only one filler is a nano-sized substance in the polymer matrix. It is the use of nanoparticles that gives polymer composites completely new and better, and in some cases, unusual properties.

Polymer nanocomposites can find their practical use in almost various fields of engineering and industrial production technology. A fairly widespread use of nanocomposites can be noted in the packaging of food products such as meat, cheese, and dairy products. Nanocomposites are quite widely used in the production of medical devices, for example, for carrying baby pacifiers, blood collection tubes, and drinking water bottles [43].

Polymer and nanoparticles form the basis of nanocomposites, which have demonstrated their uniqueness in the production of structural products. Due to the exceptional features of their properties, scientists and specialists began to pay more and more attention to finding new opportunities for their practical use in various fields of industry [44]. At the same time, polymer matrices are not only homopolymers, copolymers, block copolymers, or mixtures thereof [45]. Synthetic or natural polymers are composed of many repeating monomer units linked together to form a long polymer macrochain. The production of synthetic polymers is steadily growing, as they play a key role in the production of structural materials based on them. The most common representatives of synthetic polymers are polyolefins, polyvinyl chloride, styrene plastics, etc. [46]. In the composition of nanocomposites, not only plastics are used as a polymer matrix, but also elastomers, thermoplastic elastomers [13], and various fibers. Similarly, low molecular weight resins and high molecular weight elastomers are used as polymer matrices for various types of thermoset polymer nanocomposites [47]. Despite significant advances in the production of new and improved polymer materials, there are still a number of disadvantages in their properties that limit their use as a matrix for nanoparticles [48]. Polymers have a relatively low strength and elastic modulus at low temperatures, and therefore these materials require modernized and improvement structural features not only at the micro but also at the macro level [49]. An important component in polymer nanocomposites are nanosized fillers, or simply nanofillers, which act as a reinforcing and strengthening component. The purpose of studying the structure and properties of nanofillers is to obtain nanocomposites based on them with improved electrical, magnetic, mechanical, thermal and fire-resistant properties. The multifunctional features of the properties of polymer nanocomposites are described in detail in the literature [50-52]. Fillers in polymer nanocomposites can give them not only functional, but also special structural characteristics. Compared to traditional fillers, nanoparticles have obvious advantages, which are achieved mainly due to a significant increase in the specific surface area, which affects the improvement of the complex properties of nanocomposites. The correct selection of nanofillers and methods of their processing in combination with other components of the mixture make it possible to obtain a whole set of modified multifunctional nanocomposites for various purposes. By introducing conductive nanoparticles into a polymer dielectric, it seems possible to obtain an electrically conductive film. The dispersion of nanoparticles in a polymer matrix helps to strengthen the supramolecular structure of nanocomposites and change the physical-chemical characteristics of the surface in the contact zone, which is directly related to the formation of their functional properties. Thus, the main parameters for controlling the properties of nanocomposites are the physical chemistry of the surface, geometric shape, nanoparticle size and mixture ratio [50]. Fig 4 provides information about known nanocomposites.

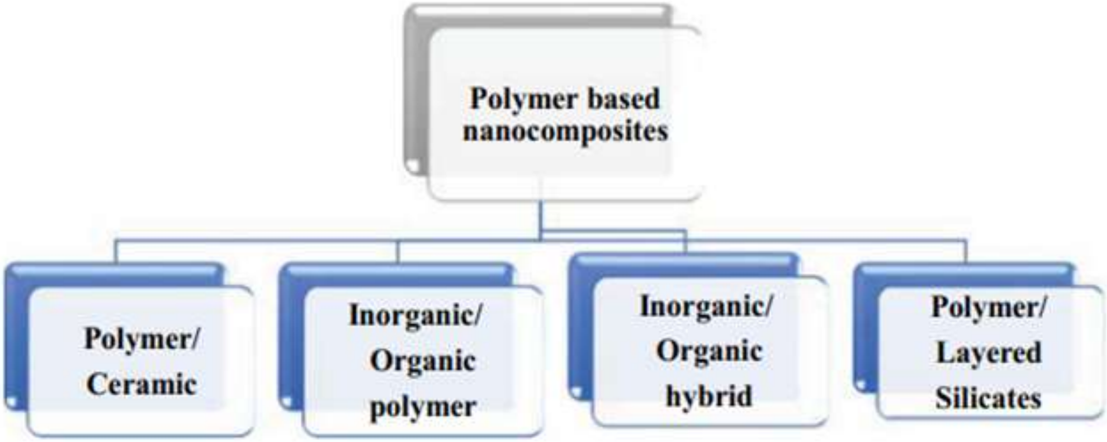

Fig. 4: Well-known polymer nanocomposites.

Fig. 4 provides information on known nanocomposites. As can be seen from this Fig, by changing the polymer base and the type of filler in the composition of nanocomposites, it is possible to vary their properties within a fairly wide range. This circumstance makes it possible to obtain a whole range of multifunctional nanocomposites for a specific purpose on their basis. This scientific direction requires systematic research on the structural features and properties of nanocomposites. As a result, a unique opportunity will be presented to approach the development of a theoretical basis and scientific approaches for interpreting the discovered patterns in the change of their structure and properties.

Various methods for obtaining polymer-based nanocomposites.

Polymeric materials, due to their high physical-mechanical, operational and technological characteristics, have become reliable substitutes for non-ferrous and ferrous metals in the process of mass production of structural products based on them. Today there is no industry where polymeric materials are not used. Modification of polymers with mineral fillers or mechanical mixing of polymer with polymer, the introduction of various types of structure formers, plasticizers, compatibilizers, cross-linking agents and other modifiers into their composition have created great opportunities for further expansion of the areas of their practical use in harsh extreme conditions [53]. The emergence of nanocomposites has, in general, led to a new revolutionary leap in the field of polymer materials science. The creation of multiphase polymer composites with the participation of organic or mineral nanostructures has changed the general stereotypical understanding and approaches to interpreting the dependence of the complex of their properties on macro- and microstructural factors.

Nanocomposites are a new generation of polymeric materials which, unlike their predecessors (filled with conventional finely dispersed powders of polymeric materials), are characterized by the fact that nanosized particles (up to 100 nm in size) are comparable to primary crystalline structures - “packets” of macrochains, which, as is known, form the basis of the supramolecular structure of a crystalline polymer. It is the commensurability of nanoparticles with the primary nanostructural elements of crystallizing polymers that allows for a significant impact on the mechanism of formation of the supramolecular structure of the polymer matrix, thereby improving the final properties of nanocomposites [54-56]. It should also be noted that nanoparticles contribute to the creation of heterogeneous nucleation centers in the polymer matrix melt to a greater extent than fillers of relatively large geometric dimensions. This is where the “size effect” of filler particles actually manifests itself. Of course, the properties of nanocomposites are determined not only by the size of the nanoparticles, but also by uniform dispersion and compatibility with the polymer matrix. This problem is especially acute when producing nanocomposites based on polar mineral fillers and non-polar polyolefins. The lack of wettability with a polymer base in some cases is one of the main reasons contributing to the deterioration of the main physical and mechanical characteristics of composite materials [57, 58].

When developing nanocomposites with predetermined properties, the following important circumstances must be taken into account: (1) chemical structure and composition of the polymer; (2) polymer mass; (3) chemical solubility from the polymer; (4) thermal stability of the polymer; (5) the degree of polymer crystallinity; (6) chemical structure of nanoparticles; (7) surface area of nanoparticles; and (8) dispersity of nanoparticles.

To obtain composite polymer nanomaterials, both traditional and non-traditional compounding methods are used:

- mixing nanofiller and powdered polymer followed by pressing;
- introduction of filler into the molten polymer (extrusion method);
- mixing the dispersion of filler particles with a polymer solution with further evaporation of the solvent;
- polymerization (the filler is dispersed in the monomer, and then polymerization occurs together with the captured nanoparticles);
- matrix synthesis;
- synthesis of graft-filled composites (based on the graft copolymerization of polyolefin with polar monomers in the presence of a filler in solution mode);
- coagulation of a polymer solution with a filler introduced into it by changing the chemical composition.

In situ polymerization, melt extrusion and solution dispersion are the most common methods for preparing nanocomposites, which ultimately influence the formation of their morphology [58].

Polymerization in solution in the presence of a nanofiller in situ

Because the solvents used to dissolve polymers are extremely toxic, polymers that cannot be safely or economically synthesized by dissolution methods are suitable for *in situ* polymerization. This method achieves comparatively better dispersion and distribution of nanoparticles (NPs) in the polymer matrix [59]. This process involves swelling of the nanofiller in a monomer solution or liquid monomer. In this case, intercalation of low-molecular monomer into the interlayer space of filler particles occurs, resulting in their swelling (Fig. 5). The advantage of this method is that it can be used to synthesize nanocomposites consisting of thermosets and thermoplastics. In addition, this allows polymers to be absorbed onto the surface of the filler, thereby improving the properties of the nanocomposite. As can be seen from this Fig, this method can be used to obtain similar partially exfoliated structures that arise as a result of uniform redistribution of intercalated nanofillers in a polymer matrix [60].

This mixing method, due to its simplicity, is the most common and is used in the production process of polymer nanocomposites. However, compared to other methods, achieving optimal dispersion of nanofiller in the polymer matrix may be more challenging [61].

The solution in the reactor is a system consisting of a polymer and a nanofiller, which can be easily dispersed in an appropriate solvent [62]. The applied methods of ultrasonic irradiation, magnetic stirring, and boiling are intended mainly for uniform dispersion of the nanofiller within the polymer matrix [63]. According to the method shown in Fig. 6, after the solvent evaporates, a nanocomposite film is formed in which the nanoparticles remain practically dispersed in the polymer volume. The main advantage of solution mixing is the reduction of gas permeability [63], ease of use and general technology for all types of nanofillers, including thermosetting and thermoplastic polymers. This method is simple and effective for creating high-quality nanocomposites using less toxic solvent such as alcohol, acetone, chloroform, water, etc. The advantage of this process is that, as a result of the effective interaction of nanoparticles with the solvent and monomer, a unique opportunity is provided to ensure their uniform dispersion in the solution over a fairly wide range [59]. After addition of the initiator and chain transfer agent, the mixture is polymerized under nitrogen atmosphere and dried under vacuum [63].

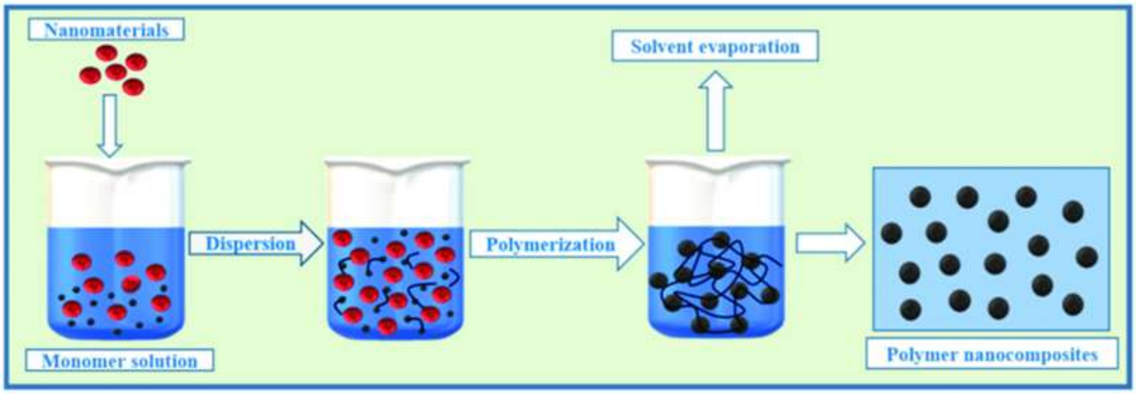

Fig. 5: Schematic illustration of the *in situ* polymerization method.

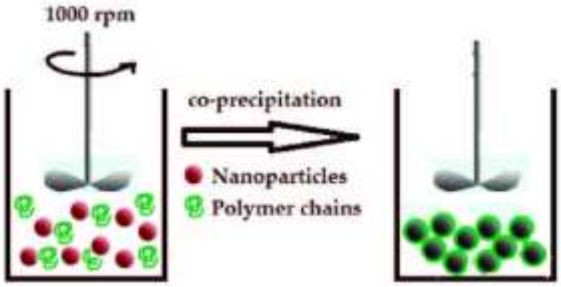

Fig. 6: Method of mixing solutions.

Synthesis of graft-filled polymer composites

This method of synthesizing filled composites in a polymer solution was first developed by Professor N.T. Kakhramanov [64]. This method has fundamental differences from solution methods for the synthesis of filled composites. This is due to the fact that complex-radical graft copolymerization of acrylic monomers with polyolefins is carried out in a solvent in the presence of various mineral fillers. The advantage of this synthesis method is that the developed initiating system based on benzoyl peroxide and aromatic amine completely eliminates the formation of a homopolymer of the grafted acrylic monomer. The graft copolymerization reaction proceeds with maximum selectivity, as a result of which there is no need to separate the homopolymer from the graft copolymer. In addition, the filler is introduced directly during the process of graft copolymerization in solution mode, which ensures their uniform dispersion throughout the entire volume of the polar polymer matrix. The authors found that a unique insulating monolayer based on a polar grafted copolymer is formed on the surface of the filler particles, which practically reduces the process of their agglomeration to a minimum. This method allows obtaining a whole range of graft-filled composites based on polyolefins, synthetic rubbers, elastoplasts and acrylic monomers [64].

Extrusion method of mixing composite materials in the melt

This is the simplest and most common method of mixing fillers with polymers. The extrusion method for producing polymer nanocomposites in melt mode consists of intensive thermomechanical mixing of molten polymer with organoclay. As a result of intercalation of the macrochain into the interlayer space of organoclay, their conformational mobility and entropy are significantly lost. Therefore, the most likely driving force in this process is the enthalpy of polymer-organoclay interaction, which plays an exceptional role in the mixing process in a viscous flow state. It is precisely due to this circumstance that polymer nanocomposites based on organoclay are very successfully obtained directly during the extrusion process [65]. Features of the extrusion method include the absence of solvents, which from an environmental point of view eliminates the presence of harmful waste. Along with this, the speed of the extrusion process and the productivity of the equipment are very high and are characterized by simplicity of technological design. In other words, the extrusion method is the most preferable for obtaining various types of polymer nanocomposites on an industrial scale, since it does not require large costs for raw materials and maintenance of the technological scheme. Fig 7 shows a schematic diagram of extrusion equipment for obtaining polymer nanocomposites. Melt blending has been used to create polymer nanocomposites containing various types of matrices, such as polycarbonate [66, 67], polyamide 6 [68], polyethylene [69], and others.

According to the above scheme, the polymer and filler, after “dry mixing,” are introduced into the extruder through a hopper. As a result of the translational movement of the screw and the temperature of the material cylinder, the polymer melts. Next, after the compression zone, it enters the dosing zone, where intensive mixing of the mixture components takes place. The polymer mass is extruded through a forming head in the form of strands, which are then subjected to water cooling. Finally, the strands are fed into a crusher to produce granulated material. Thus, each method of mixing the components of the mixture has its own advantages and can be selected depending on the type of polymer matrix and filler. The work [70] presents the results of a study in the direction of selecting the optimal technological mode for the extrusion of composite materials based on binary mixtures: high-density polyethylene (HDPE) and low-density polyethylene (LDPE) with various mineral fillers. Aluminosilicates such as montmorillonite, bentonite, and aluminum hydroxide were used as fillers. The results of experimental studies have shown that the introduction of various fillers into the composition of the LDPE+50 wt % HDPE polymer mixture has a significant impact on the choice of the optimal technological mode for their processing by extrusion and injection molding methods. An important circumstance is that the introduction of montmorillonite and bentonite into the polymer mixture helps to maintain the melt flow index (MFI) at a sufficiently high level [70].

For a long time, the science of polymer structure was based on the concept of a natural nanostructured system [71]. Considering polymers as a natural nano-object, it seemed interesting to determine possible ways of using the characteristic features of the polymer nanostructure for targeted changes in their properties. At the same time, there was a need to obtain nanoreactor structures taking into account the conditions of their formation.

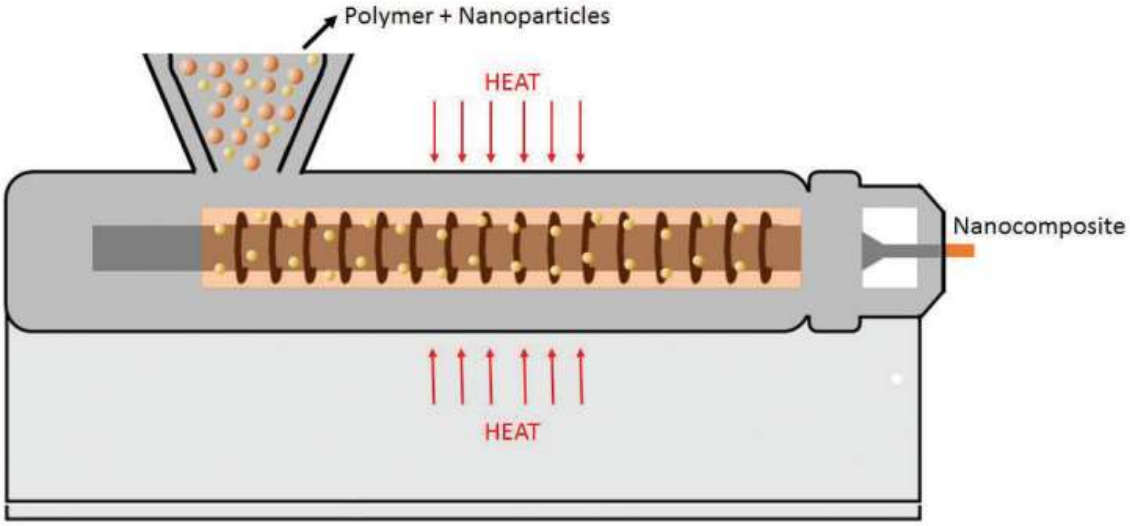

Fig. 7: Scheme of extrusion equipment for mixing and obtaining polymer composites.

The work [72] presents the results of a study of the influence of a compatibilizer on the physical and mechanical properties of polymer mixtures based on low-density polyethylene (LDPE), polypropylene (PP) and nitrile butadiene rubber (SKN-26). The fundamental possibility of improving the properties of polymer mixtures by using coupling agents based on LDPE graft copolymer with methacrylic acid is shown.

Dressing of the filler surface with organosilicon compounds

The most effective and time-tested method of improving the compatibility of organo-mineral structures is dressing the surface of mineral fillers with organosilicon compounds. A dressing size is a common organic compound with one type of functional group capable of reacting with the polymer matrix during its curing and another type of active group on the filler surface. The most common silane dressing sizes are the $RSiX_3$ type. The organic radical R ensures interaction with the polymer matrix and SiX_3 forms bonds with –OSi– groups on the filler surface. Alkoxytitanates and phosphate titanates, which play the same role as an agent for combining two dissimilar phases, and other substances are also used to increase, and sometimes to slightly reduce the bond strength of the phases, depending on the chemical nature of the PCM components [73].

The purpose of dressing is to improve the adhesive contact of the polymer matrix with the filler surface and to create a covalent bond - filler-dresssing size-polymer matrix with subsequent increase in the range of properties and processability of hybrid composite materials. For example, work [4] presents the results of a study of the influence of organosilicon dressing size on the structural features and properties of polymer composites based on low-density polyethylene and kaolin nanoparticles. The influence of the type and amount of the dressed filler on the nature of the change in the structural features and properties of polymer composites is shown. The results of the analysis of the method of synthesis of silicon-containing epoxy compounds in the process of hydroxylation of glycidyl ethers of the allyl series with methyleneethylsilane with the participation of chloroplatinic acid [5] with the formation of silicon-containing derivatives are considered. Based on the results of the experimental study, 12 organosilicon compounds were synthesized for dressing quartz nanoparticles. It has been established that the developed dressing sizes contribute to improving the compatibility of the quartz filler with the polymer, with subsequent improvement of the complex of physical-mechanical and physical-chemical characteristics of the composites. The type and concentration of the dressing used has a significant impact, first of all, on the strength properties. According to the data presented in this work, finishing was carried out in an aqueous solution of organosilicon compound at a temperature of 55°C. The nanoparticles were dressed in a 0.5–2.0% aqueous solution of organosilicon compound acidified with acetic acid to pH = 3.5, at a temperature of 55 °C for 60 min. The results of studies on optimizing the concentration of dressing sizes and quartz filler are shown, which achieve high values of physical and mechanical properties of hybrid composites. Additional recommendations are given for further improvement of the performance properties of dressed nanocomposites. Based on a comparative analysis of experimental data, it was established that nanocomposites dressed with 2-methyl-5-methyldiethylsilyl-2-(methyleneoxy-1,3-dioxolano)-pentane are characterized by comparatively high values of physical and mechanical properties. It should be noted that dressing the surface of fillers is a multi-stage, energy-intensive process. The costs of preparing mixed compositions amount to 20-30% of the cost of the composite. Despite all the difficulties of introducing filler into a polymer, certain successes have been achieved in this area, as a result of which the global production of filled composites is constantly increasing [4, 5].

The separate influence of aminopropyltriethoxysilane dressing size on the physical and mechanical properties of nanocomposites based on polypropylene and clinoptilolite (CTL) is considered. It has been established that the introduction of a dressing size improves the properties of nanocomposites. For the first time, a comparative assessment of the influence of the size of CTL particles on the main operational characteristics of polymeric materials is given. Regularities in the change in the properties of composites depending on the filler concentration are revealed [73].

It is obvious that in order to obtain composite materials with high physical and mechanical properties, it is necessary, first of all, to achieve chemical bonding of the filler particles with the polymer matrix. This is the most effective modification method, which ensures not only uniform dispersion of filler particles in the volume of the polymer matrix, but also prevents the possibility of their agglomeration with subsequent deterioration of the properties of nanocomposites. Along with this, the existence of a covalent bond between the macromolecule and metal atoms on the surface of mineral filler particles helps prevent the likelihood of their forced migration to the surface of the polymer product during processing and operation under harsh extreme conditions [74].

In the work [75-77], using the example of bentonite, talc and kaolin nanoparticles, we examined in detail the mechanism of dressing and formation of organo-inorganic hybrid gels in the composition of a nanocomposite. It has been established that, regardless of the type of filler, the entire process of obtaining hybrid gels occurs in two stages. The first stage includes the process of hydrolysis and dehydration with the formation of a dressed mineral filler. The second stage consists of an extrusion process of mechanochemical synthesis of a composite material as a result of mixing a dressed filler with a polymer base - a copolymer of high-density polyethylene with maleic anhydride (PE-*g*-MA). During the mixing process and the thermomechanical action of the extrusion equipment, maleic anhydride interacts with the hydroxyl groups of the dressing and filler nanoparticles to form a mixed type of rare-mesh cross-linked structures. Apparently, during the process of dehydration of hydroxyl groups, chemical bonds are formed between the dressing size and the filler particles, the dressing size with the dressing size, the polymer base with the dressing size, and ultimately the polymer base with the filler particles.

Below in Fig 8 is a schematic representation of possible options for the formation of a covalent bond between maleic anhydride in the copolymer and the hydroxyl groups of the dressing size and filler particles. As can be seen from this Fig, a filler particle (Fig 8), after dressing, forms a monolayer on its surface, which envelops the surface of the particle like a web. The dressing process is accompanied by a sol-gel reaction, which, as a result of hydrolysis and dehydration at hydroxyl groups, leads to the formation of a rare cross-linked structure not only at the particle-dressing size interface, but also between the dressed particles with the formation of peculiar "clusters" (Fig 8).

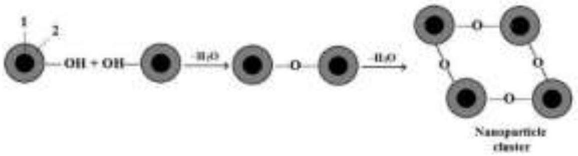

Fig. 8: Schematic representation of the interaction of dressed talc nanoparticles with the formation of cross-linked cluster structures, where 1 – nanoparticle, 2 – monolayer of dressing size.

According to Fig. 9 (a and b), as a result of mechanochemical synthesis, the addition of MA to the macrochain is possible in two variants. If the attachment of MA to the macrochain occurs at tertiary carbon atoms or at α-methylene carbon atoms, then in this case the first variant of the grafting mechanism occurs. If the attachment occurs at the site of breakage of the terminal or transvinylene double bonds in the LDPE macrochain, then the II option of MA grafting will be most likely (Fig 9a). Apparently, on the surface of dressed nanoparticles, part of the hydroxyl groups interact with polar maleic anhydride in the PE-g-MA macrochain, as a result of which the opening of the five-membered ring is observed according to the mechanism shown in Fig 9a. The further process of gelation does not exclude the possibility of interaction of the same dressed particle or cluster with two or more maleated PE-g-MA macrochains (Fig 9b).

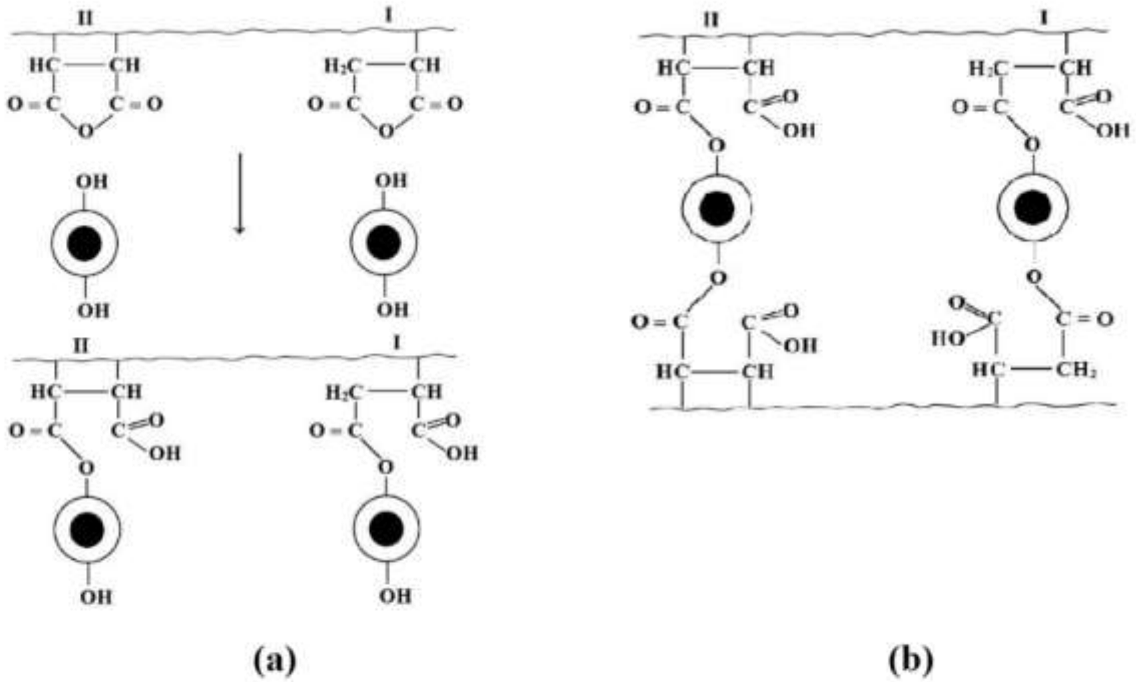

Fig. 9: Schematic representation of options for the formation of cross-linked structures involving grafted maleic anhydride with dressed talc nanoparticles: a) attachment of a nanoparticle to a macrochain; b) formation of cross-linked structures between macrochains.

On the one hand, the presence of polar groups in the macrochain increases the affinity of the filler for the polymer matrix, and on the other, by chemically binding to the macrochain, the likelihood of nanoparticle agglomeration is significantly reduced. Even if we allow the agglomeration of dressed nanoparticles, the high reactivity of hydroxyl groups will contribute to the formation of cross-linked clusters associated with the macrochain. The use of the method of functionalization of polymer macrochains contributes to a significant increase in the strength of composite materials. Thus, it becomes obvious that as a result of this reaction, the dressed filler particle through the maleic anhydride molecule in the macrochain is chemically bonded to the polymer matrix [75-77].

The correct concentration combination of the polymer matrix, filler and dressing size is one of the main factors that determines a significant improvement in the properties of composites. At the same time, the problems associated with establishing the influence of the size of mineral particles on the mechanism of bond formation with the organosilicon coating and, in general, with the polymer matrix, are practically not considered in the literature. Taking into account that the literature provides very scant information regarding dresses nanoparticles, it seemed interesting to dwell in more detail on conducting research in this direction in relation to properties. The authors of [80] examined the influence of the additions of kaolin, dressing size - aminoethylaminopropyltrimethoxysilane and zinc stearate on the main physical-mechanical properties of polypropylene-based nanocomposites. As a result of the introduction of a mineral filler of more than 10 wt %, a noticeable decrease in the tensile strength and elongation at break of the samples under consideration occurs. There is reason to believe that the most likely reason for the deterioration of the properties of nanocomposites may be associated with the introduction of a relatively larger amount of nanoparticles into the polymer matrix. Due to this, they predominantly accumulate in the interspherulitic amorphous space, as a result of which rigid reinforcement of the “passing chains” contained in them occurs. For this purpose, the most probable mechanisms of interaction between the filler and the dressing sizw are considered in the work. The results of a study of the selective and combined influence of ingredients on the main physical and mechanical properties of nanocomposites are presented. For example, it has been shown that with the combined use of zinc stearate and a dressing sizw, it is possible to increase to some extent the values of strength indicators, elongation at break and MFI of nanocomposites. Fig 10 shows a schematic representation of a dressed nanoparticle [75-77].

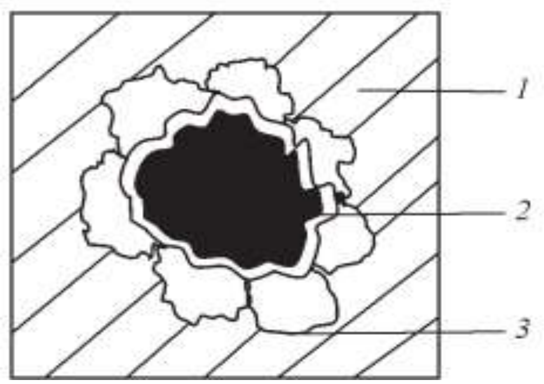

Fig. 10: Schematic representation of the process of formation of a dressing size monolayer on the surface of nanoparticles: 1 — polymer matrix; 2 — nanoparticle; 3 — dressing size.

An increase in MFI after the introduction of layered aluminosilicates creates serious technological advantages for the nanocomposites under consideration, intended for their processing by extrusion and injection molding. The combined use of zinc stearate with a dressing size makes it possible to solve a number of complex problems associated with improving the miscibility and compatibility of the polymer matrix with nanoparticles. The increase in the MFI of nanocomposites in the presence of the ingredients under consideration, with a simultaneous improvement in their strength characteristics and plassticity provides serious grounds for the assertion that the developed materials belong to the category of structural materials with predetermined performance properties. Research aimed at studying the thermomechanical properties of nanocomposites has made it possible to obtain fairly complete information about the first-order phase transition and softening temperature. At the same time, the regularities of changes in deformation depending on temperature in two states are considered: solid and viscous-flow [75-78].

Advantageous features of polymer nanocomposites and areas of their practical use

Taking into account that in recent years polymer nanocomposites have become especially popular polymer materials, many different types of nanofillers have been proposed that enhance and change the complex of their physical-mechanical and operational properties. A wide range of polyolefins, polystyrene, polyamide or nylon are used as matrices in nanocomposites, and nanocomponents are particles of aluminum or titanium oxides, or carbon and silicon nanotubes and fibers [79-82]. Nanocomposites based on polymers differ from conventional polymer composite materials in their relatively high strength characteristics, wear resistance, electrical conductivity, as well as resistance to chemical reagents and radiation aging, which allows their use in military-technical and aerospace developments. The main condition for creating a polymer nanocomposite with the necessary properties is the complete compatibility of the polymer matrix and the nanoparticles added to it. However, it is equally important to achieve the correct distribution of nanoparticles in the polymer volume to achieve the final result. Therefore, the production of nanocomposites is a high-tech industry and requires serious scientific research in the field of nanotechnology [81, 82].

Fig. 11: Application areas of polymer nanocomposites [84].

Fig 11 shows various areas of application of polymer nanocomposites. Due to their high physical-mechanical and physical-chemical properties, nanocomposites can find practical application in various fields of electronics and medicine. For example, scientists have managed to develop a method for creating anodes from silicon nanospheres and carbon nanoparticles for lithium batteries. In particular, scientists have managed to develop conductive paper made from a cellulose base and CNTs, which can be recommended for use in the production of flexible batteries, as well as thermoelectric materials with high electrical conductivity and low thermal conductivity [83-85].

It has been established that nanocomposites based on polymer matrices and nanotubes are capable of changing their electrical conductivity under the influence of external factors. By displacing nanotubes or nanoparticles relative to each other, their electrical conductivity can be changed under the influence of external factors [86-88]. Scientists also hope that nanocomposites will help speed up the restoration of the structure of damaged bones if hinges made of a polymer nanocomposite containing nanotubes are installed along them to guide the growth and regeneration of bone tissue. And in 2012, another group of researchers proposed using nanocomposites in dentistry to restore tooth enamel [89]. There is also confidence that if magnetic particles are combined with fluorescent particles, it will be possible to obtain a material that has both effects. Due to the magnetic properties of such a nanocomposite, it is possible to detect dangerous formations in the body more quickly and easily.

Nanocomposites containing zirconium oxide particles and possessing excellent catalytic properties will be useful not only in pharmacology and medicine, but also in the process of cleaning environmental objects from organic pollutants, with their subsequent processing into safe materials (“green chemistry”) [90-92].

The introduction of nanocomposites will lead to revolutionary changes in a wide variety of industrial fields, such as aircraft manufacturing, space and military technology, chemistry, energy, medicine, biology, ecology, etc. Nanocomposite materials are widely used in the automotive industry for the production of various interior elements, electronic equipment, tires, and car engine modules. Ultimately, this allows to reduce the weight of the vehicle, reduce carbon dioxide emissions, and increase the strength of the body and the reliability of the use of electronic equipment [93, 94].

Conclusions

Thus, based on the above, it can be stated that nanocomposites are the materials of the future and have a significant advantage over the original polymer matrices. It becomes obvious that the main purpose of using nanofillers is to achieve high physical-mechanical, thermophysical and technological properties of nanocomposites with their minimum concentration. The development of technology for obtaining nanoparticles and their use in polymeric materials has made it possible to obtain new types of nanocomposites that are distinguished by a set of useful properties and promising possibilities for their practical use in extreme operating conditions. It is the science of nanocomposites that has made it possible to take a new look at the development of theoretical foundations for modifying their structure and properties in the field of materials science. Scientific approaches to interpreting the relationship in the polymer-filler system have been improved. The main advantage of nanoparticles over conventional dispersed fillers is a significant increase in their specific surface area and adhesive filler-matrix contact in the interphase amorphous region. Potentially high thermal and physical-mechanical properties, low weight, fire resistance, electrical conductivity, wear resistance of polymer nanocomposites compared to conventional composites in combination allow us to recommend them for use in special areas of engineering and technology.

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