THE ENVIRONMENTAL CONDITIONS IN THE NEIGHBOURHOOD AND ON THE SURFACE OF THE INTERNATIONAL SPACE STATION: PART ONE

УСЛОВИЯ НА ОКОЛНАТА СРЕДА В БЛИЗОСТ ДО И НА ПОВЪРХНОСТТА НА МЕЖДУНАРОДНАТА КОСМИЧЕСКА СТАНЦИЯ: ПЪРВА ЧАСТ

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Abstract: *The primary role of the space materials science is to ensure the long-term trouble-free operation of materials and elements of equipment in a space environment. The achievements of space materials science are a solid foundation for solving these tasks. In this paper we present the first part of the analysis of some different aspects of the space environment and their effect on the properties of materials (such as high vacuum conditions, own external atmosphere, collisions with particles, solar electromagnetic radiation, solar wind, penetrating corpuscular radiation) which are located or are mounted on the body of the International Space Station. But there are still problems such as the electrification of satellites, the work of materials in the atmosphere of heavy nuclei, the surface potential of the International Space Station, etc., which will be the subject of our next, second part of this study.*

Keywords: INTERNATIONAL SPACE STATION, NEAR-EARTH SPACE, LOW-EARTH ORBIT, COSMIC RAYS, GAMMA RADIATION, CRYSTALLINE STRUCTURE, NICKEL COATINGS, ALUMINIUM ALLOYS, VACUUM, SPACE APPLICATIONS

1. Introduction

Aluminium-based alloys are very important structural engineering materials widely employed in the aerospace industry. The production and widespread use of aluminium (Al) and Al alloys continues to grow, largely due to the excellent combination of its properties: relatively low cost; good strength/density ratio; good plasticity and mechanical properties; ease of assembly; low neutron absorption; low gamma heating due to the low-density; to a certain extent good corrosion resistance; possibility of thermal processing and loading to a relatively high stress level; it is one of the most easily produced of all high-quality materials, resulting in lower production and maintenance costs. Severe operating conditions in air and space often limit the possibility of using these alloys directly without protection for long periods of time. Therefore, in order to reduce the influence of adverse environmental space conditions and for successful use in aerospace industry, these metals and their alloys require special surface preparation, namely deposition of different types of coatings on their surfaces. Nowadays there is a tremendous interest in extremely stable in space environment Al alloys coatings materials. In the literature and industry there are sufficient data for such coatings, but electroless nickel coatings find the most extensive application [1]. The unique combination of electroless nickel coating properties and electroless composite nickel coating, such as price, thickness, hardness, corrosion resistance and wear resistance, lubrication, connectivity and evenness of the coating, regardless of the substrate geometry make it ideal for wide applications in many different industries. Today, these coatings are firmly established as functional coatings in aerospace industry.

Therefore, in order to reduce the impact of severe space conditions and prevent from them, we must study and know how outer space conditions influence the properties of Al alloys together with their coatings. One of the motivations for this study is the previous experience and participation in the project "Solid state sensors for extra-atmospheric astronomy" and in the international outer space experiment "Obstanovka" (carried out in the Russian sector of the International Space Station (ISS)). The aim "Obstanovka" was to investigate the two and a half years influence of outer real space environment on the properties of: (a) the Al alloy B95 with additions of tungsten and nanodiamonds (ND) [2,3] and (b) the box, on which were mounted the samples of the so modified B95 alloy, which was coated by a bilayer composite electroless Ni coating (Ni/(Ni+ND)) to improve the surface characteristics of the box Al alloy [4,5]. After this exposure to the outer space influence, the samples and the box were returned to the Earth for future research.

In this paper we present the analysis of the different aspects of the space environment and their effect on the properties of materials, which are located or are mounted on the body of the ISS.

2. Conditions around and on the body of the ISS

The International Space Station is an artificial satellite, flying in low Earth orbit. The height of the ISS orbit varies with an altitude of between 320 and 435 km. It completes 15.7 orbits per day. The ISS consists of many components such as pressurized modules, external trusses, solar arrays, and other components. The ISS is affected by a whole complex of factors of the space environment [6-14]: deep vacuum, corpuscular and electromagnetic radiation of various types, meteoroids, magnetic and gravitational fields, that is, different kinds of matter, weightlessness, etc. In ISS, the temperature of the side exposed to the Sun can reach about 150°C, while the side in the dark space is in absolute cold – minus 157°C.

2.1. Impact of vacuum on materials

Vacuum is the state of a gas at a pressure below atmospheric pressure. Air pressure in the Earth's atmosphere decreases with an increase in height according to a law close to exponential. We are interested in the parameters of the atmosphere at those altitudes where the ISS can function for a long time (see above) [6-9]. In Table 1 [6] are shown the values of pressure, density and air temperature, as well as in the Earth's atmosphere, for the altitudes of interest to us. Note that the temperature given here in the fourth column characterizes only the kinetic energy of the gas particles and does not have a direct effect on the temperature of the surface of the ISS because of the extreme sparseness of the medium. A vacuum at altitudes of 320-4350 km can be characterized as high. But we are distracted from the complex character of the cosmic medium and will take into account only its rarefaction, that is, that it is primarily a cosmic vacuum. In a vacuum, any material emits gases and vapors adsorbed on the surface and located (absorbed) in the bulk of the material. In the latter case, the process of gas evolution is preceded by the diffusion of atoms and molecules of gases to the surface. Similarly, evaporation from materials of various impurities and additives occurs. Finally, evaporation (sublimation) of the base material occurs from the surface.

The evaporation rate is characterized by the mass of a substance evaporating per unit time from a unit surface of the material. This rate increases with increasing the surface temperature; it also depends on the conditions for removing vapors from the surface: the lower the vapor pressure above the surface relative to the saturated vapor pressure of the evaporating substance, the higher the evaporation rate.

It is clear that for use on open surfaces of the ISS, materials with a low evaporation rate should be chosen at the temperature to which they can be heated in outer space conditions. For example, the thickness of a plate made of cadmium or zinc is reduced by evaporation in vacuum by approximately 0.1 mm per year already at a temperature of 100-150°C, which is quite real on the surface of the ISS due to heating by solar radiation. To obtain the same thickness reduction for a plate made of Al, copper or nickel, the plate needs to be heated to 750-1000°C, and at 100-150°C these materials practically do not evaporate.

Table 1: *Change in the parameters of the Earth's atmosphere with altitude [6].*

Height, km	Pressure, Pa	Density, g/cm3	Temperature, K	Concentration of particles, cm^{-3}
300	$1,0.10^{-5}$	$2,5.10^{-14}$	1500	$8,0.10^{8}$
500	$4,0.10^{-7}$	$3,0.10^{-16}$	1600	$2,5.10^{7}$

For actual construction materials, the loss of mass due to evaporation in space vacuum is usually so insignificant that it is not necessary to take into account the reduction in the thickness of the material layers, except for the cases of special very thin films and coatings, as well as for the operation of materials at high temperatures. However, this does not mean that staying in a vacuum passes without a trace for materials.

The processes of gas evolution and sublimation substantially change the state of the surface and near-surface layers of materials by removing absorbed gases from the surface and from the volume, breaking up the oxide films on the surface, removing impurities, creating microroughness on the surface as a result of uneven evaporation, etc. All this leads to change of mechanical, optical and electrophysical characteristics of materials. And in this sense it is really possible to talk about the impact of the cosmic vacuum - "emptiness" - on structural materials. And now we turn to another problem, directly related to the work of ISS (or any spacecraft) in a vacuum.

2.2. Own external atmosphere (OEA)

The processes of gas evolution and sublimation of materials in a vacuum lead to the formation of a gas cloud near the ISS, which is affected by gravitational forces, light pressure, aerodynamic braking forces, etc. This cloud, which also includes solid particles that detach from the surface of the ISS, exhaust products engines, gases and solid particles that fall into outer space from internal compartments due to leakage, during sluicing, etc., it is customary to call that outer atmosphere of the ISS “own external atmosphere” (OEA). Part of the gas particles of OEA is excited and ionized by solar ultraviolet radiation and corpuscular streams, just as it occurs in the Earth's atmosphere.

Due to the presence of OEA, the pressure in the immediate vicinity of the ISS can significantly (sometimes by several orders of magnitude) exceed the pressure in the surrounding outer space. Besides ions, atoms and molecules of OEA, depositing on external surfaces of ISS, greatly change the physical properties of the latter.

In order to quantify the effect of impurities on the characteristics of metal alloys (including Al alloys), it is necessary to know the thickness of the deposited film, its composition and structure, the refractive index, and other parameters. Experimental study of the processes of deposition of impurities on various materials, as well as the study of the formed films, is among the important tasks of space materials science. The effect of OEA on materials and elements of equipment is mainly reduced to the following effect: surface contamination with precipitated OEA products. The particles of the OEA of ISS are acted upon by aerospace inhibition forces the residual atmosphere of the Earth, the pressure of the solar wind, the pressure of light, electrostatic and electromagnetic, as well as gravitational forces. The ISS is flying in low orbits (300-500 km.), therefore the aerodynamics inhibition of OEA particles dominates. In the presence of aerodynamic braking, a significant part of the clouds of ejected wear products of the ISS will accompany the object for long distances. However, on the density distribution of OEA directly near the ISS, the main impact is expiration mass from the ISS.

The sediment of OEA products consists mainly of organic substances with a high molecular weight. The sources of such substances on the ISS are engine fuel products, paints, electrical insulating materials, rubber, etc. Solar ultraviolet radiation contributes to fixing the settled particles on the surface, under the action of which many organic molecules are polymerized.

The transport of pollutants is carried out mainly as a direct result of the direct flow of particles from the sources to different parts of the surface of the space vehicle (ISS). With a high density of OEA, a certain fraction of the particles can get to the surface after collisions with other particles in the gas cloud, i.e. changing the original direction of motion. The transfer of charged OEA particles is affected by electric and magnetic fields near the ISS, creating additional conditions for the entry of pollutants on its surface that are out of sight from the point of emission of particles.

The model of external pollution of ISS (as well as any spacecraft) is based on the fact that all process is a simple classical transfer of masses into specialized conditions. Chemical analysis of polluting precipitation on samples (as Al alloys under consideration), placed on the outer surfaces of ISS in outer space, gives possibility to determine the ways and means of transporting pollutants materials, and mechanisms of their deposition.

The gas deposition on surfaces is determined by its pressure and coefficient of accommodation of a given gas by the surfaces of the ISS. The settling of charged or polarized particles on the conducting surfaces of the ISS differs from their settling on dielectric surfaces (portholes, lenses, thermoregulating coatings) due to the influence of electrostatic forces.

To reduce the negative impact of OEA on materials, the elements and components of on-board equipment on the outside of the ISS, certain measures are being taken to clean the contaminated surfaces (see [6,9]).

2.3. Collisions with particles

Considering the behavior of materials in the cosmic vacuum and the effect of OEA on the materials of ISS, we have mainly taken into account only the thermal motion of atoms and molecules. In the upper atmosphere of the Earth, at altitudes of 300 km, at a temperature (1 - 2).10^3K, the average thermal energy of atoms and molecules is 0.1 ± 0.3 eV. However, relative to the satellite, which is moving at a speed of about 8 km/s, the kinetic energy of the particles of the oncoming gas flow reaches 5 - 10 eV (depending on the mass of the particles). As was experimentally established, in the ionospheric plasma the surface of the satellite acquires a negative potential of 0.1 - 5 V. The kinetic energy of the positive ions bombarding the surface increases by an amount corresponding to this potential.

In addition, it must be taken into account that the ions in the upper atmosphere possess the potential energy expended for their ionization. For the components of the atmosphere, this energy lies in the range 10 - 20 eV. In addition, some of the neutral and charged particles can be in an excited state, that is, they can have potential excitation energy. As a result, the energy transferred to the ISS surface by one particle of the oncoming gas flow can reach 10 - 25 eV. Since the threshold energies of such processes as chemical reactions, dissociation, ionization, recombination, etc., lie in the interval 0.5-30 eV, different physicochemical processes occur on the outer surface of the ISS (space vehicle, spacecraft or satellite) under the action of neutral and charged particles of the upper atmosphere.

The impacts of neutral particles mainly affect the atoms and molecules of the adsorbed gas on the surface of the spacecraft by knocking them off the surface. The particle desorption of the surface of the spacecraft is also facilitated by heating the surface with an oncoming gas flow. They contribute to the heat of the material and the chemical reactions that occur on the surface with the release of heat. Unfortunately, the quantitative characteristics of such space flight reactions are known to be inaccurate so far, which makes it difficult to perform estimates.

Some chemical reactions on the surface go with the release of energy in the form of light radiation - this is the so-called chemiluminescence. One of the interesting mechanisms of chemiluminescence in orbital flight is the deactivation of excited particles of the upper atmosphere on the surface of the ISS/spacecraft. It is estimated that during solar flares, when the concentration of particles in the excited state increases sharply in the upper atmosphere, the luminescence due to this mechanism can create noticeable interference to the optical instruments of the spacecraft. The normal functioning of the on-board optical instruments can also be disturbed by the painting of the near-surface layer of optical materials under the influence of the oncoming gas flow.

With increasing altitude of the orbit, the density of the oncoming gas flow falls. Nevertheless, since the prospective thin-film constructions under development need to function in space for 10 to 20 years, the phenomenon of atomization of materials by particles of the upper atmosphere, like the phenomenon of evaporation of materials in a vacuum, can not be ignored in the design of such structures.

2.4. Solar electromagnetic radiation

On the surface of the ISS facing the Sun, in the vicinity of the Earth, on 1 m^2, every second is delivered about 1400 J of energy, transferred by solar electromagnetic radiation [6,11,13]. In other words, the solar energy flux density is 1.4 kW / m^2. And about 9% of the energy in the solar spectrum is due to ultraviolet radiation with wavelengths from 100 to 400 nm. The remaining energy is divided approximately equally between the visible (400 - 760 nm) and infrared (760 - 5000 nm) regions of the spectrum. More detailed picture of the energy distribution in the solar spectrum is given in Table 2, in which the absolute and relative values of the energy flux density are given for different spectral intervals, as well as the energy values of the radiation quanta.

Table 2: *Energy distribution in the spectrum of solar radiation [6].*

Wavelength interval, nm	Density of energy flow, W / m2	Share of total flow,%	Quantum energy, eV
Ultraviolet radiation			
10 - 225	0,4	0,03	124 – 5,5
225 - 300	17	1,2	5,5 – 4,1
300 - 400	109	7,8	4,1 – 3,1
10 - 400	126	9.0	124 - 3.1
Visible radiation			
400 - 500	201	14,3	3,1 – 2,5
500 - 600	193	13,8	2,5 – 2,1
600 - 760	250	17,9	2,1 – 1,6
400 – 760	644	46,1	3,1 – 1,6
Infrared radiation			
760 – 1000	241	17,3	1,6 – 1,2
1000 – 3000	357	25,6	1,2 – 0,4
3000 – 5000	21	1,5	0,4 – 0,2
760 – 5000	619	44,4	1,6 – 0,2

In the infrared and visible ranges, the energy of individual quanta is too small for radiation to have a direct physicochemical effect on matter. The emission of these spectral regions, which is often called thermal, affects the materials and elements of the spacecraft equipment only by heating. As the wavelength decreases, the energy of the radiation quanta increases and the situation changes. The energy of quanta can become sufficient for the destruction of matter - the breaking of molecular bonds. Most susceptible to this effect are the organic compounds.

The maximum wavelengths at which radiation causes the destruction of materials lie about 400 nm, i.e. near the short-wavelength boundary of the visible range. When the transition to the region of smaller wavelengths, in the ultraviolet range of the spectrum, the destructive effect of radiation on materials increases in accordance with the increase in the quantum energy, but with a decrease in the wavelength, the radiation intensity in the solar spectrum decreases sharply (see Table 2). Therefore, the integral effect of solar ultraviolet radiation on materials decreases in the short-wave part of the spectrum, and the effect of solar X-ray radiation on materials can practically be neglected.

The Sun supplies the ISS with electricity, feeding solar panels. In space, the heat exchange between bodies occurs by radiation, the transfer of heat due to convection and thermal conductivity is negligible. In the conditions of cosmic vacuum, the impacts of gas particles on the ISS surface are too rare. It is for this reason that the surrounding gas can not heat the ISS, although the temperature of the gas itself, as we know (see Table 1. [6]), is quite high. As noted earlier, the ISS motion in the upper atmosphere of the Earth leads to aerodynamic heating of its surface. But even at an altitude of 200 km the heat flux entering the spacecraft due to aerodynamic heating is much less than the heat flux of solar radiation.

The Earth also sends a heat flow to the surface of the spacecraft, which is due to the partial reflection of solar radiation and the thermal radiation of our planet. At low orbits, the density of this heat flux can reach 35-40% of the flux density of direct solar radiation, but with increasing altitude, it falls rapidly. The heat fluxes arriving on the ISS from other sources (stars, corpuscular radiations, etc.) can practically be neglected.

Up to a temperature of 4K, the surface of the ISS would cool if there is no inflow of heat to it from external sources, the main one being the Sun, and from sources of thermal energy onboard the ISS. The latter include special heating devices, various equipment, correction and orientation engines, crew life support systems and the crew itself. In the absence of heating by solar radiation, it is necessary to have a powerful power source onboard to ensure a normal thermal regime of the ISS (after all, without lighting, solar cells cease to function). In addition, measures should be taken to reduce the heat removal from the inside of the spacecraft to the surface. For this purpose, the body of ISS can be coated with a so-called screen-vacuum heat insulation consisting of many layers of metallized polymer film. During the hours when the rays of the Sun warmed the surface of the ISS one has to solve the opposite problem - to protect the device from overheating. This task, which is common to all spacecraft, is sometimes more complicated than protection from hypothermia. The processes of absorption and dissipation of heat by the ISS is achieved by increasing the degree of blackness of the surface and reducing the absorption coefficient. To ensure such conditions, thin layers of materials with the necessary characteristics - thermoregulatory coatings - are applied to the surface of the ISS and to various devices located outside the ISS compartment. Various paints, enamels, metallized polymer films, etc., are used as thermoregulatory coatings. All these coatings not only protect ISS from different temperatures, but also contribute to OEA. The deterioration in the properties of the thermoregulatory coatings is caused by the solar wind and under the action of solar ultraviolet radiation.

2.5. Solar wind

A solar wind is a stream of plasma continuously flowing into interplanetary space from the outer, fully ionized gas shell of the Sun - the crown. The solar wind plasma, consisting mainly of protons and electrons, moves in the vicinity of the Earth at a speed of 320-400 km/s [6,13,14]. The kinetic energy of the protons at this speed is 600-800 eV, and the electron energy is only 0.3-0.4 eV, since the electron mass is almost 2000 times smaller than the proton mass. Due to the chaotic thermal motion in the plasma, the true energy of the electrons of the solar wind is several times higher, but nevertheless they do not have any noticeable effect on the materials of the space vehicle. The main influencing factor of the solar wind is the proton flux. During flares on the Sun, the speed of the solar wind can increase to 1000 km/s, with correspondingly increasing proton energy and the density of their flow. The effect of solar wind protons on materials is reduced to the following main effects: sputtering and creation of radiation structure defects in the near-surface layer due to the introduction of protons and the "displacement" of the atoms of matter.

Thus, we have become acquainted with the effect on materials and equipment of ISS of two factors in outer space created by the Sun: electromagnetic radiation and solar wind. During the outbreaks, the Sun emits solar cosmic rays (SCR), mainly proton fluxes with energies from 1 to 104 MeV. The energy of protons SCR, as we see, many times exceeds the energy of protons of the solar wind.

Other cosmic fluxes of high-energy particles are also presented in outer space. With increasing particle energy, the depth of their penetration into the thickness of the material increases. Particles of high energy can penetrate the shell of the ISS and pose a danger to the crew and equipment located in the inner compartments. Therefore, the study of the radiation situation in space and the effects of corpuscular radiation of different species on living organisms and the most diverse materials and elements of equipment occupies one of the central places in space physics, space biology and medicine and, of course, in space materials science. Charged high energy particles are often called penetrating corpuscular radiation, or penetrating radiation.

Table 3: *High energy particles in outer space [6].*

Type of corpuscular radiation	Composition	Energy of particles, MeV	Density of a stream of particles, $m^{-2}.s^{-1}$
Radiation belt of the Earth: interior	Protons	1 – 30 > 30	3.10^{10} 2.10^{8}
	Electrons	0,05 – 05 > 0,5	2.10^{12} 5.10^{10}
Radiation belt of the Earth: external	Protons	> 0,1	1.10^{12}
	Electrons	0,05 – 1,5 > 1,5	2.10^{11} 1.10^{9}
Solar cosmic rays	Protons	$1 – 10^4$	$10^7 – 10^8$
Galactic cosmic rays	Protons Helium nuclei Light nuclei (Z* = 3 - 5) Average nuclei (Z = 6 - 9) Heavy nuclei (Z = 10 - 30)	$10^3 – 10^{14}$ for all groups of nuclei	3.10^{4} 3.10^{3} 5.10^{1} 2.10^{2} 4.10^{1}
	* Z - number of the element in the periodic system of Mendeleev		

2.6. Penetrating radiation

The main types of penetrating corpuscular radiation in space are electrons and protons of the Earth's radiation belts, galactic cosmic rays (GCR) is an isotropic flux of protons and heavier nuclei coming from remote regions of the Galaxy, and solar cosmic rays already familiar to us [11-14]. Radiation belts are relatively stable giant areas of congestion of high-energy electrons and protons held by the Earth's magnetic field. Radiation belts are enclosed in the Earth's magnetosphere. For electrons of radiation belts, the energy range is from 0.05 to 5 MeV, for protons - from 0.1 to 50 MeV. Particles of GCR have the highest energy in comparison with other types of cosmic corpuscular radiation. The GCR energy is contained in an extremely wide range, from 10^8 to 10^{21} eV, but the density of their flux is relatively small. Data on penetrating corpuscular radiation in outer space are given in Table. 3. As the energy of charged particles acting on the ISS increases, the radiation effects they cause are increased on and in the materials and elements of the equipment: formation of structure defects, ionization and excitation of the atoms of the substance, and nuclear transformations. Radiation effects inevitably change the physicochemical and mechanical properties of materials, and consequently, the performance characteristics of the elements made of them. Semiconductor, optical, dielectric and polymeric materials widely used in space technology are particularly sensitive to radiation. Metals are less sensitive to the effects of radiation.

3. Conclusion

The primary role in the implementation of space projects is to ensure the long-term trouble-free operation of materials and elements of equipment in a space environment. The achievements of space materials science are a solid foundation for solving these tasks. We briefly examined here some of the problems and tasks that space materials science is dealing with - such as the behavior of materials in high vacuum conditions, the degradation of materials on the surface of ISS and equipment elements, etc.[6-14]. But there are still problems such as the electrification of satellites, the work of materials in the atmosphere of heavy nuclei, the surface potential of the ISS, etc, which will be the subject of our next, second part of this study.

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