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An experimental study of low earth orbit atomic oxygen and ultraviolet radiation effects on a spacecraft material – polytetrafluoroethylene

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Abstract

Spacecraft traveling in low earth orbit (LEO) will react with environmental factors, such as atomic oxygen (AO), ultraviolet radiation (UV) and vacuum ultraviolet radiation (VUV), which may severely affect the lifetime of the spacecraft. Teflon, including PTFE (polytetrafluoroethylene) Teflon and FEP Teflon, is a commonly used spacecraft material. Existing studies showed that Teflon could be eroded by AO in LEO but with a lower erosion yield than most of other spacecraft materials. However, its erosion yield increases in long-term flight experiments, which might be caused by synergism of several environmental effects. In this work, experiments were conducted to investigate the erosion effects of atomic oxygen on PTFE Teflon in a ground-based simulation facility. The samples, before and after the experiments, were compared in appearance, mass, surface morphology, optical properties and surface composition. We also analysed the influence of temperature, ultraviolet radiation and vacuum ultraviolet radiation on the atomic oxygen effects. Four conclusions can be drawn: first, PTFE Teflon is eroded severely in the ground-based facility, where the erosion yield is higher than that in the flight experiments and identical to those from other ground-based facilities. Secondly, the erosion yield increases with the sample temperature. Thirdly, ultraviolet radiation has little effect on the mass loss and erosion yield of the Teflon sample in the AO experiment. Lastly, there may be some synergistic effects of atomic oxygen and vacuum ultraviolet radiation, which could be one of the main factors that cause the more severe erosion of Teflon.

Keywords: Spacecraft materials; Low earth orbit; Atomic oxygen; Vacuum ultraviolet; Polytetrafluoroethylene

1. Introduction

Various kinds of spacecraft, such as space shuttles, spaceships and space stations, are all traveling in LEO. Previous studies indicated that the LEO environmental effects, such as AO, UV, VUV and thermal cycling, might affect the normal operation and the lifetime of spacecraft. Among them, AO is the predominant and the most active component of LEO atmosphere. It causes many spacecraft materials to erode and degrade. The reason is that AO is highly oxidative and can react directly with materials. When the spacecraft is flying in LEO at an orbital velocity of 7–8 km/s, AO flux is approximately 10^{12}–10^{15} atoms/(cm^2 s) and the energy that AO impinges on the spacecraft surface is about 5 eV. These may result in the erosion and property degradation of surface materials [1,2]. Consequently, the lifetime of spacecraft will be shortened. Therefore, the study of the AO effects is a crucial area of the LEO environmental effects research. In addition, although the

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total energy of solar UV and VUV radiation, whose wavelength is from 100 to 400 nm, is only approximately 8% of the solar constant, they have shorter wavelength and their photon energy is high enough to cause surface molecule activation and some organic bond breakage, resulting in degradation of the properties of the spacecraft materials [3,4]. In addition, the synergistic effects of AO and UV or VUV may cause more severe erosion of some spacecraft materials.

Teflon is a commonly used spacecraft material. In the early short-term space flight experiments EOIM1 ~3 with the flight duration of approximately 40 h, Teflon was stable and the erosion yield was $\leq 0.05 \times 10^{-24}$ cm^3/atom [5–7]. This value is approximately 1/50 of the erosion yield of other polymers such as Kapton, Mylar, polyethylene and polysulfone. However, subsequent experiments indicated that the erosion yield of Teflon increased in long-term space flight experiments. For example, in the Lockheed Space Flight Experiment (LSFE) the average erosion yield of Teflon during its 105 days exposure was 0.13×10^{-24} cm^3/atom [8]. Furthermore, in Long Duration Exposure Facility (LDEF), which flew in LEO for 69 months, the erosion yield of Teflon was about 0.34×10^{-24} cm^3/atom [6,8,9]. These values are significantly higher than those from the short-term space flight experiments. Some researchers pointed out that the AO-induced erosion on Teflon in LEO is also a function of UV and/or VUV exposure level [9,10]. This suggests that there are synergistic effects between AO and UV or VUV on Teflon. In a research report of NASA Lewis Research Center, it was indicated that Teflon surfaces would form a hard and brittle layer after the space flight experiments and the brittleness was increased with the decreasing of the AO/solar fluence rate. For example, compared with LDEF (5.8 years in LEO), the altitude of HST (3.6 years in LEO) is higher and it exposed to more solar radiation and a lower AO flux. As a result, the embrittlement of the Teflon samples on HST was more severe than that on LDEF [9]. These results suggested that there may be some synergistic effects of AO and UV or VUV radiation.

The experiments described here were conducted in the ground-based simulation facility of Beijing University of Aeronautics and Astronautics (BUAA) to study the reaction characteristics of Teflon in LEO, quantify AO erosion effects and qualitatively analyse the influence effects of UV, VUV radiation and temperature on the AO erosion effects of Teflon.

2. Experimental facility

The ground-based space environmental effects simulation facility of BUAA was designed by ourselves. It consists of the experimental system for AO effects, UV radiation effects and VUV radiation effects experimental system, etc.

2.1. The AO effects experimental system

The configuration of the AO effects experimental system is shown in Fig. 1. The system is a hot cathode filament discharge plasma-type facility and consists of several subsystems, such as the hot cathode filament discharge, surface-restrained multiple magnetic and parameters diagnostic subsystem. The operating principles of the experimental system are: the influx of the oxygen into the vacuum chamber is controlled by a flow controller to reach a certain working pressure, and then the cathode filament is heated electrically. When the temperature is high enough, the surface of the cathode filament begins to emit electrons. The discharging voltage between the filament and the vacuum chamber walls accelerates the electrons to reach a sufficiently high-energy level. The oxygen plasma is formed through the collision ionisations and dissociation of oxygen molecules by electrons. The main components of the plasma are O_2, O_2^+, O, O^+ and e.

In addition, a large number of permanent magnets are arranged alternately by polarity (north and south) on the top and side walls of the vacuum chamber. So a surface-restrained multiple magnetic field is formed at the chamber surface to reflect the electrons flying toward the chamber walls back into the plasma. In this way the density of the electrons is increased. Meanwhile, the magnetic field exists only near the surface of the chamber walls. The magnetic field intensity at a distance of 4 cm from the chamber surface is reduced to 1% of the surface intensity (the chamber diameter is 30 cm).

The important characteristics of this system are: (1) the lifetime of the filament is long, and can reach up to 50–100 h; (2) restrained by the surface multiple magnetic field, the electron density can be increased by two orders to reach 10^{10}/cm^3; (3) the plasma has a nice uniformity – the measurement shows that the plasma is uniform within the diameter of 16 cm in the vacuum chamber; and (4) the AO flux is approximately 10^{17} atoms/(cm^2 s), which is larger than the ionic oxygen flux of 10^{14} ions/(cm^2 s). A detailed introduction to the system configuration and operating characteristics of this AO effects experimental system are available in Refs. [11,12].

2.2. The UV radiation effects experimental system

The UV radiation effects experimental system consists of a UV radiation source, electric heating film and their power supply, etc. The arrangements of each part of the system are shown in Fig. 2. The UV radiation source is a Hamamatsu-L613 deuterium lamp, with a length of 70 mm and a diameter of 30 mm. The power