Research on Test Technology of Ionizing Radiation Effect of Spacecraft Material

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Abstract. $^{60}$Co $\gamma$-ray source and 45keV electron source are used as radiation sources respectively to study the ionizing radiation effect of spacecraft material heat-shrinkable sleeve, and compare the radiation effect similarities and differences between the two radiation sources. The results show that in the damage mechanism, both $\gamma$-rays and electrons cause ionization and excitation of electrons outside the nucleus in the material, producing ionization effects, and resulting in degradation and cross-linking of the molecular chains of the material. However, in terms of macroscopic mechanical property degradation, $\gamma$-rays can cause complete loss of mechanical properties of material, while 45keV electrons only cause partial damage to the mechanical properties of the material. In addition, at the same dose, $\gamma$-rays can damage the mechanical properties of the material to a greater extent than 45keV electrons. This paper explains the phenomenon and puts forward the applicable conditions of the two test technologies.

Keywords: Spacecraft material, ionizing radiation effect, heat-shrinkable sleeve, damage mechanism

1. Introduction

There are lots of electrons in the earth orbit of the spacecraft, which mainly come from the earth's radiation belt. These space electrons are irradiated on the spacecraft, which will produce electron irradiation effects on materials such as thermal control materials, optical materials, and insulating materials used by the spacecraft, thus affecting the working life and reliability of the spacecraft [1, 2]. Therefore, it is necessary to use the ground test technology to study the damage effect of the space electron radiation environment on materials.

According to the theory of atomic physics, electrons, because of their light weight and fast motion, ionize or excite the atoms of materials when they interact with them. Ionization loss is a major way of electron loss in the material, which in turn causes the ionizing radiation effect of the material being irradiated. The electron radiation environment in space mainly comes from the radiation belt, with several keV to 100 keV electrons as the main source, and the electron flux above 1MeV is relatively small. The damage effect of the induced material is mainly caused by the ionizing radiation effect. In the ground test research work, since $\gamma$-rays can also induce the ionizing radiation effect of materials, therefore, in addition to the use of electron sources for the research on ionizing radiation effects, $\gamma$-rays are often used as radiation sources for tests [3, 4]. There are two types of ground test technologies: $\gamma$-ray test method and electron irradiation test method. However, in the two test methods, whether the ionization damage caused by different irradiation sources (electrons, $\gamma$-rays) is consistent, especially
whether the damage is consistent under the same total dose. There is little research in this area and no specific conclusions have been reached.

In this paper, the polyethylene heat-shrinkable sleeve is taken as the research object, and the electron source and $^{60}$Co $\gamma$-ray source are used to study the effects of ionizing radiation induced by electrons and $\gamma$-rays respectively. The influence of test technologies on the ground by using different simulation sources on the test results is analyzed.

2. Test Design

The electron radiation environment of the geosynchronous orbit is selected for the space electron radiation environment, and the AE8 model is selected for the earth radiation belt model selects. Figure 1 shows the relationship between the ionizing radiation dose and the shielding thickness of the space electron radiation environment of the satellite in orbit for 15 years. The figure is based on the analysis results of the solid sphere shielding model.

![Figure 1. The dose deepness curve of space irradiation](image_url)

Extrapolated from the calculated data, the total dose accepted by the exposed material in the 15-year GEO orbital environment without shielding is $2 \times 10^9$ rad (Si).

The test sample is a transparent heat-shrinkable sleeve for satellite. As one of the important protective materials of spacecraft cables, this material has been widely used in spaceflight.

In Table 1, the elongation at break is the mechanical property parameter of the high-polyethylene heat-shrinkable sleeve. Elongation at break refers to the ratio of the displacement value of the sample to the original length at the time of breaking, and the result is expressed as a percentage (%). Surface morphology, X-ray photoelectron spectroscopy and infrared spectroscopy are used to analyze the mechanism of material ionization damage.

| parameter                  | test instrument                        |
|----------------------------|----------------------------------------|
| elongation at break        | CMT4104 Eletronic Universal Testing Machine |
| surface morphology         | JEM7401 scanning electron microscope  |
| X-ray photoelectron spectroscopy | AXIS Ultra                       |
| infrared spectroscopy      | -                                     |
The dose rate of the $^{60}$Co γ-ray source irradiation test is 100 rad (Si) / s, and the total dose is $8.64 \times 10^7$ rad (Si). An electron energy of 45 keV and a total fluence of $2.0 \times 10^{16}$ e/cm$^2$ are selected for the electron irradiation test which is equivalent to a 15-year GEO orbital electron radiation environment [5].

3. Test Results and Analysis

3.1 Consistency Analysis of Damage Mechanism
Since the space is an electronic radiation environment, when using γ-rays to study the ionizing radiation effect of spacecraft materials, first, it must be ensured that the damage mechanism of ionizing radiation effect on materials is the same. On this basis, it is possible to analyze whether the macroscopic performance degradation of materials is consistent.

Figure 2 is the surface morphology of the heat-shrinkable sleeve after different irradiation tests. As can be seen from the figure, the surface of the unirradiated heat-shrinkable sleeve is relatively flat with some wrinkles and particulate matters (Figure 2a). After γ-ray irradiation, the surface of the sample did not change significantly, and the surface of the sample was slightly wrinkled or slightly peeled, but in general, the morphology did not change significantly (Figure 2b). After the electron irradiation, the surface is rougher than the original sample, and there is a bulge similar to the particles, and the surface is uneven (Figure 2c).

![Figure 2](image)

**Figure 2.** The SEM images of heat-shrinkable sleeves before and after the irradiated. (a) Before irradiation. (b) Irradiated by γ ray. (c) Irradiated by electron beam

Table 2 shows the element content (XPS analysis) of the heat-shrinkable sleeve after different irradiation tests. The high-polyethylene heat-shrinkable sleeve is prepared by the silane cross-linking method, grafting reaction between polyethylene and organosilane is used to obtain cross-linked silane grafted polyethylene, and then the heat-shrinkable sleeve is prepared by subsequent catalytic hydrolysis condensation reaction. The main component is C$_3$H$_4$, and it also contains other materials such as silicon and oxygen.

**Table 2.** Elements contents variation of heat-shrinkable sleeves

| Experimental condition | elements contents (%) |
|------------------------|----------------------|
|                       | Na 1s | F 1s | O 1s | N 1s | C 1s | S 2p | Si 2p |
| sample                | 0.2   | -    | 3.02 | -    | 96.28 | 0.05 | 0.45 |
| $^{60}$Co γ ray.      | 0.2   | -    | 7.74 | 0.25 | 91.37 | 0.06 | 0.37 |
| 45keV electron        | 0.18  | 1.08 | 15.19 | 0.44 | 79.54 | -    | 3.57 |

The results showed that the oxygen content on the surface of the samples increased after the two irradiation tests. This is because under the action of irradiation, the molecules of the high-pressure polyethylene heat-shrinkable sleeve are ionized, the molecular bonds are broken, and free radicals are formed. Oxygen molecules combine with free radicals to form C-O bonds, which cause an increase in the oxygen content of the sample after irradiation. This shows that the formation of free radicals caused by ionization damage is an important mechanism for the damage of heat-shrinkable sleeve. It
can also be seen from the results that the silicon content of the sample irradiated by electrons increased greatly. Combined with SEM observation results, electrons are likely to cause sputtering on the surface of the material, causing a small amount of polyethylene molecules to be completely destroyed, leaving silicon elements, which causes the surface silicon content to rise and the surface to have irregularities.

Figure 3 is the infrared spectrogram (FTIR) of the heat-shrinkable sleeve after different irradiation tests. Polyethylene is mainly \( \text{C}_2\text{H}_4 \) structure. From the infrared spectrum, it can be seen that there are 2928 \( \text{cm}^{-1} \) \( \text{CH}_2 \) anti-symmetric stretching vibration, 2850 \( \text{cm}^{-1} \) \( \text{CH}_2 \) symmetric stretching vibration, 1472 \( \text{cm}^{-1} \) \( \text{CH}_2 \) plane bending vibration, 731 \( \text{cm}^{-1} \) oscillating vibrations in the surface of the carbon chain and other main absorption peaks, and C-O vibration absorption peak near 1178 \( \text{cm}^{-1} \). The infrared spectrum of the heat-shrinkable sleeve after irradiation is compared with the original, the original characteristic peak becomes stronger, and the heat-shrinkable sleeve after irradiation increases the absorption peak of 1715 \( \text{cm}^{-1} \), corresponding to the C=O absorption peak, and the C=O absorption peak of the electron irradiated sample is significantly larger than that of the \( \gamma \)-ray irradiated sample. The absorption peak of C-O has also increased. It shows that after \( \gamma \)-ray and electron irradiation, the surface of the heat-shrinkable sleeve shows degradation and cross-linking [6][7].

**Figure 3.** Analysis of infrared spectrogram before and after the irradiated.
(a) Before irradiation. (b) Irradiated by \( \gamma \) ray. (c) Irradiated by electron beam

Analysis of the heat-shrinkable sleeve by different means shows that the chemical bonds that hold the atoms together of the polyethylene heat shrinkable sleeve change under the irradiation environment. This phenomenon can occur in both macromolecular main chains and branched chains. As a result, active free radicals, ionization or excitation are generated in the macromolecules and chemical reactions are initiated. Among them, the most basic reactions affecting the properties of the polyethylene heat-shrinkable sleeve are the cross-linking reaction and the degradation reaction. Cross-linking refers to the re-formation of new chemical bonds between molecules, and degradation refers to the breakage of polymer molecular chains. In fact, degradation reactions and cross-linking reactions often occur simultaneously. For the consistency of the damage mechanism of electron and \( \gamma \)-ray irradiation on polyethylene heat-shrinkable sleeve, it can be seen that the changes of surface morphology between electron and \( \gamma \)-ray is different, and \( \gamma \)-ray almost did not cause the changes of surface morphology of heat-shrinkable sleeve, while electron irradiation caused bulges and particles on the surface. However, from the perspective of molecular chain degradation and cross-linking, the two irradiation methods are consistent. Since the surface morphology may be related to the sputtering effect of electrons and does not have a dominant influence on the overall mechanical properties of the sample, it can be considered that the mechanism of micro damage caused by electron irradiation and \( \gamma \)-ray irradiation on heat-shrinkable sleeve is basically the same.
3.2 Property Damage Consistency Analysis
The mechanical properties of the samples after different irradiation tests are shown in Figure 4. It can be seen from Figure 4 (a) that the elongation at break of polyethylene heat-shrinkable sleeve increases first and then decreases under γ-ray irradiation. This may be related to the change of the leading role of polyethylene degradation and cross-linking in the irradiation process. At the beginning of the radiation, the received radiation dose is very low, cross-linking plays a major role, and the properties of the polyethylene heat-shrinkable sleeve increase. But when the irradiation continues, the degradation begins to dominate, the properties of the polyethylene heat-shrinkable sleeve begin to decline. Since the total dose of the γ-ray irradiation test is only $8.64 \times 10^7$ rad (Si), which is the dose received by the exposed material in the GEO orbit environment of about 9 months. When the radiation dose reaches the 15-year GEO orbital radiation dose, the polyethylene heat-shrinkable sleeve will be completely cracked and without mechanical properties [8]. Therefore, the mechanical properties of the polyethylene heat-shrinkable sleeve will eventually be completely lost under γ-ray irradiation.

Figure 4(b) shows the property change of the heat-shrinkable sleeve under 45 keV electron irradiation. It can be seen from the figure that under the electron irradiation, the properties of heat-shrinkable sleeve does not first rise and then decline, but shows a rapid decline and then tends to be stable. This is because the dose deposited at the electron minimum fluence point in the material is much higher than the radiation dose range when the degradation is dominant, so there is no increase in properties. In addition, after the electron irradiation reached a certain fluence, the properties of the polyethylene heat-shrinkable sleeve showed a stable trend, indicating that the electron irradiation could not completely destroy the polyethylene. The reason is that 45 keV electrons can only be deposited in materials of several micrometers thick, while the polyethylene heat-shrinkable sleeve has a certain thickness, and electrons cannot act on the entire material. Since only a very thin layer of material loses its properties, the mechanical properties of the polyethylene heat-shrinkable sleeve are not completely lost due to low energy electron irradiation.

In addition, the total electron fluence is $2.0 \times 10^{16}$e/cm$^2$, which is equivalent to the 15-year GEO orbital electron radiation environment. It shows that under the same irradiation dose, the polyethylene heat-shrinkable sleeve is more seriously damaged by γ-ray irradiation, while under electron irradiation, the degree of damage is small.

![Figure 4. The changes of elongation at break of the polyethylene heat-shrinkable sleeve in irradiations. (a) Irradiated by γ ray. (b) Irradiated by electron beam](image)

3.3 Analysis
The space electron radiation environment mainly induces ionizing radiation effects in materials. When the ionizing radiation effect on the polyethylene heat-shrinkable sleeve is carried out on the ground, from the damage mechanism of the material, both γ-ray sources and electron sources will cause degradation and cross-linking of polyethylene. Although there is a difference between electron irradiation and γ-ray irradiation in terms of surface properties, for bulk materials, this difference does
not affect the relationship between macroscopic property change and damage mechanism. Therefore, from the damage mechanism, the ionizing radiation effect of $\gamma$-ray source and electron source to the materials researched is consistent.

From the macroscopic mechanical properties of the polyethylene heat-shrinkable sleeve, the degree of damage of $\gamma$-ray source and electron source to the mechanical properties of the heat-shrinkable sleeve is very different. First, when the $\gamma$-ray source is used for irradiation, due to the large penetration depth of $\gamma$-rays, the whole heat-shrinkable sleeve is affected by the rays, and the mechanical properties decrease until they are completely lost. When the 45keV electron source is used for irradiation, due to the small penetration depth of electrons, only the superficial heat-shrinkable sleeve is subject to electronic action. The mechanical properties of the heat-shrinkable sleeve decrease and then tend to be stable. In the end, the mechanical properties will be stable at a value and will not be completely lost. Secondly, at the same dose, $\gamma$-ray irradiation damages the mechanical properties of the heat-shrinkable sleeve more, which may also be related to the depth of $\gamma$-ray action. Only the surface properties of heat-shrinkable sleeve change under electron irradiation, so the overall property degradation is small. Through damage mechanism analysis and property damage analysis, it can be known that $\gamma$-ray can be used to study the ionizing radiation effect of materials in the space electron radiation environment, but it cannot be used to evaluate the change of the property damage degree of the material in the space electron radiation environment with the in-orbit time (the in-orbit time determines the radiation dose received by the material under the premise that the orbit is known). When evaluating the property damage of materials, it is necessary to select appropriate electron sources according to the dose depth distribution of spatial electron radiation deposited in the materials and carry out related evaluation work.

4. Conclusions
This paper compares two test technologies commonly used to study the ionizing radiation effects of space electron radiation environment on spacecraft materials, namely the test technologies using $\gamma$-ray sources and electron sources as simulated radiation sources, respectively. The results show that both $\gamma$-rays and electrons can produce ionizing radiation effects on the material, resulting in degradation and cross-linking of the polyethylene heat-shrinkable sleeve. This is the micro-damage mechanism that causes the degradation of the macroscopic mechanical properties of the heat-shrinkable sleeve. In this point, the two test methods are consistent.

From the perspective of macroscopic mechanical property degradation of the heat-shrinkable sleeve, the $\gamma$-rays and electrons have different penetration depths, so there is a big difference in the damage of macroscopic mechanical properties of the material. $\gamma$-rays can cause overall damage to the material, while electrons can only cause damage to the material within the depth of electron penetration. And $\gamma$-rays damage the material more than electrons at the same dose. In this point, the two test methods are inconsistent.

In conclusion, when studying the ionizing radiation effect of spacecraft materials, $\gamma$-rays or electrons can be used as radiation sources to carry out tests; When assessing the degradation of the in-orbit performance of spacecraft materials, the electron source should be selected as the radiation source, and detailed test design and test research should be carried out according to the space electron radiation environment.

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