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Organic polymer materials in the space environment☆

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ABSTRACT

The space environment is a complex environment full of microgravity, high vacuum, high and low temperature, strong radiation and plasma. Polymers used in the space environment will inevitably experience aging and degradation which result in changes of the material mechanics, physics and chemical properties, until they lose usefulness. To make a material that can be used for a long time and whose performance is not changed in the space environment, its ability to resist environmental factors must be excellent. Therefore, this paper provides an introduction to the harmful conditions in the space environment and their effects on the polymers, also it reviews the aging mechanisms of the adhesives used in the space environment and the effect of thermal cycling, stress, electromagnetic radiation and ionizing particles on the properties of polymers and optical devices, to provide the reference basis for selection, modification and reliability analysis of materials used in the space environment.

Contents

1. Introduction . . . 38
2. The space environment and its effect on organic materials . . . 38
   2.1. High vacuum . . . 38
   2.2. Thermal cycling . . . 38
   2.3. Charged particle irradiation . . . 39
   2.4. Solar electromagnetic radiation . . . 40
   2.5. Atomic oxygen . . . 40
3. Effects of space environment on polymeric materials . . . 41
   3.1. Adhesive . . . 41
   3.2. Packaging material . . . 41
   3.3. Adhesive tape . . . 42
   3.4. Coating material and oil paint . . . 44
4. Aging mechanism of polymers in space environments . . . 44
   4.1. High-temperature aging . . . 44
      4.1.1. High-temperature aging of silicone rubber . . . 44
      4.1.2. High-temperature aging of epoxy resin . . . 45
      4.1.3. High-temperature aging of acrylic resin . . . 45
      4.1.4. Thermal degradation of nylon polymers . . . 45
   4.2. Low-temperature aging of adhesive . . . 46
   4.3. Radiation aging mechanism . . . 46
   4.4. Charged particle aging mechanism . . . 47
      4.4.1. Theoretical analysis . . . 48
   4.5. Thermal vacuum environment aging mechanism . . . 49
5. Space physical field on polymer, optical device properties . . . 50

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0376-0421/

5.1. Temperature field effect 50
5.2. Mechanical field effect 51
5.3. Radiation field effect 52
5.4. Atomic oxygen effect 54
6. Conclusions and outlook 55
Acknowledgments 55
References 55

1. Introduction

Due to their high toughness, high elasticity, good insulation, low density, high or low melting point, easy molding processing, molding, etc, polymeric materials have been widely used in the aerospace technology [1–5]. For example, Wright [6] reviewed the aerospace applications of polymers , including adhesives, coatings, all kinds of fibers, and composite and nanocomposite materials. These polymer materials are used as lubricants, insulating paint, temperature control cladding materials, PCB (Printed Circuit Board), optical fiber materials for optoelectronic devices and high strength composite materials in spacecraft.

The space environment is very demanding on materials as they need to maintain performance under the impact of thermal cycling, high vacuum, space radiation, atomic oxygen, tiny meteoroids and space debris [7–11]. Outgassing has always been a concern for organic materials under vacuum and thermal cycle as it will cause changes in material composition, dimensions, and ultimately performance of materials [12]. The outgassing products condense on the surface of sensitive components, causing pollution and corrosion, performance reduction of sensitive devices, and even material failure [13–16]. Since polymeric materials are widely used in aerospace electronics bonding and encapsulation, their structural change will directly affect the performance and reliability of the sensitive components and parts, and may endanger the human lives in the spacecraft [17–19]. For example, Cynthia L. Lach et al [18] analyzed the effect of temperature and gap opening rates on the resiliency of candidate solid rocket booster O-ring materials. The deformation failure of the rubber O rings on the "Challenger" solid rocket caused its explosion. Therefore, a good understanding of the typical aging mechanisms of polymer materials during space flight conditions and the influence of the materials' structural and optoelectronic properties is critical to the selection, modification and reliability analysis of polymer material to be used during space flight. Flight experiments are critical to understanding the engineering performance of materials exposed to specific space environments. Likewise, the spacecraft designer must have an understanding of the specific environment in which a spacecraft will operate, enabling appropriate selection of materials to maximize engineering performance, increase mission lifetimes, and reduce risk. David et al [20] presented a methodology for assessing the engineering performance of materials baselined for a specific spacecraft or mission, and provided an overview on the effects of the space environment on materials performance. Miller and coworkers [21] briefly discussed and gave examples of some of the degradation experienced on spacecraft. They also discussed the use of ground and space data to predict durability. NASA [22] and ESA [23] developed specifications for the selection of polymer materials for space use. Fayazbakhsh [24] presented a method of materials selection for applications in the space environment considering the outgassing phenomenon. These studies have important implications for the research on aerospace materials, as well as the selection and performance evaluation of aerospace materials.

On this basis, this paper provides an introduction to the harmful conditions in the space environment and its effect on the polymers. It also provides a review of the aging mechanisms of the adhesives used in the space environment and of the effect of thermal cycling, stress, electromagnetic radiation and ionizing particles on the properties of polymers and optical devices.

2. The space environment and its effect on organic materials

The space environment [25] includes both the natural space environment caused by natural factors and the artificial space environment caused by human factors. The near-earth space environment is the most active area for current spacecraft. It exposes the spacecraft to a high vacuum, high and low temperatures, ultraviolet radiation, atomic oxygen corrosion, proton and electron irradiation, space plasma radiation, micro meteors, space debris, etc. The environment therefore will affect the spacecraft's orbit and attitude, and will cause radiation, mechanical and chemical damage. It will also affect spacecraft systems, such as charge/discharge, communications, measurement and control system, etc. [26–27]. These effects are discussed in more detail.

2.1. High vacuum

Materials exposed to a vacuum environment for a long time will experience outgassing from the surface of the material. The main consequences of outgassing are the contamination of surfaces, loss of dimensional stability and some other detrimental effects on material properties. The contamination problem becomes severe when the contaminant layer undergoes fixation by interacting with other space environmental components like ultraviolet radiation, thermal cycles or atomic oxygen. An example is given by Banks et al [28] for silicone contamination interacting with atomic oxygen and forming a stable SiO_2 layer. The outgassing process not only affects the material's performance, but volatile substances may produce pollution on the surface of the optical devices, causing a performance degradation of nearby sensitive devices. This is very harmful to the whole spacecraft [29]. The standard materials contamination screening procedure, ASTM E-595 [30], obtains the outgassing properties of materials by measuring the total mass loss (TML), collected volatile condensable materials (CVCM) and the water vapor regain. Values for TML of $\leq 1\%$ and CVCM of $\leq 0.1\%$ are acceptable for standard space systems. Patrick [31] reviewed the vacuum properties of TML (Total Mass Loss) and CVCM (Condensed Volatile Condensible Material) for some typical spacecraft materials which show significant outgassing, as shown in Table 1.

2.2. Thermal cycling

The spacecraft ambient temperature changes as it enters and exits the earth's shadow. The temperature fluctuates greatly with change of altitude, season and presence of thermal protective measures. During a 90 min low earth orbit cycle, the surface temperature of the spacecraft commonly fluctuates from -100 to