Chapter 5

Nanotechnologies as the Way to Mastering the Microworld

1. Definition and the History of the Field

Definition and scale. The humankind has been using nanomaterials for a long time whereas the ideas of nanotechnologies have appeared quite recently. Now with the current knowledge about nanoparticles one can explain the peculiar properties of the well-known materials created in ancient times such as various enamels, painting materials, damask steel, *etc*.

Nanotechnology is a widely used concept which can be conventionally defined as *an interdisciplinary field of applied science and technology which develops practical methods and research*, *analysis and synthesis*, *and also methods of production of nanomaterials by a controlled manipulation of separate atoms and molecules*. The broad range of topics covered by nanotechnologies makes it problematic not only to define them, but also to classify nanoproducts (to specify the latter a special group within European Commission was created).

Now the Technical Committee ISO/TC 229 defines the nanotechnologies as follows (ISO 2005):

– knowledge and control of processes, as a rule, on the nanometer scale, including the scale of less than 100 nm in one or more measurements;

– use of properties of the objects and materials on the nanometer scale which differ from the properties of free atoms or molecules, for the creation of more perfect materials, devices, and systems realizing these properties.

Thus, the main point in nanotechnologies is control of matter on a scale smaller than 1 micrometer, normally between 1–100 nanometers (to 100 nanometers in one measurement; one nanometer is equal to one milliard share of the meter, or 10^{-9} m).

Why did nanoparticles become so popular? At this level the fundamental property of matter clearly shows up, that is realization of antipodal properties in its various systems. For example, at the macrolevel gold is a conductor, but at the nanolevel it is an insulator. The particles of some substances sizing from 1 to 100 nanometers show very good catalytical and adsorptive properties, while other materials show wonderful optical properties. At the nanolevel the relation between the surface and volume changes, and thus, the properties of matter change. In nature there exist nanosystems capable to get organized in special structures, gaining new properties, for example, the biopolymers (proteins, nucleic acids).

The peculiarity of nanoscience consists in the fact that it deals with atoms − compound particles of matter (a nanometer equals to a conditional construction of ten atoms of hydrogen built in a row). Now scientists already can operate with separate atoms and merge them in blocks. In other words, in prospect, it will be unnecessary to saw a tree to receive a toothpick, theoretically, it will be possible to force atoms to 'construct' it. Such an approach opens fantastic opportunities for creation of new materials with desirable properties. The prospects of this field were announced by the Nobel laureate Richard Feynman in the report 'There's Plenty of Room at the Bottom', presented in 1959 at the California Institute of Technology at the annual meeting of the American Physical Society. The scientist assumed that it would become possible to mechanically move single atoms by means of a manipulator; at least, this process will not contradict the known physical laws. Feynman offered a way of atom-by-atom assembly of objects that would allow reducing expenses and saving energy in production. This direction was actively supported by scientific community and the era of discovery of nanocomposite materials began. At present, various ingenious means and forces are applied as such nuclear manipulators, but the solution to the problem has not been found yet.

2. Nanotechnologies as an Outcome of the Cybernetic Revolution. The Origin of the Discipline and Field of Research

As it has been already mentioned, the first practical steps in nanotechnologies, as well as the ideological interpretation of the field, were made in the 1950s (and the term, according to some scholars, was introduced in 1974 by the Japanese physicist Norio Taniguchi). In other words, nanotechnologies appeared to be the result of the Cybernetic Revolution. However, for quite a long time they remained in the background of other important results. Practical interest in nanotechnologies rapidly grew at the end of the initial phase of the Cybernetic Revolution, in the 1980s, with the publication of Eric Drexler's books *Engines of Creation: The Coming Era of Nanotechnology and Nano-Systems: Molecular Machinery, and Computation* (1987; see also Drexler 1992). However, the term became widespread when caught-up by mass media. With the beginning of 'the nanotechnological race', the word 'nano' frequently appears on television and in print. It meant that nanotechnologies started to be considered as a strategic branch of the future hegemony (together with others: biotechnologies, green power industry, *etc.*). Its ultimate task is to win the market of industrial production of new, important and highly sought technologies. The country which will succeed it can ensure its own economic growth and development for many years.

The race of nanotechnologies began at the US suggestion which launched the competition. During President Clinton's governance there started the development of the first program of the US National Science Foundation for studying the problems of nanotechnology. Explaining interest in the development of nanotechnologies, Clinton, in particular, declared, 'I earmark 500 million dollars in the current fiscal year (2001. – *L.G., A.G.*) for the state nanotechnology initiative, which will enable us to create new materials in the future (surpassing in characteristics the ones we have today thousands of times), to download all data in the Congress Library on a tiny device, to diagnose cancer in a few affected cells and to achieve other amazing results. The initiative being offered is for at least twenty years and promises to lead to important practical results' (see also Lane and Kalil 2007).

Almost at the same time at the request of the government a similar program was launched in Japan. A series of projects directed at development of nanodevices was planned, and the Angstrom Technology Project with financing of 185 million dollars became the most significant among them. For ten years 80 firms participated in its realization. The Western European countries also joined the race and conduct researches in nanotechnologies within appropriate national programs. In Germany, nanotechnologic researches are generally supported by the Ministry for Education, Science, Research, and Technology. In Great Britain the management of this direction is realized by The Engineering and Physical Sciences Research Council, and also by the National Physical Laboratory. The first specialized journals *Nanotechnology* and *Nanobiology* appeared. In France the developmental strategy of nanotechnologies is defined by the National Center for Scientific Researches. In Russia the Russian Corporation of Nanotechnologies or Rusnano was founded; in 2014 its nanoproduction amounted to US$ 1 billion. There appeared the club of nanotechnologists which has united scientists and industrialists from various branches. More and more attention nanotechnologies get in China, South Korea, many other states, including Russia whose starting positions are supposed to be rather good in this area (Dementiev 2008).

Now nanotechnology is one of the most intensively developing branches of economy.

3. The Development of Nanotechnologies in the Course of the Cybernetic Revolution

The characteristics and opportunities of nanotechnologies correlate with the concept of the Cybernetic Revolution, which is not surprising since they originated within this revolution and besides, will play more and more important role in the process of its development. The stages of development of nanotechnologies even better fit the periodization of the Cybernetic Revolution, than biotechnologies and medicine.

1. The initial phase of the Cybernetic Revolution (from the 1950s to the early 1990s) was the period of formation of the field. Conditionally speaking, concerning nanotechnologies this is the period starting from 1959 when Richard Feynman presented the idea about constructing new materials from nanoparticles till Bill Clinton's initiative in 2000. This period is characterized by quite numerous scientific discoveries, many of them, however, had no application at that time.

For example, in 1956 D. N. Garkunov and I. V. Kragelsky described the effect of wearlessness. They found the phenomenon of spontaneous formation of a thin copper membrane in pairs of friction between bronze and steel in aircraft parts. This membrane reduced deterioration and frictional force by ten times or more. The thickness of the membrane does not exceed 100 nanometers (the similar system functions in human joints). It exemplifies that the friction is not only a destructive process, but under certain conditions it can be self-regulating, thus opening new unknown properties. In 1968, Alfred Cho and John Arthur, the researchers from the Bell Company (USA), developed the theoretical bases of nanoprocessing of surfaces (see Rybalkina 2005: 21).

At that stage the development of nanotechnology in many respects was defined by the creation of devices of probe microscopy and devices of appropriate size. These devices are a sort of eyes and hands for the nanotechnologists. In particular, in 1981 the German physicists created a microscope which made it possible to see separate atoms, and in 1985 the American physicists created the technology allowing precise measuring particles of a nanometer diameter.

The modernization phase (the period of distribution of innovations) of the Cybernetic Revolution is the period of the formation of 'modern nanotechnology' (from the 1990s to the 2020/30s). Nanotechnologies became involved in industrial production, the nanotechnology race between countries started and many projects and whole institutes of nanotechnologies were created. The number of goods produced by means of nanotechnologies is rapidly increasing. The investments in researches increase, while nanomaterials penetrate into various spheres: engineering, medicine, transport, aerospace, and electronics, *etc*. According to the data from BCC Research (2012), the sales volume of nanotechnology products in 2009 amounted 11.67 billion dollars.

Euphoria from the opportunities provided by nanotechnologies. The analytics associate the first stage of the development of nanotechnologies (between 2000 and 2005) with the so-called 'passive nanostructures' (incremental nanotechnologies), but generally it involved production and use of nanodisperse powders. They were added in order to modify the properties of basic construction materials: metals and alloys, polymers, ceramics, and also are used in cosmetics, pharmaceuticals, *etc*. Now this is a rather primitive generation of nanomaterials already widely used in production, and they can be found in many goods. However, only few nanoprojects are applied in high-tech branches of industry.

The wide prospects provided by nanotechnologies, stirred up by certain interests and mass media, caused euphoria of forecasts the majority of which have proven wrong or will hardly come true.[1] These forecasts seem quite natural. People want the process of creation of innovations

[1] For example, according to the forecasts of the British Trade Department, the demand for nanotechnologies will annually make more than one trillion dollars by 2015, and the number of experts engaged in this branch would increase to two million people.

and their implementation to go faster; at the same time they do not see obstacles and challenges and do not take into account the economic crises which may change plans. Thus, the volume of nanoproduction is continuously growing despite the fact that the growth rates are not so fast as it has been predicted earlier.

A number of analysts suppose that after 2020 the era of 'radical nanosystems' in the form of nanorobots will start. At this stage nanobiotechnological and nanomedical systems will develop and significantly change human life, first of all, increasing life expectancy. However, the theory of production revolutions maintains that in spite of numerous innovations appearing at the modernization phase, they will hardly make a breakthrough while many will remain of low demand at all. At the same time the discoveries which will become the basis for the breakthrough are prepared while the breakthrough itself will happen later. In the field of nanotechnologies it will most likely happen between the 2030s and 2050s. Thus, the achievements of nanotechnologies which, according to a number of researchers, will come by the 2020s (but, of course, not all of them), will actually take place one or two decades later. Nevertheless, in the coming decades the achievements already tested today in different areas will be developed.

4. What Characteristics of the Cybernetic Revolution does the Development of Nanotechnologies Manifest?

The synthesis of new materials with desirable properties. One of the major challenges for nanotechnology is to make molecules group in a necessary pattern and self-organize in order to receive new stuff or devices. The supramolecular branch of chemistry deals with this problem and explores interactions that can organize molecules in a certain way, creating new substances and materials. There are different processes of self-assembling, for example, the electrochemical anodic oxidation (anodizing) of aluminum, in particular, the one that leads to the formation of porous anodic oxidic membranes. At present within the field of nanocomposite construction they develop different technologies to produce substances with various properties, for example protective, self-cleaning, antibacterial, *etc*.

The growing self-regulation within systems. Self-organization of nanoparticles and self-organizing processes. A close connection between nanotechnologies and growing self-regulation within systems is based on the opportunity to make use of the processes of self-organization of matter, forcing molecules and atoms to be ordered in a certain spatial and structural way. The creation of new materials with desirable properties is a direct way to make systems work according to the predetermined scenarios. No wonder that nanotechnologies produce striking examples of different self-regulating systems, for example, self-cleaning nanocoatings (*i.e.*, self-cleaning mechanisms to remove bacteria from vessels or self-cleaning nanopolish products for car glass). The nanopolishes modify surface in such a way that a drop of water slides on it, collecting all the dirt, whereas on a smooth surface, on the contrary, a water drop, while slipping, leaves dirt on the surface. It is called the 'lotus effect'. The idea is borrowed from nature: the leaves of lotus are covered with the smallest wax bulges and cavities, and thus, water flows down from them, completely washing away the dirt.

Miniaturization is the phenomenon characteristic of the current technological progress. We can see that most devices, gadgets, and professional tools become smaller in size and more convenient. Miniaturization transforming into microtization is most visible in nanotechnologies. Modern processors consist of more than a billion of transistors, but nanodevices will allow increasing this number by an order of magnitude. Now there is a race to reduce the manufacturing processes for semiconductors and chips to nanometers. Some companies have already changed to 45, 32, 28 nanometer process. The Intel Company uses 32-nm process for tablet computers and smartphones, and the Qualcomm Company uses 28-nm process for manufacturing chips. The Intel Company already starts mastering 14-nm process. In the last decade the process diminished in size approximately by three times (from 90 nanometers to 32 nanometers). In the near future they strive to achieve the size of 7 or even 5 nanometers. Whether it will be successful and possible to achieve the invention of a principally new generation of computers due to such a decrease in size is not clear yet.

Nanotechnologies, energy efficiency and economy. Many nanotechnologies aim at energy saving and invention of alternative energy sources. So, the trend of small-size process technology not only increases the operating speed of electronic devices and packing density on the chip, but also reduces their energy consumption. For example, 'smart glass' for rooms is capable to react to changing illumination and environmental temperature by corresponding change in transparency and heat conduction. There are many various projects of such saving. Thus, a wide use of electronic paper could prevent deforestation. Nanotechnology also can help to solve the problems of sewage treatment.[2]

Nanotechnologies are already actively applied in agriculture, in particular, in the production of fodders which allows a considerable cutting their consumption and providing the best accessibility. In crop farming the use of nanopowders with antibacterial components provides increasing resistance to poor weather conditions and increases productivity of many food crops, for example, potatoes, crops, vegetable and fruit and berry crops.

5. Forecasts

5.1. Nanotechnologies as a breakthrough component at the final phase of the Cybernetic Revolution (in the 2030s and 2070s)

One can trace all the characteristics of the Cybernetic Revolution in the future development of nanotechnologies: the vigorous development of bionanotechnology and nanomedicine, the invention of technologies of self-regulating systems (in which nanorobots independently or as a part of more complex technology will play an important role), the production of new materials, saving of materials and energy (*e.g.,* in house due to nanomaterial for window glass; by delivering a minimum portion of medicine directly to the damaged area or even to separate cells) miniaturization, targeted actions, *etc*.

Connection with medicine: large opportunities. Despite serious progress of nanotechnologies in electronics and other branches, the real nanotechnological revolution will most likely happen at first in medicine that will give an additional impulse to the development in other areas. As a result, the breakthrough in the final phase of the Cybernetic Revolution will be provided by deep integration of medicine with biotechnologies and nanotechnologies which will bring the emergence of various technologies of self-regulating systems. We have already mentioned some directions of integration of these branches in the previous

[2] The Chinese scientists created a system which can produce electricity by decomposition of organic substances, alongside removing organic compounds from waste water. Yanbiao Liu with colleagues developed a photocatalytic fuel cell on the basis of nanotubes which uses solar energy to destroy organic compounds in waste water and converts chemical energy into the electric one.

sections. In general the prospects of such integration are already evident. So, according to some forecasts, chimerical nanobiostructures (capable of transposing medical nanosensors, medicines and even reconstructing cells of an organism) will be created in a decade or so and in 15 years they will become everyday practice. Of course, their active use in diagnostics and developing means to acquire immunity will become an important direction in nanotechnologies. We already have examples of this process now. The Engelhardt Institute of Molecular Biology (part of the Russian Academy of Sciences) applied nanotechnologies to create a biochip allowing quick diagnosing of a number of dangerous diseases, including tuberculosis. The development of nanotechnologies to create materials imitating properties of, for example, bone tissue will be quite promising. Nanotechnologies are already implemented in such surgeries as nano neuro knitting for repair of severed optic tract, implantation of artificial limbs with high precision, cardiological surgery, *etc*.

One of the directions where huge efforts of nanotechnology are concentrated is the struggle with cancer. For example, the Institute of Cancer in the USA voted 150 million dollars for such researches.

One can suppose that cancer treatment will become possible as soon as there is found a means to better target a certain layer of cells in a necessary part of the organism. However, it is possible that cancer will be defeated without destroying cancer cells, but by means of the method to fight metastases. The work is conducted in various directions here. Perhaps, the organism will give a clue. For example, it is known that metastases do not appear in heart tissues: obviously, there are some defense mechanisms which should be discovered (Marx 2013).

There are some examples of new directions of the cancer control based on nanotechnologies. For example, the system of carcinoma treatment is being developed based on heating of nanoparticles of iron oxide which are put into the infected tissue and influenced with a magnetic field as a result of which particles heat up and destroy cells. At present, this method is passing clinical testing phases; however, the lifetime of the patients who underwent a cure considerably exceeded the time forecasted by doctors. A problem with this method is the exact injection of the iron oxide particles into the tumor cell.

At the Laboratory of Nanophotonics at Rice University in Houston, Professors Naomi Halas and Peter Nordlander invented a new class of nanoparticles with unique optical properties – nanoshells. With a diameter twenty times smaller than red blood cells (erythrocytes), they can freely move in the blood system. Special proteins, that is antibodies attacking cancer cells, are specifically attached to the surface of cartridges. Some hours later after their injection the organism is beamed with infrared light which nanoshells transform into the thermal energy. This energy destroys cancer cells, and the neighbouring healthy cells are almost not injured at that.

The important direction of research in the area of oncotherapy consists in automatic ‘smart’ hitting of the malignant cells by nanoparticles. The thing is that only one-millionth part of the revolutionary new substance Herceptin, used to treat a considerable number of patients with breast cancer, would target the diseased cell. To make the transportation of Herceptin more effective, a group of American scientists invented a special model of a capsule from porous silicon into which the medicine is injected and is directly delivered just to the damaged cell. Now this technology is being clinically tested. The American scholar Mark Davis discovered a special capsule which has a structure similar to sugar and therefore is not rejected and not excreted by the organism. A preparation is put into this capsule and can be stored in the organism for weeks. It is searching for a tumor moving within the blood-vascular system. Cancer cells are more acidic, than the usual, healthy cells, and, when finding such cells, the capsule opens and discharges the strong medicine. A patient with a pancreas terminal cancer, at the stage of metastasis was subjected to such cure and is still alive and even did not lose his hair after chemotherapy.

A future direction of medicine is the development of diagnostic methods that are also cost-cutting. We have already spoken about nanochips which can play an important role here. The nanorobots which will be able not only to perform medical functions, but also to control individual cellular nourishing and excrete waste products will be put into practice. Nanorobots can be used for the solution of a wide range of problems, including diagnostics and the treatment of diseases, fighting ageing, reconstruction of some parts of human body, production of various heavy-duty constructions (Mallouk and Sen 2009).

It is clear that some promising technologies which are forecasted today, will fail to become successful in the future. But there is no doubt that the use of nanomaterials, nanorobots suitable for research, and other nanotechnologies will create important backgrounds for the future era of self-regulating systems in medicine.

The connection with biotechnologies and agriculture. Other important directions of nanotechnology are research in the field of nanobiotechnologies. One can mention here the development of controlled protein synthesis technologies for receiving peptides with desirable immunogenic properties. Vector systems for the cloning of immunologically significant proteins of the causative agents of the diseases and vaccines of the new generation possessing a high activity and safety are created. Research is being conducted on creating nanoparticles for making genetically engineered proteins, the development of biochips and test systems for biological screening (Persidis 1998), immune monitoring and forecasting of dangerous and economically significant contagions of animals. Biochip technology is constantly improving and their manufacturing is cheapening (Rusmini *et al.* 2007).

It is expected that by means of nanotechnologies and use of robots the development and application of biotechnologies will significantly advance in the direction of creating self-regulating systems of farming, where agricultural operations will be for the most part performed in an autonomous mode. Many technologies will appear to promote this process. Thus, the implementation of membrane systems for cleaning, and also special biocidal coverings and silver-based materials will facilitate and increase the level of managing the farm livestock and providing them with high quality water. It is assumed that the use of nanotechnologies will allow changing technology of cultivation of lands due to the use of nanosensors, nanopesticides and a system for decentralized water purification. Nanotechnologies will make it possible to treat plants at the genetic level and allow creating high-yielding plant varieties especially resistant to unfavorable conditions (Balabanov 2010). Today there are some innovative ideas which can be further elaborated in the agriculture. In particular, there appeared microbial preparations based on associative, endophytic and symbiotic bacteria. These preparations are intended to produce and convey various enzymes and low-molecular biological active agents (nanoobjects) in plants. These can improve adaptation of plants to unfavorable environmental conditions: pollution by toxic metals, salinization, superacidity, *etc*. A fundamental approach to getting high quality seed material is essentially developed. This approach is as follows: biologically active and phytosanitary components which can increase the adaptation of seeds and plants to real negative environmental conditions are constructed in the form of multifunctional nanochips.

5.2. Various prospects of usage of nanotechnologies within the Cybernetic Revolution and at the mature stages of the scientific-cybernetic production principle

Nanotechnologies have considerable prospects. The components of nanoelectronics, photonics, neuroelectronic interfaces and nanoelectromechanical systems will be developed. Then on the basis of the achieved results we can expect advance in development of nanosystems capable to regulate self-assemblage, the creation of three-dimensional networks, nanorobots, *etc*. One can also speak about the use of molecular devices, nuclear design, *etc*. Especially alluring prospects are observed in the development of nanomechanics, nanomechanical engineering and nanorobotics.

Quite long ago there appeared an idea to store data using peculiar environmental phenomena (*e.g*., magnetic, electric, and optical), with advent of nanotechnologies it becomes possible to store information, for example, by means of replacement of silicon, the basic material in the production of semiconductor devices, or by carbon nanotubes. In this case a bit of information can be stored in the form of numerous atoms, for example, of 100 atoms. It would reduce the sizes of processors by an order of magnitude and essentially increase their operation speed. Now the number of transistors in the processor reached a billion and more. However, a few years ago the task was to create a processor with more than one trillion transistors by the 2010s (that would lead to radical increase of the ICT opportunities). Most likely, this is an unreal task to achieve even by the 2020s, before the beginning of the final phase of the Cybernetic Revolution. It is supposed that this level will be achieved later, as we are already in the process of developing this phase (this would also open new horizons for a full replacement of the information computer equipment due to a transition from using silicon to nanomaterials).

However, it is possible that the smallest computers will have an essentially new basis. According to Eric Drexler, it is nanomechanics, not nanoelectronics, can become such a base. He has developed mechanical constructions for the main components of the nanocomputer. Their main components can be pushed in and out cores interdependently locking the movements of each other (Balabanov 2010).

From special structures, such as fullerenes, nanotubes, nanocones and others, molecules can be gathered in the shape of various nanodetails – tooth wheels, rods, bearing details, rotors of molecular turbines, moving parts of manipulators, *etc*. The assembly of the finished parts into a mechanical design can be realized by using the assemblers (self-assemblers) with the biological macromolecules attached to the details capable of selective connection with each other. This idea was realized by Professor James Tour and his colleagues from Texas Rice University who in 2005 created a molecular mechanical design – the all-molecular four-wheel nanocar about 2 nanometers wide consuming light energy. It consisted of about 300 atoms and had a frame and axes. The development and creation of the nanocar took eight years. The scientists plan to create nanotransport devices, the nanotrucks, to transport molecules to conveyors in nanofactories (*Ibid*.).

Certainly, this is more like toys, than research for practical use. They remind us of the steam toys like the mechanisms created by the Greek mechanic Heronus Alexandrinus, who amazed the audience in the first century AD. They hardly had any similarity with a steam-engine. But unlike Heronus who even did not think of a practical use of steam, the current nanotechnologists are absorbed with practical application. Therefore, the creation of nanomechanical engineering is quite real, though a long-term perspective. It will most likely happen close to the end of the current century. The same refers to nanorobotics. At present, the expected designs of nanorobots and their use exist only in forecasts.

There is an opinion that in the 2030s some nanodevices will be implanted into human brain and will be able to perform the input and output of necessary signals from the brain cells and this can even make learning and getting education become unnecessary. But it causes great doubts. Even if such a cyborgization is realizable in principle, it will occur much later.

Anyway it is obvious that both nanomechanical engineering and nanorobotics will propel the development of self-regulating systems to a new level towards the formation of an industry that will design such systems (similarly, the use of cars promoted their industrial manufacturing – mechanical engineering).