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Numerical simulation on atomic oxygen undercutting of Kapton film in low earth orbit

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ABSTRACT

A Monte Carlo model describing the interaction between atomic oxygen undercutting with polyimide Kapton film of spacecraft surfaces in low earth orbit is presented. The physical process of atomic oxygen undercutting is elaborated and a binary chained list optimization technique is used to reduce computations. In order to analyze the impact–reaction probability in three-dimensional space, a new mathematical impact–reaction probability based on the mapping theory is established to be the important reaction parameter for predicting the difference of undercutting patterns between two-dimensional and three-dimensional spaces. Numerical simulations are carried out with different initial defect widths, orbit inclination angles, thermal assimilation–reaction coefficients and thickness of protective layers, as well as their combining action conditions. Results agree well with the NASA long duration exposure facility experimental data. The maximum undercutting depth is larger than the maximum undercutting width at all times, which reduces with increase in orbit inclination angle, thermal assimilation–reaction coefficient, three-dimensional space and thickness of the protective layer. Comparing three- and two-dimensional spaces, the maximum depth is decreased by approximately 20% for 28.5° orbit inclination angle.

1. Introduction

Low earth orbit (LEO) environment can cause considerable damage to vulnerable spacecraft materials, which experience a severely rugged environment, including atomic oxygen (AO), ultraviolet radiation, thermal cycling, micrometeoroid and debris bombardment [1–10]. AO, the predominant species in LEO, has about 8 km/s impacting velocity at ram impact velocities, corresponding to the total kinetic energy of 4.5 eV with the character of extreme reactivity [11]. Because the space temperature of LEO is about 1200 K, the thermal motion of AO must be considered. Thus, the relative impacting velocity is the addition of thermal motion velocity and spacecraft ram velocity vectors [12]. Spacecraft materials that are susceptible to oxidation must be protected for long durations in LEO to prevent out-of-operation condition of thermal control protection or degradation of several materials' properties. Hence it is very important to understand the detailed erosion processes that occur at various AO environments.

To date, most of the ground-based experimental data are simulated and obtained in the low AO fluence conditions. Its drawback is it cannot meet the requirements of high dose AO fluence in orbit environments. Meanwhile, the quantity of ground-based test data is inadequate due to the limitation of test conditions such as expensive cost of equipment, expenditure of test and long periods of test operation. Therefore, it is very important to make use of a reasonable

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Nomenclature

D	diameter, thickness
equ.	equivalent
E	erosion reaction coefficient
F	fluence
H	height
L	length
N	number
W	width
R	reaction
P	probability
θ	impact angle

physical and mathematical model as well a numerical simulation technique to predict and to provide a large quantity of accurate data for practical spacecraft designation. Of course, the model and source code must be validated by flight data.

A Monte Carlo model describing the interaction between atomic oxygen undercutting (AOU) with polyimide Kapton film of spacecraft surfaces in low earth orbit has been used widely [13–21]. Its function is to accurately predict the AOU patterns in both space and ground-based AO environments, and to provide a large quantity of reference data for implementing effective protection. Based on ground-based undercut profiles at scratch sites, the computation model is utilized to simulate the erosive effects between AO and volatile oxidation products (Kapton film) at defect sites in protective coatings where atomic oxygen impacts the oxidizable material. Previously, Bitetti et al. [10], Anon [11], Bourassa and Gillis [12], Banks et al. [13,14] and Barid [18] had compared the MC predicted results with actual space flight samples, which helps us to understand and to improve the MC model. The purpose of this paper is to explore the AOU effects caused by various LEO environments and validate by the NASA long duration exposure facility experimental data [19]. The variations of undercutting patterns, such as maximum undercutting depth, are further studied under complex orbit environments.

2. Physical process and mathematical model of undercutting

2.1. Physical process

The physical process of AOU is assumed to be a particle transport procedure. Space flight test indicated that erosion occurs at microscope defects in protective coatings (see Fig. 1). When AO collide with protective Kapton films and cause defects, the reaction occurs at the initial collision–reaction probability. The reacted AO are absorbed and the unreacted AO continue to complete their transportation course by means of diffusion or mirror reflection. If AO collide again with the Kapton film, reaction or reflection must occur at the new collision point. At the beginning of contact between AO and Kapton material, the film surface takes on a flat profile and erosion holes are still not formed. Most of the unreacted AO are reflected to the space environment. Immediately after erosion holes are produced, the possibility of unreacted AO getting reflected to space environment is reduced. Thus, reaction probability increases with increasing of impact opportunity. Until absorption from erosion hole at defects, AO would be reflected continually and react with the Kapton film in accordance with the defined reaction probability (see Fig. 2).

2.2. Mathematical model

2.2.1. Assumption conditions

(1) For defects or scratches in protection coating, AO motion direction is limited to the vertical normal plane from material surface. (2) The atomic oxygen velocity vectors have random orientations and their speed distribution is Maxwellian, which cause the AO impact velocities to be distributed in directions and energies. (3) Protection coating will not take part in the reaction of AO and the mean free path of AO is too large for recombination and formation of oxygen molecules. (4) After impact between AO and the material, the reflected rays of unreacted AO are classified into diffuse reflection and mirror reflection. In diffuse reflection, thermal exchange occurs because kinetic energy of AO is equal to the speed of thermal atomic oxygen. At the same time, AO will depart from the surface by means of diffuse reflection. The distribution direction must be in compliance with the law of cosine distribution. In mirror reflections, AO maintain the identical energy and also the same impact–reaction probability in the next collision.

2.2.2. Monte Carlo simulation

The film consists of an orthogonal array of square cells, which represents a uniform grid exposed to simulated oxygen atom impacts in two-dimensional space. Model atoms are driven to enter the defect and impact the

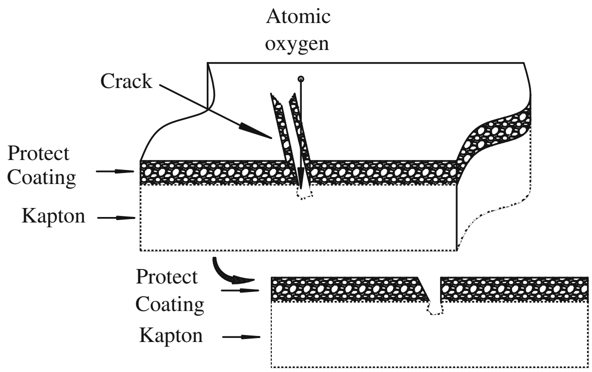

Fig. 1. Undercutting defect site.