CHAPTER «ENGINEERING SCIENCES»

ANALYSIS OF THE GLOBAL MARKET OF NANOMODIFIED INTELLIGENT POLYMER COMPOSITE MATERIALS

Ivitskiy Igor[1]

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Abstract. The work objective is to analyze the global market of nanomodified intelligent polymer composite materials and the capability to implement the developments of Ukrainian scientists in the global market. The nanotechnology market goes through its rampant development as evidenced by the increase of investments in the industry as well as the number of scientific research results, patents and publications on this topic. The number of companies representing the nanotechnology increases every year as well as the volume of commercially sold products manufactured with the use of nanotechnology. Today the achievements of nanotechnology are extensively involved in almost all branches of the economy. The researches consist of four parts. The first part provides the general information about the materials researched. The second part provides the general information about nanomodified intelligent polymer composite materials: their properties, range of application, producing technology. The third part is devoted to the review of publications, which are available in the published information source in this field. The fourth part is the analysis of the global market of nanomodified intelligent polymer composite materials. The main market trends are highlighted, the structure with a breakdown into countries and the types of materials, the characteristics of production and the consumption are given. Furthermore, the prices for the main types of nanomodified intelligent polymer composite materials are considered. The Ukrainian market of nanomodified intelligent polymer composite materials is considered in the fifth part, namely: its main factors and the

[1] Candidate of Technical Sciences,
Associate Professor at Department of Chemical, Polymer and Silicate Engineering,
National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, Ukraine

development trends are highlighted. The market development forecasts are determined in the sixth part based on the factors considered. The analysis of existing works in this field showed that in spite of, for example, the variety of existing technologies at the present time there are no universal technologies and equipment for preparing the nanomodified intelligent polymer composite materials and their processing into the essential parts. Therefore the development of effective technical means of creating and forecasting their stress-strain state is extremely important for the science and the industry. The work highlights the following factors characterizing its development at the present time, namely: the common problem for the entire global market of the nanomodified intelligent polymer composite materials is the high cost of the production and low overall production; the market is most developed in the regions characterized by positive dynamics of the entire nanotechnology sector in: the USA, Europe and China; the demand for such intelligent polymer composite materials is mainly formed in the military and medicine fields; the global market is great interested in creating the technologies and compositions of new materials and expanding the fields of their application; the Ukrainian market of nanomodified intelligent polymer composite materials is 7-10 years behind the world leaders in this field.

1. Introduction

The purpose of this research is the comprehensive analysis of the global market of nanomodified intelligent polymer composite materials (NMIPCM) and the possibilities of implementation of the developments made by Ukrainian scientists in the world market.

NMIPCM is a polymer composite materials that has the specific properties due to its modification with the carbonic nanofillers (nano-tubes) with intelligent sensors and actuators are brought into its structure which allow controlling the stress-strain state of the products and carrying out the certain transformation of the shape or structure of the polymer composite materials.

The intelligent sensor is the microsized measuring device in the form of constructive set of one or more measuring value transducers which is measured and monitored and which produces the output signal suitable for the remote transmission, storage and use in control systems and has the rated characteristics.

The sensors based on various materials and processes have been being used for a long time in the different fields of engineering, converting the non-electrical signals into electrical ones. The intelligent sensors that are used for intelligent polymer composite materials have the form of microsized sensor devices brought into the polymer composite.

Making the continuous online monitoring of stress-strain state of the structural elements will allow resolving a large variety of matters. The implementation of intelligent sensors to the design structure will give the opportunity to remote control and monitoring of the stress-strain state directly during the operation in real time.

The use of intelligent sensors for the manufacture of parts and assemblies for the spacecraft, for example, allows providing the continuous monitoring of integrity with monitoring of the stress-strain state. Such control allows responding to the critical loads and deformations in due time which significantly increases the level of safety.

The electromagnetic field momenta are recorded during the initiation and development of cracks, fiber breaks and material separation. Electromagnetic emission makes it possible to predict with high accuracy the material strength, the ultimate load, the remaining life time of the product which is operated under the static, dynamic and vibration load. When a material is subjected to dynamic loads (impact, momentum acoustic or thermal effects) then the emission occurs both at the point of effect and in the direction of propagation of the acoustic waves and it contains the information about the internal structure of the material.

The total global consumption of exceeds $13 billion [1]. This field is one of the most developed commercial segments of the nano-composite market. The average annual growth rate is 15%.

2. Field of NMIPCM application

At present time the well-defined definition of the term «nanotechnology» has not defined. According to the most common approach the nanotechnology is a set of techniques and methods used in the research, design and production of the nanostructures, devices and systems including the targeted control and modification of the form, size, interaction and integration of their constituent nanoscale elements (about 1-100 nm) the presence of which leads to the improvement or to the appearance of additional operational and / or consumer features and properties of the products produced [2].

Under the concept of a nanotechnological is included as follows:

– directly nanoscale objects with the specific for the nano-rage sizes at least one measurement (nanoparticles, nanopowders, nanotubes, nanofibers, nanofilms);

– macroscopic objects (volume materials, individual elements of devices and systems), the structure of which is controlled, created and modified at the level of individual nanoelements.

The devices or systems are considered manufactured with the use of nanotechnologies if at least one of their main components is the object of nanotechnology, in other words there is at least one stage of the technological process the result of which is the object of nanotechnology.

It is important to understand that the nanotechnology market is not quite correctly to consider as the independent industry; rather it is worth talking about the increasing role of nanomodifiers in various industrial areas.

One of the leading trends in the development of the global industry is increase in the number of researches and publications in the field of nanotechnology and increase in the number of patents regarding the nanotechnology development. At the same time the range of possible applications of intelligent sensors and actuators in polymer composite materials is being increased. At present the following challenging fields of NMIPCM application can be distinguished (Table 1).

In Table 1 – The typical fields and possible applications are listed only. Of course, there are a number of developments that go beyond these fields.

Nanomodified polymers are used to significantly improve the performance of structural, operational and special properties of products. As the modifiers the separate synthesized carbon nanotubes (CNTs) are used the sizes of which do not exceed 100 nm, are usually used. CNTs have an extremely high Young's modulus of about 1 TPa which can be compared with diamond (1.2 TPa) and demonstrate the strength 10-100 times higher than the constructional steel. In addition the polymer nano-composites possess the electrical conductivity of 105-107 cm/m and they can change the dielectric polymer to the conductive composite.

Intelligent polymer composite materials are most often used as the shells of power and special purpose structures. The intelligent shell represents the whole of electronic devices that carrying out the reception, processing and transmitting the information. They are placed directly in the casing itself which is made of NMIPCM.

Table 1

Challenging fields of NMIPCM application

Industry segment	Segment's branches	Possibility of application
National security and defense	Military industrial establishment	– control of stress-strain state and the integrity of military mobile units in real time; – getting more detailed information on stress-strain state in the destruction of armor during the test
	Personal protection	– increasing the strength of personal protective equipment, reducing their weight; – online monitoring of damage to protective equipment
	Military-tactical facility	– improved the performances and the environmental protection; – control of the integrity and serviceability status of the communication links
	Government call	– protection against unauthorized reading of information from communication links by means of control of stress-strain state of links with the range
Public health service	Prosthesis	– improving the properties of artificial implants (heart valves, nearthrosis); – getting the information about stress-strain state of implants in order to timely respond to their wear; – changing the shape of extremity prosthesis with the help of intelligent actuators
Aerospace segment	Space industry	Getting the information about the state of the most critical nodes (aerodynamic shrouds, stabilizing fins) in real time; – more detailed information on stress-strain state during the test
	Aircraft industry	– control of the operational performances of parts and nodes of the aircraft during the flight; – acceleration of inter-flight servicing of aircrafts due to online monitoring of stress-strain state nodes
Mechanical engineering industry	Automotive industry	Control of the critical components for the implementation of advance maintenance; – comprehensive information about stress-strain state during the safety tests
	Shipping industry	– control of the integrity of the ship's bottom during the navigation; – control of stress-strain state of the ship hull under the action of external forces and acts of nature

Since the early 1980 within the framework of the "Forcast-1" project (USA) hundreds of advanced developments have been considered and about 70 of which were selected in 1985 for further improvement under the "Forcast-2" project. The shells with NMIPCM are being developed for spacecrafts in the Astronautics Laboratory (Edwards, California Air Force Base), in Langley Research Center (NASA) and in Wright Brothers Research Center (Wright-Patterson, Ohio Air Force Base. The following companies as Hughes Aerocraft, Rockwell International, Westinhaus, Lockheed, Boeing, McDonnel Douglas are involved in this process.

The development of NMIPCM, which is capable of self-diagnosis and adaptation, has allowed moving to the production of aircraft of 5th generation with the high level of operational characteristics. As an example, aircraft "Raphael" (front part of the fuselage and most of the wing structure are made of NMIPCM, manufactured by Dassault-Berg, France) is shown in Fig. 1, aircraft JAS-39 (covering and wing segments with longerons, manufactured by Saad-Scania, SAAB, Sweden); F-35 Joint Strike Fighter (USA), F / A-22 Raptor (USA) manufactured by Lockheed Martin and project 1.44 (MIG, Russia); transitional up to the 5th generation SU-30 MKI (analogue F-18), SU-34, SU-27 SKM, SU-30 MK, SU-35, MIG 29 SMT. These aircraft replace the aircraft of 4th generation such as F-15, F-16 (US), MiG-29 and Su-27 (Russia).

NMIPCM is used to further developing the aircrafts. Improving the aerodynamic characteristics of aircraft is associated with the use of aeroelastic wings (the Active Aeroelastic Wing project).

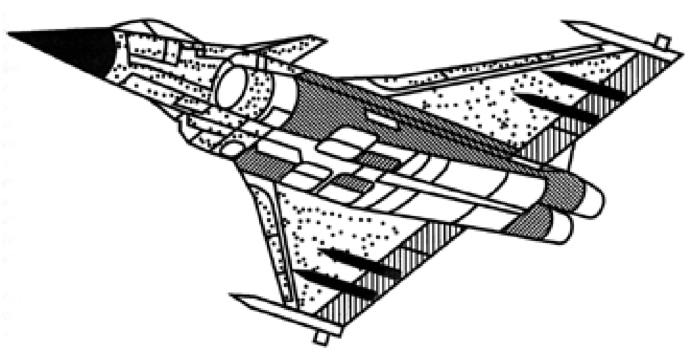

Figure 1. Aircraft of the 5th generation «Raphael» (marked designs made of NMIPCM)

It should be noted that the issue of obtaining the data from the intelligent sensors inserted into the polymer composite materials is multidisciplinary. On the one hand, the matter concerns the technology and equipment for inserting the sensors into polymer composites, interpreting the data on the stress-strain state and other properties obtained from sensors and it is associated with the polymer engineering and chemical mechanical engineering industry. On the other hand, the matter of receiving the signals coming from the cover thickness of the intelligent sensors and their further processing associated with the non-destructive testing. At the same time, the creation of the intelligent sensors relates to microelectronics.

3. Analysis of publications

The intensive scientific research is being conducted in the world in the fields of creating the technologies and equipment for the production of NMIPCM, in particular on the basis of experimental and numerical techniques and modeling of these processes. Among them there are scientists from the USA such as Mr. Welles, Mr. Tisdale, Mr. Spinks, Mr. Kane-McGuire, Mr. Smila; Mr. Carpi from Italy, Russians are Mr. Mikhailin Y.A., Mr. Sokolov I.I., Mr. Kogan D.I., Mr. Popov Y.A., Mr. Kablov Y.N., Belarusian Mr.S.M. Pesetsky and others.

Among the achievements of scientists the publications [3-6] can be highlighted. The scientific work [3] considers the creation of intelligent polymer systems based on electroactive sensors that allow controlling the disturbance on the product, allow monitoring the parts and assemblies in real time. The possibility of using the intelligent polymer in the medicine is considered in scientific works [4; 5], in particular for such highly responsible applications as prosthesis of joints, artificial cardiac valves and etc.

Ukrainian scientists, in particular Mr. Buketov A.V., are engaged in the study of the physical properties of epoxy nanocompositions based on the carbon tubes [7] as well as the effect of temperature on these properties.

The peculiar properties of the development of innovative technologies for manufacturing NMIPCM within the framework of the state program of the Republic of Belarus “Development of innovative technologies and techniques for the production of competitive composite materials, matrices and reinforcing elements for 2016-2020” (the State Client of the program is corporate group “Belneftekhim”) are considered in the scientific work [8].

Russian scientists are also actively engaged in the development of this field [9-12]. Also the State Institute of Aviation Materials (VIAM, Moscow) has been deeply involved in development under the leadership of academician Kablov E.M. A research technology has been developed for the formation of NMIPCM, in particular, by inserting the sensor elements into the structural material based on the fiber Bragg grating which allows online monitoring of the stress-strain state of structures in service.

The prototypes of innovative NMIPCM and technology have been developed by the specialists of FSUE "VIAM" with state support which is used for the manufacture of helicopter longerons which should work in the conditions of variable power loads, high humidity and with significant temperature differences.

The analysis of existing works of scientists also shows that despite, for example, the variety of existing components with the shape memory, the modern fiber-optic and piezoelectric sensors and technologies, at present time there are no match-all technologies and equipment for the manufacture of NMIPCM and their processing into important parts. Therefore the development of effective facilities for manufacture of NMIPCM and predicting their stress-strain state is particularly relevant for the home science and industry and it can put these developments in line with the foreign prototypes.

4. Analysis of the global market of NMIPCM

The nanotechnology market is experiencing its rapid development as evidenced by the growth of investment in the industry as well as the number of scientific research, patents and publications on this issue. Every year there is increase in the number of companies representing the nanotechnology as well as the volume of commercially sold products manufactured with the use of nanotechnology. Today the achievements of nanotechnology are actively implemented in almost all sectors of the economy.

The rapid development of scientific nano-research is reflected in a huge quantity of publications (about 800 thousand of articles are published annually) as well as the increase in the number of patents for inventions and China is considered as the leader.

Nanotechnology-derived products account for about 0.01% of global GDP and it is expected to grow to 0.5% by 2022 [13]. The main efforts for the development of the nanotechnology market are the support provided by the state.

Based on the analysis of the global nanotechnology market in its development two main trends can be emphasized:

– Increase in the number of researches and publications in the field of nanotechnology and the increase in the number of nanotechnology patents;

– Investment growth in branch, strengthening the competitive activity for the leadership between countries.

It should be noted that at the moment the flows of public investment in nanotechnology have slowed down somewhat. At the same time the state, following the results of 2018 and preliminary estimates of 2019 regained the role of the main investor in the nanotechnology sector by reducing the share of corporate financing.

Today the direction of NMIPCM sector is determined by all leading experts as the most promising innovation direction in all key industrial sectors of the world economy. The attractiveness of the market determines the active entry of new participants. Thus more than 16,000 nanotechnology companies have been created in recent years and their number doubles every 1.5-2 years. The practice shows that the growth rate of companies in Western markets is higher than the dynamics of the market as a whole by average of 30-40%.

According to the inquiry of business representatives in the USA, 52% of company executives believe that the prospects for the development of their business will be linked to nanotechnology the next 5 years [14]. There are already about 1,000 "road maps" (package plans that need to be implemented to achieve a particular goal) associated with nanotechnology in the USA. Almost the same rates have been found in Europe [15].

It is worthwhile to say that in the context of globalization of research in the field of nanotechnology there are many examples of the inter-regional and transnational funding.

Among the most spectacular examples the following can be highlighted:

– German chemical giant BASF announced the agreement with the Singaporean company NanoMaterials Technology on joint research regarding the properties of NMIPCM;

– Dow Corning USA has established the strategic partnership with the German Nanogate company which is nanoparticle developer;

– General Electric has installed the equipment for nano-research in China and India;

– materials science giant Rohm & Hass opened a technical center in Taiwan;

– Irish pharmaceuticals developer Elan collaborates with US companies Merck and Abbott.

The rapid development of scientific research in the field of nanoindustry is reflected in a huge flow of publications, namely: about 800,000 of them are published annually and the increase in the number of patents for inventions. By the number of publications in a given country one can estimate the development of the sector as a whole. The leaders in the number of publications are China, the USA and EU.

China takes the lead in terms of the total number of patents in the field of nanotechnology – Chinese companies, universities and individuals account for about 30% of all patents granted in the world. According to the official statistics the number of nano-inventions exceeds 3 thousand ones [16].

The distribution of patents in the field of nanotechnology by country [1] is as follows (Figure 1).

The distribution of patents obtained in the world among the known technologies is shown in Figure 3.

Among the major companies that invest the most in the nanotechnology research are IBM, Motorola, HP, Lucent, Hitachi USA, Corning, DOW.

6,440 US nanopatents out of the 6,770 were registered to institutional owners and three largest of which are the University of California, IBM,

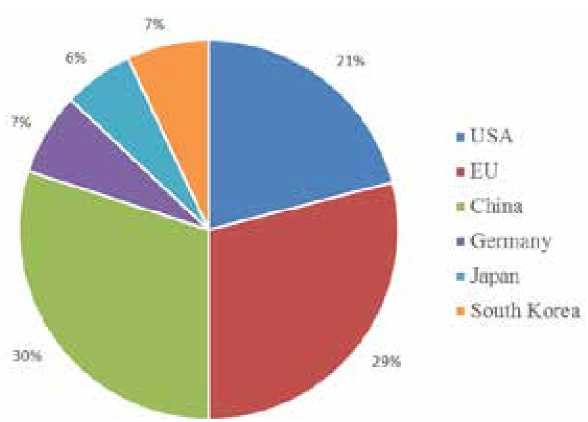

Figure 2. Distribution of patents in the field of nanotechnology by countries

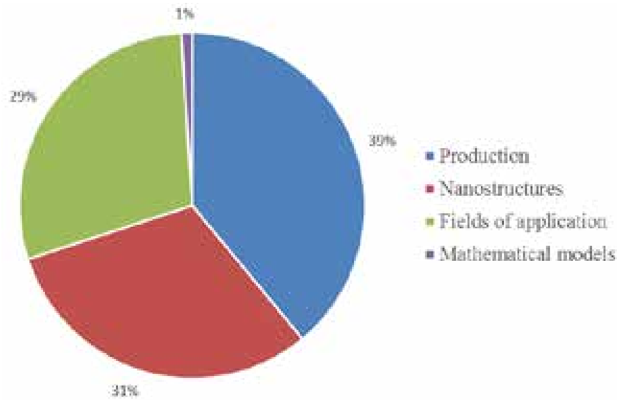

Figure 3. The distribution of patents in the field of nanotechnology divided by technologies

Eastman Kodak. There are also 7 more owners of nanopatents (each has more than 1% of all American nanopatents) – General Electric, MIT, Rice University, Hewlett Packard, Intel, 3M and DuPont.

It is noteworthy that 3 out of 10 are the universities which indicate a high level of interaction between the scientific educational institutions and the companies.

The patent activity of US nanotechnology companies is mainly concentrated in the field of semi-finished and final nanoproducts with the special concentration observed in the field of semi-finished products [17].

The following classification is widely used in the world for the application of nanomaterials in industry:

– nanoelectronics;
– nanoengineering;
– functional nanomaterials and high-purity substances;
– functional nanomaterials for space engineering;
– nanobiotechnology;
– constructive nanomaterials;
– composite nanomaterials;
– nanotechnology for security systems;
– functional nanomaterials for energy.

5. Analysis of the Ukrainian market of NMIPCM

At present the share of Ukraine in the global technology sector is about 0.3% but on the nanotechnology market is 0.04%. Ukraine paid its attention to nano-development for 7-10 years later than other countries.

As a result Ukraine lags far behind the world nanotechnology leaders at the present stage namely: China, the United States and the EU, as in terms of the development of research scientific works as the commercialization of inventions. This is evidenced by the number of international nanotechnology patents – there were only about 50 in 2018 (the proportion of Ukrainian inventions is less than 0.2%).

The Ukrainian nanotechnology market is in its infancy and the commercial applications of nanotechnology in industry are almost not available. This is evidenced by the fact that the number of enterprises that have already begun the stage of commercialization of their inventions is less than 20% of the total number of participants in the sector.

If we consider the Ukrainian market in equivalent to the global segment (with the division of nanomaterials, nanoinstruments and nanodevices into the market) then the most developed is the market of nanoinstruments. According to Research Techart estimates the volume of the Ukrainian market of analytical equipment for the research of nanostructures is about 0.3-0.5 billion UAH per annum. Meanwhile it is the devices market that entails one of the most important barriers to market development. The vulnerability of the Ukrainian nanoindustry is the lack of the developed competitive production of the scientific instrument-making industry. As a result the Ukrainian companies are faced with the need to purchase expensive imported equipment.

For the development of the Ukrainian market of NMIPCM it is necessary to solve the following matters:

1. Develop the technologies for modifying the polymer matrix of CNT with the required level of homogenization of the mixture.

2. Develop technologies for introducing the intelligent sensors into the polymeric material in order to obtain NMIPCM with given level of the technological and physical – mechanical properties.

3. Determine the minimum required number of intelligent sensors to ensure the possibility of obtaining the sufficient level of information about the stress-strain state of the polymer composition and products made of it.

4. Develop the methods for modeling the three-dimensional movement of complex rheological media in the active channels of the shaped form.

5. Develop the engineering recommendations for improving the designs of mixing-forming devices for entering the required number of sensors and product forming out of NMIPCM.

6. Preparation for the implementation of the developed calculation procedure and the equipment designs into the production to manufacture the competitive products based on NMIPCM.

It can be considered that the Ukrainian market has the potential to increase its share in the global nano-market. This is evidenced by the presence of advanced nano-developments of Ukrainian scientists which are the competitive in the global market.

At present there are technologies and equipment for entering an intelligent sensors into the polymeric material during its production using the extrusion, die-casting and pressing processes [18-22]. When designing the technological processes of production of NMIPCM it should be noted to take into account the wall effects which have the significant impact on the process in connection with the location of the intelligent sensors mainly in the wall layers of the product [23-27].

However, despite the assurances of experts the nanotechnological breakthrough in Ukraine will be possible only when prefix nano will no longer be just a buzzword of the entrepreneur's lexicon but it will become the real indicator of innovative activity and investment attractiveness.

6. Forecasts of the NMIPCM market development

In the future by 2020-2022 the nanomaterials (carbon nanotubes, nanowires, nanoporous materials, nanoparticles, nanostructured metals, quantum dots, nanocomposite and thin films) and the production of NMIPCM will be in the greatest demand [28].

According to the forecast of BCC Research [29] the global market of end user of nanomaterials will have the following structure until 2020:

– nanoelectronics – 42%;
– environmental protection – 20%;
– energy – 11%;
– consumer goods production – 10%;
– biomedicine – 6%;
– other industries – 11%.

The volume of primary nanoproducts sales in the world market in 2018 was $26.7 billion including the nanomaterials and their applications in industrial sectors. The main volume of the market is formed by the sale of nanomaterials ($11.2 billion) among the sectors are "Processing industries" ($4.4 billion), "Electric-power industry" ($4.2 billion), "Medicine and Biotechnology" ($2.9 billion .), as well as «Special equipment» ($3.3 billion). Taking into account the inter-temporal changes the rating of sectors in terms of sales volumes in the med-term will remain. However the largest growth is expected in the electronics industry.

The cost of sold consumer goods and nanoproducts and / or nanotechnologies is almost 35 times higher than the sales of primary nanoproducts and amounts to $920 billion. This gap is explained by the established practice of full cost considerations of the entire consumer product when determining the value of nanoproducts. As a result the total actual capacity of the global market for nanoproducts in 2018 (taking into account the full cost of consumer products) reached $947 billion [29].

The main part of consumer nanoproducts sold is represented in the aerospace industry, the military industrial establishment, the automobiles and medicine.

The main fields of consumption by 2022 from the point of view of foreign experts will be as follows: the production of nanomaterials, nanoelectronics, pharmaceuticals and biomedicine, chemical industry, environmental protection and transport.

The most advanced sectors and the directions of scientific research works in the field of nanotechnology are as follows:

– Military industrial establishment (critical parts of mobile equipment);

– electronics and IT (radar systems, target sight systems, lasers, transmitting system, processing and data storage systems);

– electric-power industry (improving the efficiency of existing equipment, fuel elements, alternative energy)

– medicine and biotechnology (pharmaceutical products delivery);

– processing industry (increasing the working life and accuracy of machinery and equipment, reducing the operating costs, new operational performances and materials and etc.).

The structure of global investments in nanotechnology (46% – the public sector, 48% – the corporate sector, 6% – the venture capital) established by 2018 according to most experts, will be changed due to the increase in the share of corporate financing and stabilization / decrease in the share of venture capital. In terms of cumulative government funding in 2018 Japan ranked first ($4.5 billion), USA took the second position ($4.0 billion), EU – the third one ($3.5 billion) and People's Republic of China ranked the fourth one ($2.3 billion) [30].

According to US NSF estimates [31] on a global scope by 2022, the field of nanotechnology will require 2 million workers and 5 million auxiliary (servicing) work positions.

According to the forecasted model of the development of the global nanotechnology market for the period up to 2022 the nanotechnologies will become commonplace in almost all industries and their share will reach 15% of global production. The most widely they will be applied in the military, medical and biotechnological industries [32].

7. Conclusions

Based on the consideration of the global market of NMIPCM the following indicators can be highlighted which characterize its development at present as follows:

1. The shared problem for the entire market of NMIPCM is the high cost of production and the low production volumes.

2. The most developed market for NMIPCM is in regions characterized by the positive inter-temporal changes of the entire nanotechnology sector in the USA, Europe and China.

3. Demand for NMIPCM is formed mainly by the military and medicine sectors.

4. The global market has a great interest in creating the technologies and formulas of new NMIPCM and expanding the scope of their application.

5. The Ukrainian market of NMIPCM has been falling 7-10 years behind the world leaders in this field.

References:

1. Executive Office of the President President's Council of Advisors on Science and Technology (2018). Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative, October 2018, 88 p.

2. International Organization for Standardization (2008) ISO/TS 27687:2008 Nanotechnologies – Terminology and definitions for nano-objects – Nanoparticle, nanofibre and nanoplate, Geneva.

3. Wallace G. G., Teasdale P. R., Spinks G. M., Kane-Maguire L. A. (2013). Conductive Electroactive Polymers: Intelligent Polymer Systems, Third Edition. Northwest: CRC Press, 263 p.

4. Carpi F., Smela E. (2011). Biomedical Applications of Electroactive Polymer Actuators. Chichester: Wiley, 463 p.

5. Hoffman A. S. (2011). "Intelligent" Polymers in Medicine and Biotechnology. *Macromolecular Symposia*, Vol. 98, pp. 645-664.

6. Honeychurch K. C. (2014). Nanosensors for Chemical and Biological Applications, 1st Edition. Birmingham: Woodhead Publishing, 372 p.

7. Buketov A., Maruschak P., Sapronov O., Brailo M., Leshchenko O., Bencheikh L., Menou A. (2016). Investigation of thermophysical properties of epoxy nanocomposites. *Molecular Crystals and Liquid Crystals*, Vol. 628, pp. 167-179.

8. Pesetskiy S. N. (2013). Polimernye kompozity tekhnicheskogo naznacheniya [Polymer composites for technical purposes]. *Nauka i innovatsii* [Science and Innovation], no. 9(127), pp. 7-10.

9. Mikhaylin Yu. A. (2009). Spetsial'nye polimernye kompozitsionnye materialy [Special polymer composite materials]. St. Petersburg: Scientific background and technology, 660 p.

10. Popov Yu. O., Kolokol'tseva T. V., Khrul'kov A. V. (2014). Novoe pokolenie materialov i tekhnologiy dlya izgotovleniya lonzheronov lopastey vertoleta [A new generation of materials and technologies for the manufacture of helicopter blade spars]. *Aviatsionnye materialy i tekhnologii* [Aviation materials and technologies], no. 2, pp. 5-9.

11. Timoshkov P. N., Kogan D. I. (2013). Sovremennye tekhnologii proizvodstva polimernykh kompozitsionnykh materialov novogo pokoleniya [Modern technologies for the production of polymer composite materials of a new generation]. Trudy VIAM [Proceedings of VIAM], no. 4.

12. Kablov E. N. (2012). Strategicheskie napravleniya razvitiya materialov i tekhnologiy ikh pererabotki na period do 2030 goda [Strategic directions for the development of materials and technologies for their processing for the period up to 2030]. *Aviatsionnye materialy i tekhnologii* [Aviation materials and technologies], no. 2, pp. 7-17.

13. Report of BCC Research (2017). Nanomaterials. Global Nanomaterials Markets, May 2017, 250 p.

14. Business Communications Company. Brauer S. Nanotubes: Directions and Technologies. GB-245R. Norwalk (2017). Business Communications Company, 249 p.

15. Resolution P6_TA(2017)0328 of the European Parliament on regulatory aspects of nanomaterials, 2017.

16. Asian Technology Information Program (2017). *Nanotechnology in Asia.* Tokyo: ATIP, 19 p.

17. Fuji-Keizai. Molecular Modeling for Nanotechnology: Technologies, Applications and Market Outlook. New York: Fuji-Keizai U.S.A, 127 p.

18. Ivitskyi I. I. (2018). Extrusion of Intellectual Polymer Materials. *Web of Scholar*, no. 5(23), vol 1, pp. 15-8.

19. Sivetskyi V. I., Sokolskyi O. L., Ivitskyi I. I. [and other] (2016). Metody ta prystroi dlia vyhotovlennia vyrobiv z intelektualnykh polimernykh kompozytsiinykh materialiv [Methods and devices for making products from intelligent polymer

composite materials]. *Visnyk NTU «KhPI». Mekhaniko-tekhnolohichni systemy ta kompleksy* [Bulletin of the NTU «KhPI». Mechanic-technological systems and complexes], no. 4(1176), pp. 95-101.

20. Ivitskiy, I.I., Sokolskiy, O.L., Kurilenko, V.M. (2016). Simulation of Intelligent Sensors Dipping Into the Melting Polymer Composite. *Technology Audit and Production Reserves*, vol. 5, no. 3(31), pp. 22-26.

21. Ivitskiy, I., Sivetskiy, V., Bazhenov, V., Ivitska, D. (2017). Modeling the Electrostatic Control Over Depth of the Introduction of Intelligent Sensors into a Polymer Composite Material. *Eastern-European Journal of Enterprise Technologies*, vol. 1, no. 5(85), pp. 4-9.

22. Bazhenov, V., Protasov, A., Ivitskiy, I., Ivitska, D. (2017). Simulation of Nanomodified Polymers Testing by the Electric Capacitive Method. *Eastern-European Journal of Enterprise Technologies*, vol. 4, no. 5(88), pp. 4-9.

23. Sokolskyi O. L., Ivitskyi I. I. (2014). Method of Accounting Wall Slip Polymer in Modeling Channel Processing Equipment. *Modern Scientific Research and their Practical application*, no. 10, pp. 136-140.

24. Sokolskyi O. L., Ivitskyi I. I., Sivetskyi V. I., Mikulonok I. O. (2014). Vyznachennia viazkosti prystinnoho sharu u formuiuchykh kanalakh obladnannia dlia pererobky polimeriv [Determination of the viscosity of the wall layer in the forming channels of equipment for the processing of polymers]. *Naukovi visti NTUU «KPI»* [Scientific news of NTUU «KPI»], no. 2, pp. 66-69.

25. Ivitskyi I. I., Sokolskyi O. L., Sivetskyi V. I., Mikulonok I. O. (2013). Chyslove modeliuvannia vplyvu prystinnoho sharu na protses techii polimeru v pererobnomu obladnanni [Numerical simulation of the influence of the wall layer on the process of flow of polymer in the processing equipment]. *Khimichna promyslovist Ukrainy* [Chemical industry of Ukraine], no. 6, pp. 34-37.

26. Ivitskyi, I. I. (2014). Polymer wall slip modelling. *Technology Audit And Production Reserves*, no. 5/3(19), pp. 8-11.

27. Ivitskiy I. I., Sokolskiy A. L., Mikulionok I. O. (2017). Influence of a Lubricant on the Flow Parameters of a Molten Polymeric Material in Channels of Forming Devices. *Chemical and Petroleum Engineering*, no. 53, issue 1-2, pp. 84-88.

28. Bins&Associates (2017). Nanocomposites Market Opportunities. Sheboygan (US): Bins&Associates, 640 p.

29. Nanotechnology (2018). San Jose (US): Global Industry Analysts, 597 p.

30. Commission Recommendation of 18 October 2018 on the definition of nanomaterial (2018). 2018/696/EU.

31. Report of United States National Science Foundation (2017). National Nanotechnology Initiative. Washington, D.C, 38 p.

32. Eurotechnology Japan. Fasol G. (2017). Bio-Nanotechnology in Japan: Public Initiatives, Venture Capital, New Initiatives, and Impact on Foreign Corporations. Tokyo: Eurotechnology Japan, 357 p.