Electron irradiation effects on the mechanical properties of polyethylene

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Abstract. Studies on space electron radiation effect for evaluating property degradation of space materials are one of the important things for exposing the faults of the materials in orbit. Here the influence of electron flux and energy on the electron irradiation effect of polyethylene that is one of the common materials in spacecraft has been studied. Due to the analysis results of SEM and FTIR, it is proposed that the irradiation damage mechanism of the materials is independent of electron flux and electron energy. The molecular structural modifications and chemical changes of the materials have all occurred after each electron irradiation test. But the degree of damage on the mechanical properties of polyethylene during the electron irradiation test is dependent on electron energy. The mechanical properties of polyethylene will completely be lost after electron irradiation when the energy of electron is above 1 MeV, and the polyethylene will be broken down.

1. Introduction
Materials launched into space are subjected to harsh environment involving trapped electrons [1]. These can lead to severe degradation of materials [2]. One key element for the materials that is planned for use in space involves the availability of relevant laboratory test data about electron irradiation effects on these materials. Although laboratory can provide electron irradiation source, the radiation environment simulated in laboratory is quite different to the actual space electron radiation environment [3-5]. Due to time and cost considerations, the test data of irradiation effects on materials in laboratory are almost always obtained from accelerated test protocols. Accelerated tests are usually preformed by applying high irradiation flux which is much higher than actual space electron radiation environment. Moreover the electron simulated in laboratory is usually monoenergetic, while energy of the space electron varies widely from keV to several ten MeV. So it is very difficult to evaluate the performance of a material in real space. It will be helpful by studying electron irradiation effects on the materials with different irradiation energy and flux to understand the degradation of a material in space radiation environment.

Polyethylene is one of the common materials in spacecraft, such as heat-shrinkable sleeves, structural materials [6]. Here we will present the electron irradiation effects on the mechanical properties of polyethylene under different irradiation conditions. It is found that the wide varieties of simulated radiation environments (energy, flux) induce a same dominant radiation effect, but the degrees of degradation effects are different.
2. Experimental

The experimental sample is polyethylene heat shrinkable tubing. The inner and external diameters of it are 0.8mm and 2.0mm respectively. The length of each tubings is about 50 cm.

Electron gun and liner electron accelerator is selected as simulated electron sources. The polyethylene heat shrinkable tubing is irradiated by electron beams with energy of 45keV preformed at Beijing Institute of Satellite Environment Engineering of China using a combined irradiation facility, and of 1MeV and 2MeV preformed at the Xinjiang Technical Institute of Physics and Chemistry Chinese Academy of Sciences using a Van de Graaff generator. The fluxes of electron is $2.0 \times 10^{10} \text{e/cm}^2/\text{s}$, $8.3 \times 10^{10} \text{e/cm}^2/\text{s}$, $2.33 \times 10^{11} \text{e/cm}^2/\text{s}$ and $4.05 \times 10^{11} \text{e/cm}^2/\text{s}$ respectively.

All the samples after electron irradiation were characterized by scanning electron microscopy (SEM, S-4800, Japan), fourier transform infrared spectroscopy (FTIR, Nicolet 510M spectrophotometer, USA), electro-mechanical universal testing machines (CMT4104, China). The mechanical properties of tensile strength were analyzed.

3. Result and discussion

The possibility of radiation simulator application is based on similarity of physical processes in materials causing property degradations under the space environment and under simulation sources. So the degradation mechanisms of polyethylene in each electron irradiation test should be same.

Figure 1 shows the SEM images of the test samples before and after electron irradiation under different conditions. The surface of the sample is very smooth before electron irradiation as shown in Figure 1 (a), but the morphologies of the samples changes a lot after electron irradiation. First, we compare the morphologies of the sample when the energy of electron is same, while the flux and fluence are different (Figure 1 b-d). There are many fissures on the surface of the sample after 1MeV electron irradiation when the electron fluence reaches $2.0 \times 10^{16} \text{e/cm}^2$ (Figure 1 b). If the flux of electron is higher and the fluence of electron is lower, less fissures has appeared as shown in Fig.1 d. If the flux of electron is low enough, no fissure will be obtained (Figure 1 c). All these mean that the fluence of electron is one of the key parameters which will determine the morphologies of the samples after electron irradiation. When the fluence of electron is high enough, some fissures will appear on the surface of polyethylene heat shrinkable tubings, which must lead to the degradation of mechanical properties of the polyethylene heat shrinkable tubings.

Second, we compare the morphologies of the sample when the flux and fluence of electron are same, while the energies are different (Figure 1 b, e, f). It presents that some fissures have been obtained on the surface of polyethylene heat shrinkable tubings when the energies of electron are above 1 MeV (Figure 1 b f). When the energy of electron is only 45keV, no fissure will appear. All these mean that the energy of electron is another key parameter which will determine the morphologies of the samples after electron irradiation.
Figure 1 SEM images of polyethylene heat shrinkable tubings before and after electron irradiations. (a) Before electron irradiation, (b-f) After irradiation with different irradiation conditions. (b) Energy, 1MeV. Flux, $8.3 \times 10^{10} \text{e}/\text{cm}^2/\text{s}$. Fluence, $2.0 \times 10^{16} \text{e}/\text{cm}^2$; (c) Energy, 1MeV. Flux, $2.0 \times 10^{10} \text{e}/\text{cm}^2/\text{s}$. Fluence, $0.6 \times 10^{16} \text{e}/\text{cm}^2$; (d) Energy, 1MeV. Flux, $4.05 \times 10^{11} \text{e}/\text{cm}^2/\text{s}$. Fluence, $1.6 \times 10^{16} \text{e}/\text{cm}^2$; (e) Energy, 45keV. Flux, $8.3 \times 10^{10} \text{e}/\text{cm}^2/\text{s}$. Fluence, $2.0 \times 10^{16} \text{e}/\text{cm}^2$; (f) Energy, 2MeV. Flux, $8.3 \times 10^{10} \text{e}/\text{cm}^2/\text{s}$. Fluence, $2.0 \times 10^{16} \text{e}/\text{cm}^2$

The fissures on the surface of polyethylene heat shrinkable tubings indicate that the polyethylene heat shrinkable tubings become brittle. So the molecular structure of polyethylene has been changed. To confirm this, the molecular structure of polyethylene before and after electron irradiation was analyzed by FTIR.

FTIR spectra of polyethylene before and after electron irradiation at various electron energies are presented in Figure 2. From the results obtained, it is worth noting that after electron irradiation, small structural modifications occurs as indicated the appearance of C=O stretching for carbonyl group (2928 cm$^{-1}$) and –CH$_3$ stretching group (1715 cm$^{-1}$). The absorbance at 731 cm$^{-1}$ (consecutive methylene linkages), 1472 cm$^{-1}$ (H-C-H bending of methylene group) and 2850 cm$^{-1}$ (H-C-H stretching of methylene group) for all the polyethylene decreases remarkably after electron irradiations. All these support the occurrence of chain crosslinking as well as scissioning and breaking down of network structure in polyethylene during the electron irradiation process, which is accordance to the SEM results [7-9].
The tensile strength values ($\sigma$) of polyethylene are presented in Figure 3 as a function of electron fluence. It is shown that the tensile strength values of all the samples decrease gradually during electron irradiation, no matter what the electron irradiation conditions are. The degradation of tensile strength will be stable when the electron fluence is high enough about $2 \times 10^{16}$ e/cm$^2$. But if the electron irradiation energy is different, the degradation of tensile strength of polyethylene is different. When the electron irradiation energy is 45 keV, the tensile strength will decrease to 2/3 of the original value. If the electron irradiation energies are 1 MeV and 2 MeV, the tensile strength will decrease to zero, which means the polyethylene heat shrinkable tubings lose all their tensile strength. All the fissures shown in Figure 1 also prove that.

It is easy to understand that the tensile strength values of polyethylene will decrease with the increase of exposed electron irradiation fluence until the values are gradually stabilized. But the results between 45 keV and 1 MeV or 2 MeV electron irradiations are quite different. To explain this phenomenon, the maximum electron ranges in polyethylene were calculated by CASINO software. The results present that the maximum electron ranges of 45 keV electrons in polyethylene is about 40 $\mu$m, while 1 MeV and 2 MeV are about 5 mm and 12 mm respectively. The total thickness of polyethylene heat shrinkable tubing is about 2.4 mm. So the energy of injected electron will depose in a very low layer in polyethylene heat shrinkable tubing when the electron energy is 45 keV. Part of the mechanical properties of the polyethylene will be lost. While the electron energies are 1 MeV and 2 MeV, the energy of injected electron will depose in the whole polyethylene heat shrinkable tubing. So the mechanical properties of the polyethylene will be completely lost. The polyethylene heat shrinkable tubing will be broken down as shown in Figure 4 when the fluence of higher energy electron is high enough.
Figure 4 The photo of polyethylene heat shrinkable tubing after 1 MeV electron irradiation with fluence of $4.0 \times 10^{16} \text{e}/\text{cm}^2$

4. Conclusion

The mechanical properties of polyethylene have been studied after various irradiation conditions, such as electron energy and flux. Molecular structural modifications and chemical changes have occurred in the polymeric chains during electron irradiation process. The effect of irradiation dose on the tensile strength of polyethylene shows that mechanical properties of the polyethylene shall be partly lost when electron energy is 45 keV, and be completely lost when electron energy is 1 MeV or 2 MeV. The evolution of the mechanical properties coincides perfectly with the molecular structure variation and chemical changes deduced from SEM image and FTIR spectra.

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