Potential Space Applications of Nanomaterials

Lev S. Novikov and Ekaterina N. Voronina

Abstract This paper deals with physical fundamentals of nanomaterial structure and properties, their classification and the peculiarities of different classes, and the main potential applications of these materials in the next generation spacecraft. Some results of the experimental and mathematical simulation of the space environment influence on nanostructures are given.

Keywords Nanomaterials • Nanostructures • Nanocomposites • Spacecraft • Space environment • Durability

Introduction

Nanomaterials surpass traditional materials for space applications in many aspects due to their unique properties associated with nanoscale size of their constituents. This superiority in mechanical, thermal, electrical and optical properties will evidently inspire a wide range of applications in the next generation spacecraft intended for the long-term (~15–20 years) operation in near-Earth orbits and the automatic and manned interplanetary missions as well as in the construction of inhabited bases on the Moon.

Nanocomposites with nanoclays, nanotubes and various nanoparticles as fillers are one of the most promising materials for space applications. They may be used as light-weighted and strong structural materials as well as multi-functional and smart materials of general and specific applications, e.g., thermal stabilization, radiation shielding, electrostatic charge mitigation, protection from atomic oxygen influence and space debris impact, etc. Next-generation electronic components based on nanoelectronics, spintronics and photonics, as well as nanoelectromechanical systems, will provide great advantage over conventional microelectronics in performance, noise-immunity, energy consumption and heat emission.

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All these materials and components should be durable to most space environment factors and their effects. For the implementation of the nanomaterials and nanotechnologies in the spacecraft engineering it is necessary to develop next-generation ground-based facilities for studying the nanomaterials properties and behavior under the space conditions and to create physico-mathematical models describing properly the various space environment effects on the nanostructures.

This paper deals with the main potential applications of nanomaterials and nanotechnology in the next generation spacecraft for solving novel scientific and technological problems, and with methods of nanomaterials modeling and testing.

Nanomaterials and Nanostructures

The peculiar properties of nanomaterials are determined by the presence in their structure of nanoobjects—particles or grains, fibers, platelets, etc. with at least one linear dimension in nanoscale (size range from approximately 1–100 nm) [1, 2]. The lower boundary of this range approaches the size of atoms and molecules, but its upper one that separates nanoobjects from microobjects was set rather arbitrary. In general, it is not possible to associate unambiguously this upper boundary with any characteristic dimensional parameters that determine the material properties.

The strong influence of material nanostructure on its properties is caused by so called nanometer length scale effects which can be of classical and quantum nature. The nanoscale effects appear when the size of structural objects becomes comparable with a certain parameter of material which has a considerable influence on some physical-chemical processes in the matter and consequently on the material properties. A mean free path of charged particles, a diffusion length, etc. may be regarded as such parameters in the case of classical length scale effects, and for quantum ones its role is usually played by the de Broglie wavelength.

Another parameter of nanostructures called dimensionality, corresponds to the number of dimensions that lie within the nanometer range, and is used for analyzing the quantum confinement effects. According to this parameter, all objects may be divided into four groups [1, 3]:

3D-objects—bulk materials;
2D-objects—nanofilms, nanoplatlets;
1D-objects—nanofibers, nanotubes, nanorods, etc.;
0D-objects—nanoparticles, nanopores, nanocrystals, quantum dots, etc.

In a 3D-object electrons may move freely in all three dimensions. In a film whose width is comparable with the de Broglie wavelength (2D-object), electrons move without restrictions only in the film plane, but in the perpendicular direction they are in a deep potential well, that's why 2D-objects are usually called quantum wells. In 1D-objects, or quantum wires, two dimensions are comparable with the de Broglie wavelength. If the electron movement is limited in three directions, a

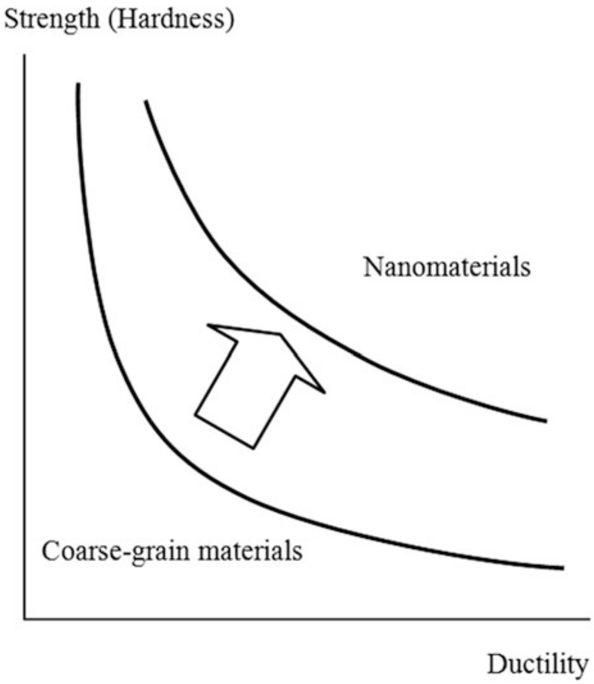

Fig. 1 Strength (hardness)/ductility ratios for bulk materials and nanomaterials

nanostructure becomes a 0D-object, or a quantum dot with discrete electronic states.

Due to nano-length scale effects, nano-structured materials acquire novel mechanical, thermal, electrical, magnetic and optical properties, which can surpass the properties of conventional bulk materials. Figure 1 demonstrates qualitatively that nanomaterials possess higher mechanical characteristics in comparison with conventional materials [4].

The creation of polymer nanocomposites with fillers of various shape and composition may play the pivotal role in spacecraft development and implementation of challenging space projects. Among possible fillers, the main attention is paid to carbon nanostructures: fullerenes, carbon nanotubes (CNT) and graphene that represent particular allotropic forms of carbon [5].

CNTs possess excellent mechanical characteristics. Because of low CNT density (1.3–1.4 g cm^{-3}), specific strength of the material, made of nanotubes, reaches record values. The electrical resistivity of individual single-walled CNTs has been measured under ballistic conductions to be as low as 10^{-6} Ω cm [6], CNT thermal conductivity is also very high: one of reported values is of ~3500 W m^{-1} K^{-1} [7].

Properties of graphene are unique in many respects. This material possesses very high strength and thermal conductivity which was measured to be (3–5) × 10^3 W m^{-1} K^{-1} [8]. Charge carrier mobility in perfect graphene reaches 10^5 cm V^{-1} s^{-1} at 300 K, and this value is much larger than in Si (~1.5 × 10^3 cm V^{-1} s^{-1}) [9]. Because of such excellent electrical properties, graphene nano-ribbons (strips of a graphene monolayer with widths of several nanometers) are of special interest. Currently many researchers consider graphene nano-ribbons as the most promising substitute for silicon as a semiconducting material for nanoelectronics.

It should be noted that recently much attention is paid to nanoobjects of the similar structure, but of different composition. For instance, the investigations of nanotubes and sheets of hexagonal boron nitride are developed very rapidly. Boron nitride nanotubes (BNNTs), structural analogues of CNTs, attract much attention due to their excellent mechanical properties, high thermal stability and high resistance to oxidation, but as opposed to carbon nanostructures, BNNTs are electrical insulators with a wide band gap of ~5 eV [10].

Nanomaterial's Durability, Modeling and Testing

To estimate the possibilities of nanomaterial's space applications, it is very important to obtain the data concerning their durability to the impact of different space environment factors. If the durability of most conventional materials to the space environmental factors is investigated thoroughly, for nanomaterials such research is in its beginning.

A spacecraft is exposed in space to a wide range of space environmental factors: fluxes of high energy electrons and ions, cold and hot plasma, solar electromagnetic radiation, micrometeoroids and space debris, etc. [11]. Existing experimental and theoretical data demonstrate that nanomaterials responses to various space environment effects can differ substantially from those of conventional bulk spacecraft materials [12, 13].

The most important factor which reduces the reliability and lifetime of spacecraft equipment is the damaging impact of space radiation. Nano-structured materials can demonstrate higher radiation tolerance than conventional materials [14, 15]. When an electron or ion with the energy, typical for space radiation environment, interacts with a nanostructure, the energy transferred from the particle to it is only a small part of the projectile energy [16]. Therefore, only a small number of structural defects or additional charge carriers appear in a nanoscale object with the irradiation. The conditions of defects and charge migration in nanomaterials and in bulk materials differ substantially, too. The high stability of CNTs against forming and accumulating structural defects due to ionizing radiation may be explained by their ability to "heal" defects. The number of radiation defects is reduced also because a significant part of carbon atoms displaced from hexagonal lattice can be sputtered from the CNT without additional collisions with other atoms.

In nano-structured materials, due to the large number of grain boundaries, a distinct radiation resistance mechanism may exist. The grain boundaries and interfaces can capture interstitials and then release them into the lattice to destroy any vacancy that forms in the vicinity of the boundary [14]. Some nanoscale objects

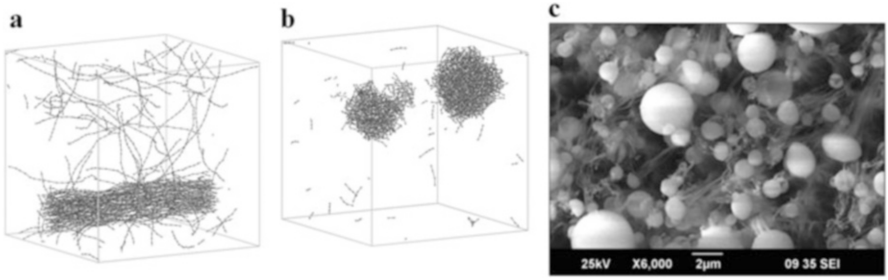

Fig. 2 (**a**, **b**) Examples of equilibrium structure of polymer composite with agglomerated nanotubes (**a**) and nanoparticles (**b**) obtained with DPD simulation. (**c**) SEM image of polymer nano-composite surface after AO exposure

including CNTs may play the role of grain boundaries as sinks for defects of all kinds. It should be noted that when a large number of defects is accumulating, the crystal structure of materials may be destroyed, so at high radiation doses the amorphization of nanostructures can be achieved [15, 16]. For polymer nanocomposites, the serious danger is the atomic oxygen that is the main component of Earth's atmosphere over the altitude range of 200–800 km and its interaction with the materials. Hyper-thermal (~5 eV) oxygen atoms can cause the erosion of polymer matrix and damage nano-fillers (e.g., carbon nanostructures) [12].

Therefore, detailed investigations of processes of space environment impact on nanostructures and nanomaterials via methods of both mathematical modeling and laboratory simulation are needed. For computer modeling it is necessary to apply and develop so called multi-scale simulation [17], and for experimental research the correct choice of regimes of ground-based tests for nanomaterials (types, energies, flux densities of radiation and emission applied, etc.) is of great importance.

Some results of computer simulation with dissipative particle dynamics method (DPD) of CNT and nanoparticles agglomerating into micro-sized objects within a polymer matrix are given in Fig. 2a–c shows such agglomerated objects observed in a polymer nano-composite after the atomic oxygen exposure [18]. It can be seen that these agglomerates protect underlying polymer chains and provide the decrease in mass loss of the composite material.

Potential Applications of Nanomaterials in Space

The necessity in broad applications of nanomaterials and nanotechnology in spacecraft design and construction in the near future is caused by the emerging changes in spacecraft design and usage.

All spacecraft may be considered as operating in some information systems because they either gather extensive information (e.g., on space environment conditions, the Earth's surface, etc.) or transfer a great amount of data. The new satellite system concept assumes the development of multi-satellite cluster systems,

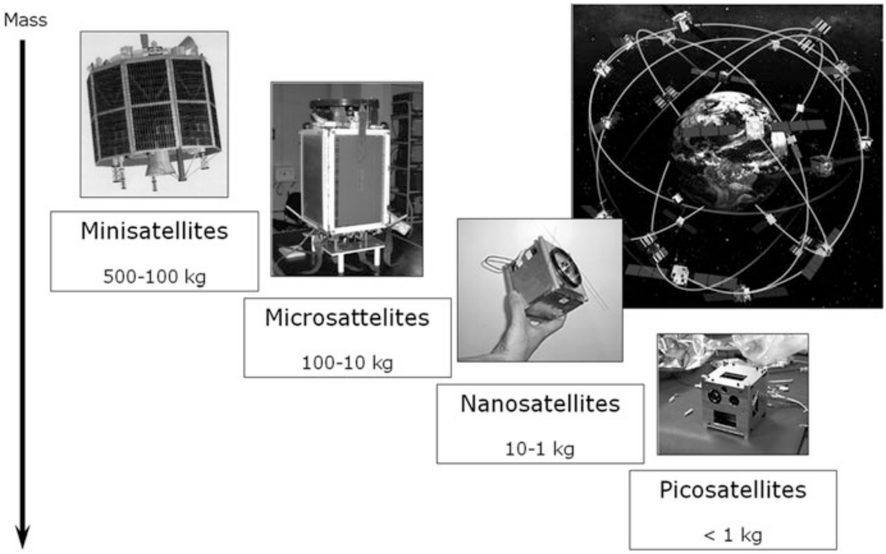

Fig. 3 Classification of small spacecraft

or satellite constellations [19], in which dozens of satellites on different orbits operate according to coordinated programs and share information not only with ground-based control centers but with each other.

Satellite constellation should include small-size lightweight satellites capable of executing most functions of conventional large and heavy-weight ones. The success of creation of such spacecraft is entirely determined by the level of applied technologies, the availability of new materials with required operating characteristics and the degree of miniaturization of electronic components used in spacecraft equipment. Therefore the realization and advance of this concept are in close connection with the progress in the field of nanotechnology. The classification of such spacecraft according to their mass is given on Fig. 3.

Along with creation of small satellites, nanomaterials and nanotechnologies will be widely applied in development of next-generation heavy satellites and manned spacecraft, in building so called ‘space elevator’, solar power space stations, as well as in implementation of the major space projects of the first half of twenty-first century: manned mission to Mars and inhabited bases on the Moon.

In recent years, in a number of countries, expert assessments were prepared in order to evaluate possibilities of nanomaterials and nanotechnology usage in spacecraft construction and operation and to outline the main directions of their applications. Some programs of the nanotechnology implementation into the space exploration, developed in the early 2000s [20, 21], provide the following main directions:

1. Multifunctional structural and functional materials, including smart materials;
2. Nanoelectronics components;

3. Materials and devices for power supply system of the spacecraft (energy storage, fuel cells, solar cells, etc.);
4. Spacecraft subsystems and payloads with nano-sensors, nanoelectromechanical systems, etc.;
5. Life support systems;
6. Futuristic projects which cannot be realized without the nanotechnologies.

According to NASA experts [22], nanotechnology can have a broad impact on space projects in aeronautics, planetary science, and space exploration owing to

Reduced vehicle mass.
Improved functionality and durability.
Enhanced power generation, storage and propulsion.
Improved astronaut health management.

In NASA Nanotechnology Roadmap [22], the great attention is paid to creation of light-weighted, ultra-strong, damage tolerant, multifunctional materials as well as smart-materials, including self repairing and self-diagnostic ones. Increasing levels of system design and integration is considered as a very important task to achieve enhanced efficiency of space technologies. The development of integrated complex systems for energy generation, storage and distribution, including highly efficient solar cells on quantum dots, ultra-capacitors, wires and cables network made of nanotubes, is of great significance. The very important research direction is the development of next-generation propulsion systems of different types. Nano-sensors of different kind and complexity (for temperature, pressure, humidity sensing, autonomous distributed sensors for chemical sensing, biosensors, etc.), spacecraft nanoelectronics, especially graphene based electronics, and various miniature instrumentation tools will play a crucial role in future space mission.

Polymer nanocomposites are considered in most cases as light-weighted multifunctional materials that can be used for solving different tasks. By varying the composition of matrixes and fillers one may impart distinctive properties to nanocomposites, so they may fit to a wide range of applications as structural and functional materials. In the short-term period light-weighted and strong nanocomposites will undoubtedly be used in spacecraft structural components due their advantages over conventional metals and ceramics. One of very important applications of nanocomposites is the development of multifunctional coatings to protect against hypervelocity impact and space radiation, to provide thermal shielding for the safe entry into atmosphere, to preserve spacecraft thermal regime during the flight, to impart required optical and electrical properties to spacecraft surface, etc. Polymer nanocomposites may be applied in radiation protection systems for interplanetary spacecraft and inhabited Lunar bases. To reduce the weight of protective radiation shields and the intensity of secondary radiation particles which are produced due to the interaction of space radiation particles with material atoms, it is effective to use the materials that consist of low-Z atoms. Thin conducting films made of nanocomposites and transparent network of CNT can be applied to provide equipotential conditions on the spacecraft surface under space plasma charging conditions and to remove electrical charges from it.

Conclusions

1. In the near future nanomaterials and nanotechnologies will play a very important role in development and construction of next-generation spacecraft and in implementation of the major space missions.
2. Polymer nanocomposites with various nano-fillers, including carbon and boron nitride nanostructures can be applied as multifunctional spacecraft materials.
3. To investigate nanostructures and nanomaterials durability to the space environment impact it is necessary to develop rapidly special methods of mathematical simulation and ground-based testing.

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