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Protection of Materials from Space Radiation Environments on Spacecraft

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Abstract. Spacecraft in orbit will encounter space radiation environments such as electron, proton, heavy ions, gamma ray, etc; and results in the space radiation effects such as single event effects, total ionizing dose effects, displacement damage effects, surface charging and discharging or electrostatic discharging, internal charging effects. So protection from space radiation should be given to the spacecraft. The protection principle and validity from space environments on spacecraft is introduced firstly, and then mass shielding material, ESD protection material, and radiation hardening functional material, were discussed. At last, some development directions on protection material from space radiation environments are proposed.

1. Introduction

During the orbital operation of the spacecraft, it will encounter severe tests from various space radiation environments, such as electrons, protons, heavy ions, photons, etc., which can cause single-particle effects, total dose effects, and other total dose effects of spacecraft materials, components, subsystems, etc. Surface charge and discharge effects, internal charging effects, displacement damage effects, etc., cause degradation of material or device performance. Therefore, in the design and development of spacecraft, it is necessary to strengthen the material selection and structural protection design of spacecraft to ensure that the spacecraft does not cause failure or failure due to space radiation during the orbit, effectively improving the spacecraft space in orbit.

At present, the world's major space powers have invested a lot of efforts in the research and development of spacecraft radiation protection materials, and have done a lot of work on spacecraft structural design, and have achieved a lot of beneficial results, providing huge spacecraft design. s help. China's spacecraft development faces a severe situation [1], such as the orbital type and orbital environment is complex; satellite high performance, long life, high reliability requirements; equipment miniaturization, lightweight, low power consumption, etc., it is necessary to further strengthen the space The development of space radiation protection materials and the strengthening of structural protection design.

This paper introduces the design principles and the latest status of space radiation protection materials and protection structures from three different dimensions of materials, subsystems (or components) and spacecraft, in order to provide support for the design of long-life and high-reliability spacecraft in China. It also provides direction for the development of space radiation protection materials and protective structures for spacecraft in China.

2. Space Radiation Environment and Effects

Space radiation environments come from star-trapping radiation belts, solar cosmic rays, galaxy cosmic rays, and they are composed of electrons, protons, heavy ions, photons and so on [2].

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High-energy charged particles or high-energy photons in a space radiation environment can cause temporary damage or permanent failure of spacecraft materials or devices, including single-particle effects, total ionization dose effects, displacement damage effects, surface charge and discharge effect, internal charging effect, ultraviolet radiation effect, etc.

Radiation damage to spacecraft caused by space radiation environment mainly includes ionization damage and displacement damage. Ionization damage refers to the ionization of target atoms and the excitation of extranuclear electrons in the material caused by incident particles, thereby forming electron-hole pairs in the material, resulting in severe degradation of semiconductor device performance, causing single-particle effect and total dose effect; and high-energy photons and The action of the polymer material causes the chemical bond of the polymer material to break and form new bonds, degrading its physical and chemical properties. Displacement damage refers to the interaction of incident particles with atoms in the material and exchange of kinetic energy, causing the target atoms in the material to leave the original position to form interstitial atoms and create vacancies. A displaced atom may collide with other atoms multiple times, creating a shift chain. The vacancies or interstitial atoms generated by atomic displacement usually have strong reactive electrical properties and are trapping traps for carriers or carriers in semiconductors.

According to the action time of the radiation damage effect, it can be divided into long-term effects and transient effects. Long-term effects are long-term changes or degradations in the performance of materials or devices. Transient effects are those that can alter or degrade the properties of a material or device in a short period of time, and the effects of recovery or interruption will soon occur [3].

3. Protection Principle and Effectiveness

3.1. Principle of Protection

When charged particles with a certain energy are incident on the target material, the charged particles interact with the nucleus or electrons of the target substance on the path, and a part of the kinetic energy is transferred to the electron or nucleus of the target material to gradually lose energy, and finally stops at In the target material, this process is called the slowing process. During the moderation, the energy loss and angular deflection of the charged particles in the target material are the result of various interactions between the incident charged particles and the electrons and nuclei in the target material. The collision process mainly consists of the following four types: the charged particles collide with the target nucleus; the charged particles collide with the target atom; the charged particles of the charged particles and the target atoms of the charged particles and the target atoms of the charged particles collide with the target nucleus; the charged particles collide with the target atoms A resilient collision occurs.

The protection of materials from space radiation is related to the ability to block and the effectiveness of protection. The stopping power is the energy loss when the charged particles pass through the unit path, and is represented by (-dE/dX). Therefore, the stopping power is related to the kind of the charged particles, the energy, and the properties of the target atoms.

According to the quantum classical theory, the electron-stopping formula (Bethe-Block formula) of heavy charged particles in the target material is

$$(-dE/dX)_{ion} = \frac{4\pi z^2 e^4 NZ}{m_0 v^2} \left[\ln\left(\frac{2m_0 v^2}{I}\right) + \ln\left(\frac{1}{1-\beta^2}\right) - \beta^2 - \frac{C}{Z} \right]$$

Where: heavy charged electrons prevent electrons; E is charged particle energy; X is charged particle incident depth; m0 is electron rest mass; N is atomic density; Z is atomic number; τ is the ratio of electron kinetic energy to its static energy; $\beta = v / c$, v is the electron velocity, c is the speed of light; I is the average ionization and excitation potential energy; δ is the correction factor.

The stopping power has the following characteristics: 1) The stopping power is only related to the speed of the incident particle, regardless of its quality. 2) The stopping power is proportional to the square of the charge number of the incident heavy charged particles. When the incident particle velocity is the same, the particles with a large number of charges prevent the large size. 3) The stopping power is proportional to the product of the atomic number and density of the target substance,

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and the substance with high atomic number and high density prevents the ability from being large. 4) The stopping power is related to the energy of the incident particles. Therefore, mass shielding methods are generally employed, i.e., when the thickness of the shielding material is greater than the range of charged particles in the material, the incident particles will be blocked in the material.

3.2. Protection Effectiveness

One problem with the mass shielding method is that secondary space radiation and shielding materials produce secondary radiation, such as secondary neutrons, recoil protons, bremsstrahlung, etc., and the dose contribution of secondary radiation increases with mass thickness. It also gradually increases. For example, when the mass barrier is less than 10 g•m-2, the primary proton dose is much larger than the secondary proton and secondary alpha particles; when the shielding quality reaches 20 g•m-2, the primary and secondary proton doses are It's almost the same. Therefore, the thickness of the mass shield is not as thick as possible, and there is a cost-effectiveness problem of radiation protection.

The effectiveness of shielding is determined by the transport of the space radiations through the materials. The relevant transport equations are the linear Boltzmann equations for the flux density $\phi_i(X, \Omega, E)$ for particle type j as [4]

$$\Omega \bullet \nabla \phi_j (X, \Omega, E) = \sum \int \sigma_{jk} (\Omega, \Omega', E, E') \phi_k (X, \Omega', E') d\Omega' dE' - \sigma_j (E) \phi_j (X, \Omega, E)$$

Where $\sigma_{j}(E)$ and $\sigma_{jk}(\Omega, \Omega', E, E')$ are the shield media macroscopic cross sections. The $\sigma_{jk}(\Omega, \Omega', E, E')$ represent all those processes by which type k particles moving in direction Ω' with energy E' produce a type j particle in direction Ω with energy E (including decay processes).

There may be several reactions that produce a particular product, and the appropriate cross sections for equation are the inclusive ones. Exclusive processes are functions of the particle fields and may be included once the particle fields are known. The total cross section $\sigma j(E)$ with the medium for each particle type is

$$\sigma_{j}(E) = \sigma_{j,at}(E) + \sigma_{j,el}(E) + \sigma_{j,r}(E)$$

Where the first term refers to collision with atomic electrons, the second term is for elastic nuclear scattering, and the third term describes nuclear reactions where we have ignored the minor nuclear excitation processes. The corresponding differential cross section is similarly ordered. Many atomic collisions ($\sim 10^6$) occur in a centimeter of ordinary matter, whereas $\sim 10^3$ nuclear coulomb elastic collisions occur per centimeter, while nuclear reactions are separated by a fraction to many centimeters depending on energy and particle type.

The protection properties of material are given by the product of the corresponding atomic cross section and the density of each atom type in the material. It is generally believed that hydrogen has the best atomic properties for the protection of unit mass materials. The reason can be attributed to the fact that the electron number per unit mass is the largest, the average electron valence bond is the smallest, and the largest atom per unit mass. In addition to this, hydrogen atoms are more likely to transfer energy to colliding ions. Simple hydrogen atoms do not provide a large number of secondary particles to the radiation field, which limits the formation of secondary radiation.

Therefore, it is necessary to use a material with a higher atomic number to protect the bremsstrahlung generated by high-energy electrons. In order to reduce the secondary bremsstrahlung, the protective layer should select a low atomic number material. Therefore, the cabin structure should choose a protective structure with a combination of high and low atomic number materials, and the outer layer of the structure should use low atomic number materials to reduce the generation of bremsstrahlung.

4. Space Radiation Protection Materials

Space radiation protection materials are composed of quality shielding protective materials, electrostatic protection materials and anti-radiation functional materials.

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4.1. Quality Shielding Protective Materials

The mass shielding method is the basic method used in current manned space radiation protection. Charged particles gradually lose energy as they pass through the material, and finally, capture a sufficient number of electrons to stop. When the thickness of the shielding material is greater than the range of a charged particle in the material, the incident particles will be blocked in the material. Therefore, a material of a certain thickness can shield the particle radiation of a certain energy range (depending on the kind of the particle) and reduce the energy penetrating the particle. However, the increase in the thickness of the shielding material poses some problems, mainly due to the increase in the weight of the spacecraft and the secondary radiation [4-5].

Figure 1 show the absorbed doses of 17 different materials for the same radiation environment [6].



Figure 1. Absorbed dose of different materials in radiation environments [6]

It can be seen from figure 1 that the content of hydrogen in the material increases, the absorbed dose per unit mass of the material increases.

In theory, liquid hydrogen is the best shielding material, but there are still many problems in practical applications. Therefore, the preferred shielding material is water, which is not as effective as liquid hydrogen, but much better than aluminium. The requirements for high-performance shielding materials are: the maximum number of electrons per unit mass, the largest cross section of nuclear reaction per unit mass, and the least number of secondary particles. The United States has invested a lot of manpower and material resources in the research of new materials and methods for radiation protection. According to NASA research, polyethylene is a better radiation protection material. Therefore, the United States provides a sleeping bag made of polyethylene in the astronaut's rest area, which can provide some radiation protection for astronauts during sleep.

By using materials of high-quality elements, high-energy charged particles, especially heavy ions, can be effectively shielded, and a large amount of bremsstrahlung radiation will also be generated. Considering the protection of the Galaxy cosmic rays, the shielding effectiveness of the unit mass thickness material increases with the decrease of the atomic number. Therefore, how to effectively combine with low atomic number elements and high atomic number elements through design is an effective way to passively protect space radiation.

4.2. Electrostatic Protection Materials

During the orbital operation of the spacecraft, its surface may cause charging and discharging effects due to charging. To this end, the surface material of the spacecraft needs to be anti-static. Since the outer surface of the spacecraft is mostly covered by a temperature-controlled thermal control coating, the antistatic effect can be achieved by improving the electrical conductivity of the thermal control coating. For example, a transparent conductive film of indium tin oxide is plated on the outer surface

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of the mirror reflection thermal control coating, and a conductive component is added to the coating type thermal control coating. Thermally controlled coatings with electrical conductivity are also known as antistatic thermal control coatings.

Among the film-based thermal control materials, PI (polyimide) based and F46 (polyperfluoroethylene propylene) based antistatic thermal control coatings are commonly used. The ITO/PI/Al antistatic thermal control coating is a secondary surface mirror type thermal control coating based on PI film. The aluminum film was deposited by vacuum evaporation on the back side of the PI film. In order to suppress the charge and discharge effect of the space, a transparent conductive film, usually ITO (indium tin oxide), is plated on the outside. The conductive ITO/PI/Al thermal control coating has a very low α S/ ϵ H ratio, and is mainly used for the heat dissipation surface of the satellite, and has a strong adaptability to the space environment. Another material is to coat the transparent conductive film ITO on the other side of the F46 film to obtain a certain electrical conductivity, thereby avoiding the charge and discharge effects of charge accumulation on the surface of the thermal control coating. The conductive F46 silver-plated (aluminized) secondary surface mirror has the characteristics of light weight, good stability, can be made into a large area product, and is easy to install, and is widely used in various space vehicles [7].

The lacquer-based thermal control coating consists of two parts, a pigment and a binder (also known as a binder). The absorption of sunlight by the finely dispersed pigment in the coating and the infrared radiation characteristics of the substrate constitute the entire coating. While satisfying the thermal control performance, the purpose of antistatic is achieved by selecting a conductive pigment such as ZnO, some typical thermal white paints such as S781, ACR-1, SR107-ZK and so on.

4.3. Anti-radiation Functional Materials

Some spacecraft materials, due to their specific on-orbit performance (such as light transmission properties), require high space environmental adaptability in space radiation environments. Taking the material selection of a spacecraft observation window as an example, quartz glass has better radiation resistance. Because of its high brittleness, K9 glass is usually used as a support window in the inner layer. However, during the ground simulation test evaluation of space radiation environmental effects, K9 glass turned black due to its poor radiation resistance. Therefore, the purpose of anti-radiation can be achieved by adding a high atomic number of heavy metal oxides PbO, BaO, Bi2O3 or the like or a rare metal material in the glass manufacturing process.

5. Conclusion

The space radiation environment poses a serious threat to the safety and reliability of spacecraft in orbit. It is always the direction of aerospace science and technology workers to improve the radiation resistance of spacecraft through material selection and structural design.

Since mass shielding needs to consider the combined effects of primary and secondary radiation, it is also necessary to consider the limitations of aerospace loads on quality. Therefore, the development of composite materials composed of low atomic number elements and high atomic number elements, while reducing the mass of spacecraft, improving its radiation resistance is an important development direction of spacecraft protective materials. At the same time, the application of nanotechnology in spacecraft radiation protection materials is also a research hotspot.

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