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Degradation modeling of satellite thermal control coatings in a low earth orbit environment

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ABSTRACT

Thermal control coatings are widely used in passive thermal control systems of satellites. These coatings ensure that the temperatures remain within the safe operating limits. The purpose of this paper is to present a degradation modeling method for thermal control coatings used in satellites in a low earth orbit (LEO). The materials investigated in the present study include the S781 white paint and the F46 second surface mirror. The LEO environmental factors that cause the degradation of these materials and the corresponding failure mechanisms are discussed first. With in-orbit telemetry temperatures, an energy balance equation is used to calculate the solar absorptance of the coatings on several LEO satellites. Results show that the solar absorptance of the coatings degrades significantly over time and can thus be used as a crucial performance parameter for the characterization of coating degradation. A Wiener process with time transformation is used to model the nonlinear degradation characteristic of solar absorptance. The first hitting time is employed to model failure time with consideration of a critical degradation level. The degradation modeling method is accurate, and the results provide insight into the life prediction and thermal design optimization of LEO satellites.

1. Introduction

Low earth orbit (LEO) satellites frequently encounter various extreme environmental conditions such as drastic temperature excursion. In sunlit periods, one side of a satellite directly faces the sun, whereas the other side faces cold space. This state causes a large temperature gradient between the different parts of the satellite. In non-sunlit periods, both sides are exposed to cold space. Many satellite subsystems, however, require a small temperature range to ensure their precision and efficiency. Thus, a thermal control system is indispensable such that it ensures a satellite temperature that remains within safe operating limits (Chen et al., 2012). Generally, engineers divide the thermal control systems into two categories: passive and active. The passive thermal control system is frequently adopted in LEO satellites. The passive thermal control system utilizes various thermal control coatings with requisite solar absorptance (α_s) and thermal emittance (ε_h). As a result, the coatings can help stop heat getting in on the sun-facing sides and getting out on the shadowed sides.

Surveys on several returned satellites have revealed that complex space environments have unfavorable effects on coating materials, causing surface recession and mass loss in satellites and impairing the satellite's optical efficiency (Novikov and Chernik, 2006; Shen et al., 2009). Recently, satellites with high reliability and long mission durations are in demand due to increasing engineering requirements. However, the prolonged exposure of coatings to complex space environments usually results in degraded coating system performance and may cause premature mission failure. In the past few years, the degradation of thermal control coatings has become a significant obstacle to the success of satellite missions. For these reasons, degradation modeling of thermal control coatings is highly significant in the design and application of long-lifetime satellites.

Generally, LEO satellites require thermal control coatings with a low-α_s and high-ε_h to resist high temperatures during the sunlit periods. Unfortunately, research shows that the aging and recession of most coating materials increase the value of α_s gradually and consequently induces a long-term temperature increase in satellites. In the past decades, many ground-simulation tests have been conducted to study the influence of a space environment on coating material degradation. Several ground-based simulators, such as the CEETC2 in the National Aeronautics and Space Administration (NASA), CEETC3 in the Marshall Space Flight Center (MSFC), and SEMIRAMIS in the French Office National d'Etudes et de Recherches Aerospatiales (ONERA), are well-known. Sharma

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and Sridhara (2012) performed a long-term radiation test on the northern and southern faces of a stabilized satellite to simulate three years of a geostationary orbit. They tested various coating materials, such as white paint, white anodizing, multilayer insulation materials, varnish coated aluminized polyimide, and germanium coated polyimide. Their results showed that the solar absorptance values of nearly all these materials increased after ultraviolet and particle irradiation, whereas the emittance values of all the samples had negligible changes. In ONERA (Marco et al., 2003), the effects of exposure of certain coatings to a given space environment, including ultraviolet, proton, and electron, were studied. Furthermore, Marco et al. (2003) proposed three empirical models based on the exponential function to model solar absorptance degradation over time. Through the ∅800 mm vacuum-combined radiation system, Liu (2008) studied the solar absorptance degradations of the S781 and SR107 white paints. They also developed an exponential model that predicts the solar absorptance changes of the two coatings in a combined radiation environment.

However, no ground-based simulators can thoroughly simulate a complete orbital environment (Angirasa and Ayyaswamy, 2014). Compared with simulation tests, telemetry data are more useful and valuable in the analysis of thermal control coating degradation. Until now, few studies have analyzed solar absorptance changes in the coatings of satellites during in-orbit flight. The solar absorptance increase in the 16 types of thermal control coatings have been studied and modeled through 10-year telemetry data from the P78-2 satellite launched in 1979 (Hall and Fote, 1991). The study of Naegeli (2012) described the solar absorptance increases of fused silica optical solar reflectors on the geosynchronous satellites SPACENET I and SPACENET II, which were built by the GE Astro Space Division and launched in 1984.

In recent years, degradation models based on the stochastic process have attracted significant attention (Kharoufeh and Cox, 2005). As a well-known stochastic process, the Wiener process is widely used in degradation modeling and reliability assessment because of its favorable mathematical properties (Balka et al., 2009; Wang et al., 2014). A Wiener process is stochastic in nature because of its inherent randomness in manufacturing, materials and operating environment; thus, the model is suitable for the degradation of satellite components in a complex space environment. For example, Jin et al. (2013) used the Wiener process to model the capacity fading of secondary batteries in spacecrafts and predict their residual life. Li et al. (2015) proposed a Wiener model for satellite momentum wheels and then used it to conduct reliability estimation and life prediction.

The objectives of this paper are twofold: (1) to investigate the failure mechanisms of S781 white paint and F46 SSM in LEO environment, and (2) to quantitatively model the solar absorptance degradation of the two coatings. We first analyze the damaging factors in LEO satellites that cause the coating degradation, and we then focus on the thermal, chemical, and physical interactions between the coating materials and these factors. An in-orbit flight experiment with three LEO satellites is conducted to evaluate the degradation of the two coatings. Temperature measurements are obtained in this experiment to monitor the evolution of the solar absorptance. Based on the failure mechanisms analysis, a Wiener process with time transformation is used to model the increase of solar absorptance over time. We employ the concept of first hitting time (FHT) to describe the time when the solar absorptance reaches a specified critical value. We then compare the reliability of S781 white paint and F46 SSM.

The remainder of this paper is organized as follows. The compositions, properties, and failure mechanisms of S781 white paint and F46 SSM in a LEO environment are analyzed in Section 1. Section 2 discusses the in-orbit telemetry data from the three LEO satellites. In Section 3, the content of the degradation modeling and analysis of the results are conducted. Conclusions are provided in Section 4.

2. Failure mechanisms analysis

2.1. Coating composition

S781 white paint and F46 SSM are widely used in LEO satellites because of their low solar absorptance and high infrared emittance. The coatings studied in this paper are both developed by the Shanghai Satellite Engineering Research Institute. The compositions of the two coatings are shown in Figs. 1 and 2.

As shown in Fig. 1, the S781 white paint (S781) comprises zinc oxide (ZnO) and organic binder, such as silicone rubber, silicone resin, and epoxies resin. The ZnO works as the white pigment because it is chemically stable, nontoxic, and cheap. The organic binder of S781 is epoxies resin. Given its light weight, S781 can be readily painted on various metal and nonmetal satellite surfaces.

Fig. 2 depicts the composites and schematic drawing of a silver-backed F46 second surface mirror (F46 SSM). The silver reflector is metalized on one side of the F46 layer, which is a polymer material composed of fluorinated ethylene propylene (commercially known as FEP). Given that F46 is transparent, most of the solar radiation passes through it and is reflected by the silver backing. Thus, the silver layer is called a second surface. The SiOx layer works as a binder that attaches the silver reflector and satellite surface. To protect the F46 layer from atomic oxygen (AO) erosion and charge accumulation, a conducting indium tin oxide (ITO) film with adequate thickness (~100 nm) is tacked on as the outer layer. The main characteristics of F46 SSM are its excellent emission of infrared radiation and its high resistance to ultraviolet radiation. Thus, F46 SSM is widely used in satellite coatings and cover slips for solar cells.

2.2. Low earth orbit environment

The LEO has an altitude of 160–1500 km. The LEO is useful for scientific satellites, such as those used to measure various atmospheric parameters. Harsh environments are a challenge for LEO satellites. Unlike the geosynchronous orbit (GEO) environment, the LEO environment abounds in atomic oxygen, ultraviolet radiation, vacuums, charged particles, micrometeoroids, and space

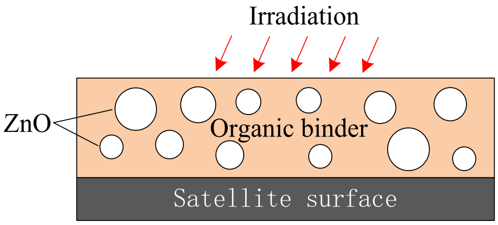

Fig. 1. Composites of S781 white paint.

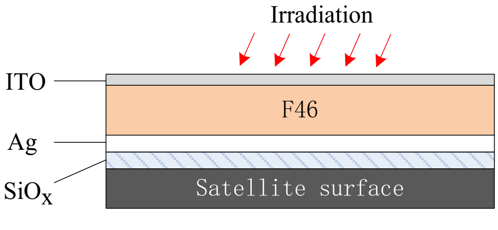

Fig. 2. Composites of F46 SSM.