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Study of Space Microimpacts on Solar Cells and Evaluation of Resultant Degradation

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Space microdebris effects were simulated on a newly developed coaxial plasma accelerator; characteristics of damage morphologies on cover glass and the damage equation, which describes the dependence of damage morphology dimension on the impact parameters, were obtained. The methods to evaluate surface damage ratio and transmittance degradation of solar cells were investigated and applied to a typical sun synchronous spacecraft. For a lifetime of 10 years, the surface damage ratio of solar cell is 0.61 percent on average and amounts to 2.3 percent in the worst case. The averaged and most severe possible transmittance degradations are 0.5 and 1.5 percent, respectively.

I. Introduction

MICRODEBRIS, which composes the most part of the space debris flux, may pose significant threat to exposed materials and components on spacecrafts by hypervelocity impacts. The returned samples from the long duration exposure facility (LDEF) [1], Hubble Space Telescope (HST) [2], European retrievable carrier (EURECA) [3], etc., have shown intense micropits and perforations after years of exposure. According to the calculation by MASTER-2005, more than 99.9999% of the total debris flux in geosynchronous Earth orbit (GEO) and sun synchronous orbit (SSO) regions is attributed to microdebris smaller than 1 mm, although they occupy no more than $0.1\ 10^6$th in mass. Therefore, the microdebris may have significant influence for their dense population although the damage by single impact is less dangerous.

Solar cells, as brittle components, are particularly endangered. Because of the high relative impact velocities of up to 15 km/s the damaged region is enlarged with respect to ductile materials. Typical damaged area on the cover glass consists of a central pit surrounded by a large spallation zone, approximately 10 times the incident particle size, and for oblique incident particles the damaged area is lager [4,5]. Apart from the direct damage, clouds of secondary fragments generated by the primary impact also cause further damages and pollution to solar cells. For space missions of long lifetime, cumulated microimpacts may lead to continuous functional degradation and even destruction.

In this paper, the major characteristics of microimpact to solar cell are investigated on a newly developed coaxial plasma accelerator. Based on the simulation results, the damage equation for cover glass was established, and a primary model for assessing solar cell surface damage and degradation due to microimpacts was accomplished and applied to SSO solar cell degradation prediction.

II. Hypervelocity Microimpact Simulation

A. Coaxial Plasma Accelerator

All experiments were performed on a newly developed coaxial plasma accelerator [6]. As shown in Fig. 1, the accelerator mainly consists of coaxial gun, compression coil, capacitor banks, and ignition switch. When the switch is closed, the working gas in the coaxial gun is breakdown under high voltage and a plasma is produced, which is then continuously accelerated to a speed of tens of km/s by a magnetic pressure of $\mathbf{j} \times \mathbf{B}$. As the plasma is pressed into the coil, it discharges to the turnings and generates a current in the coil. The helical current then induces a vortex current in the plasma, and their interaction leads to a compressing force and pushes the plasma into dense hypervelocity flow, which drags the particles on a Myler film placed against the nozzle into high speed.

The designed total deposited energy for the accelerator is approximately 100 kJ, and the launching speed mainly depends on the discharging energy, which is controlled by changing the capacitor voltage and number of capacitor banks. The facility can launch particles with diameters of $50 \sim 200\ \mu$m to velocities of $1 \sim 15$ km/s.

B. Experiment Arrangement

To simulate the space microdebris hypervelocity impacts, particles of $20 \sim 1000\ \mu$m were launched to velocities of $1 \sim 15$ km/s to impact solar cell cover glass samples (20 mm × 40 mm × 0.15 mm) pasted on an aluminum target perpendicular to the beam. During the experiments, particles of different materials such as corundum (Al_2O_3, $20 \sim 200\ \mu$m), glass (SiO_2, $50 \sim 200\ \mu$m), steel (Fe, $200 \sim 1000\ \mu$m), et al were applied to investigate the effect of debris density on the impact morphology. Because of fragmentation during acceleration the real projectile sizes had to be measured, for which a Myler film of 3 μm thickness was placed 10 cm in front of the target, and by measurements of the perforations on the film the projectile diameters were obtained. The experiment arrangement is displayed in Fig. 2.

The particle velocity was detected by piezoelectric sensors and optical scattering diagnostics, with the former placed at the back of the sample on the target and the latter installed in the flying tunnel. They generate transient signals induced by impacts or scattered light as particle arrives, according to fly time method the particle velocity can be obtained through the signals.

To study the dependence of the crater morphology on the impact parameters, the velocity, size and impact site for each incident particle have to be specified, for the convenience of which the launched particles were filtered by two skimmers installed at the ends of the tunnel to keep as little as possible particles to pass through. If two particles arrive at the sample in the same shot, their impact sites and velocity signals have to be distinguished from each other with the help of multiple piezoelectric sensors.

C. Experiment Results

Most hypervelocity microimpacts on solar cell surfaces tend to exhibit similar morphologies. A typical crater includes three regions [4,5] as shown in Fig. 3: the bowl shaped central pit (with diameter D_{pit}), surrounded by a halo of shattered glass (D_{halo}), then by a

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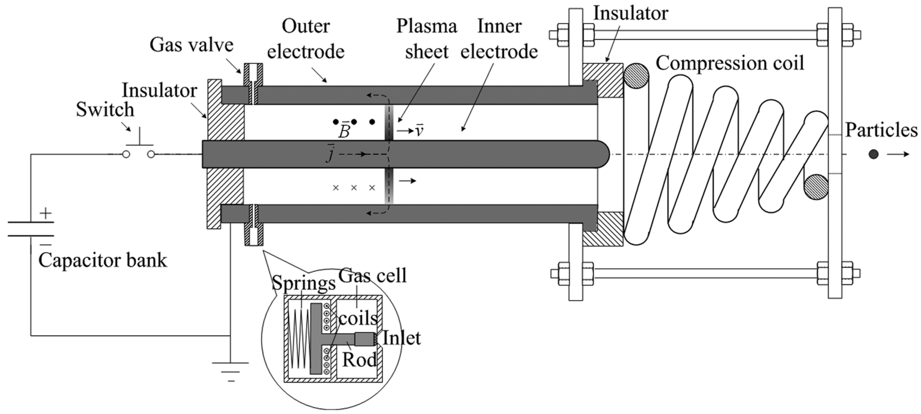

Fig. 1 Schematic diagram of the coaxial plasma accelerator.

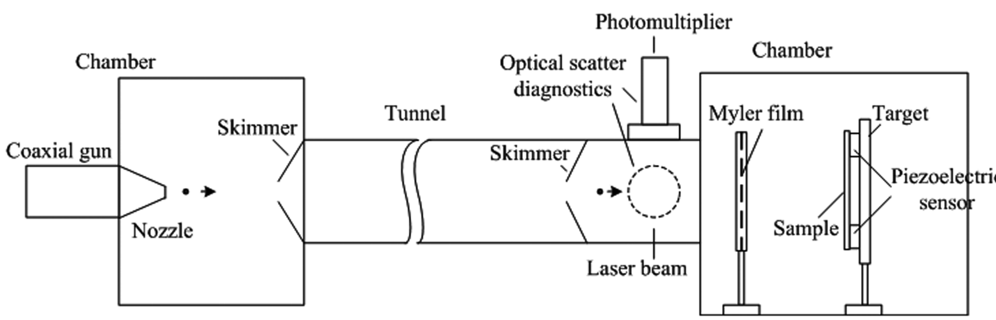

Fig. 2 Schematic diagram of the experimental arrangement.

conchoidal cracking zone (D_{co}). Radial cracks may occur around the outside of the impact. For some of the smaller craters, the shattered zone is ambiguous. The dimensions for every zone were marked under microscope, and statistical analysis was performed to find the general characteristics.

Statistics showed that the ratio of D_{pit}/D_p (D_p: particle diameter) mostly falls between 0.5 and 2 (Fig. 4), and that of D_{co}/D_{pit} between 2 to 10 (Fig. 5).

The damage area depends on the impact parameters including the size, velocity, and density of the incident particle and the properties of the target material [7,8]. The diameters of conchoidal zone D_{co} and central pit D_{pit} were used to describe the damage area, their dependence on the impact energy are presented in Fig. 6 and 7, respectively. By fitting with the formula $D = aE_p^\alpha$ the damage equations were obtained:

$$D_{pit} = 900E_p^{0.4} \tag{1}$$

$$D_{co} = 3708E_p^{0.35} \tag{2}$$

D_{pit} is diameter of central pit (μm), D_{co} is diameter of conchoidal zone (μm), and E_p is particle energy (J).

To be able to perform a conservative damage analysis, a modified damage law has to be used that covers the most damage scattering. The fitted curve that describes the largest possible damage due to scattering was plotted in Fig. 7 and denoted by "Conservative." In fitting the two upper most scattered data were neglected considering the abnormal scattering may be caused by wrong measurements. The equation describing the maximum damage is

$$D_{co\text{-}max} = 7128E_p^{0.35} \tag{3}$$

In the frame of this study, the angle dependence of the damage was not taken into account, for which many experiments were needed to generate statistics. However, the resultant uncertainties can be neglected because the angle dependence of the damage is weak [9].

With the damage equations, it is possible to evaluate the surface damage ratio and the degradation of the solar cell properties for space mission with long lifetime, which are introduced in the next section.

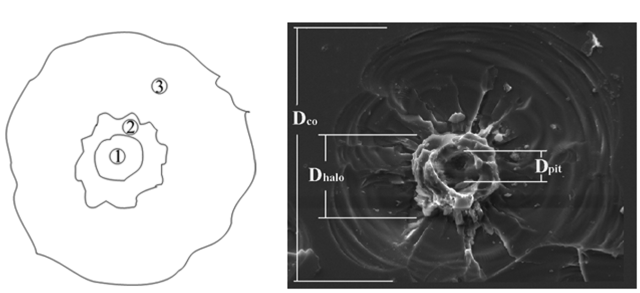

Fig. 3 Typical impact crater. The three typical regions marked on the left side are 1) central pit (diameter D_{pit}), 2) shattered zone (diameter D_{halo}), and 3) conchoidal cracking zone (diameter D_{co}).

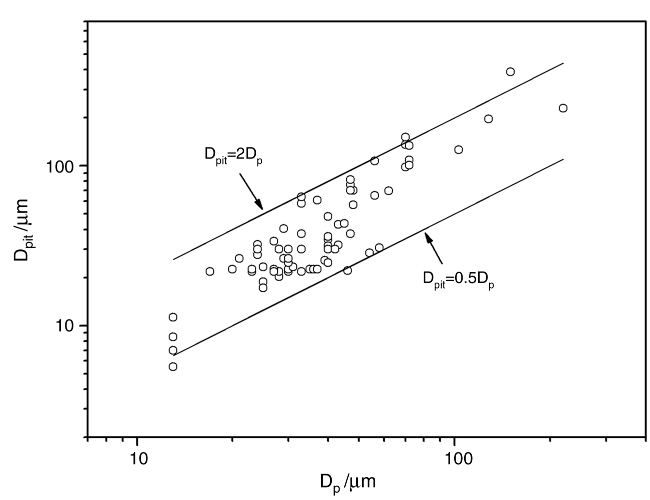

Fig. 4 Statistical relation between the central pit and incident particle diameter.

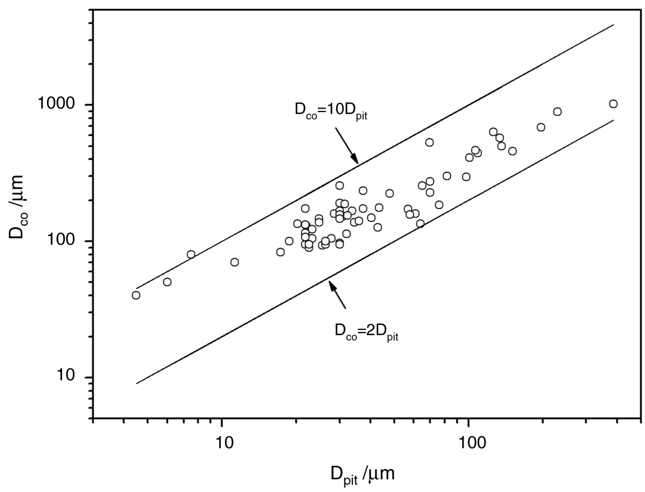

Fig. 5 Statistical relation between the conchoidal zone and central pit diameter.

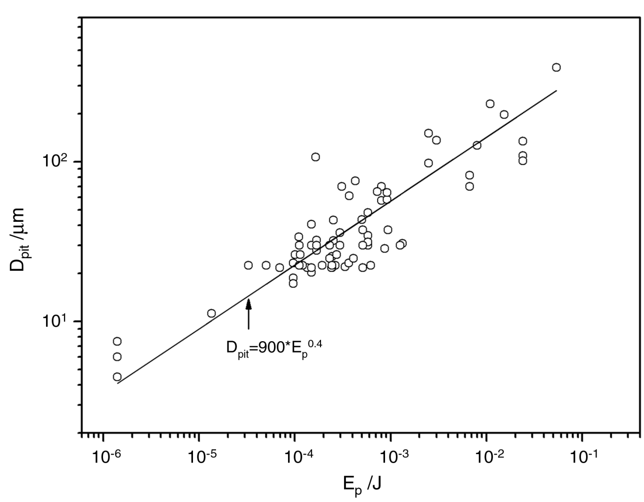

Fig. 6 Central pit diameter as a function of particle energy.

III. Evaluation of Solar Cell Degradation

A. Surface Damage Ratio

Surface damage ratio is defined as the sum of the damaged areas per unite sample area, which can be described as

$$\beta = \frac{A_{\mathrm{co}}}{A} = \iint \pi \left(\frac{D_{\mathrm{co}}}{2}\right)^2 f(D_p, v)\mathrm{d}D_p \mathrm{d}v \tag{4}$$

A_{co} is damaged area for a solar cell, A is total area of a solar cell, $f(D_p, v)$ is flux of space debris, which is a function of the debris size (D_p) and velocity (v). D_{co} is a function of debris energy according to damage Eq. (2) and (3) and can also be described by D_p, ρ_p (debris density) and v:

$$E = \frac{1}{2}\rho_p\left[\frac{4}{3}\pi\left(\frac{D_p}{2}\right)^3\right]v^2 \tag{5}$$

By substituting damage equation into formula (4) and integrating with respect to D_p and v, the surface damage ratio β can be obtained. A calculation for a typical SSO spacecraft with altitude of 800 km and inclination of 98 deg was performed as an instance. The flux including both microdebris and meteoroids was calculated by MASTER-2005 model, and the integration was made within the ranges of $1 \sim 1000$ μm and $1 \sim 40$ km/s. Both the averaged and severe surface damage ratios were calculated, and the latter corresponds to the largest possible damage in Eq. (4). As shown in Table 1, the surface damage ratio of solar cell due to microimpacts is about

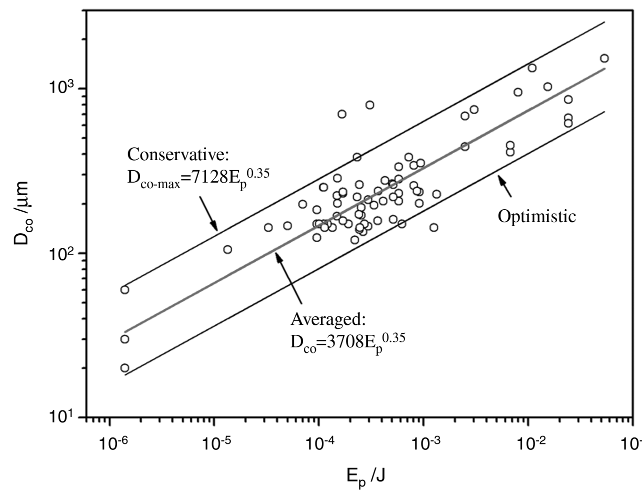

Fig. 7 Conchoidal zone diameter as a function of particle energy.

0.61% for a lifetime of 10 years half of which is attributed to micrometeoroids. For the worst case, the possible damage ratio amounts to about 2.3%.

B. Solar Cell Degradation

Damages to solar cell surfaces due to space microimpacts directly lead to decrease of the transmittance of the cover glass and result in further degradations in output power, open circuit voltage, and short circuit current, etc. The decrease of transmittance can be evaluated according to surface damage ratio as follows.

For a typical crater (with area of A_{co}), its transmittance (T_{co}) can be measured by a test light spot (with area of A_0) that covers the crater ($A_0 > A_{\mathrm{co}}$). If the original transmittance of the glass is T_0, then the transmittance for the region covered by the light spot is

$$T = \frac{A_{\mathrm{co}}T_{\mathrm{co}} + (A_0 - A_{\mathrm{co}})T_0}{A_0} \tag{6}$$

Thus by measurement of T, the transmittance of the crater region T_{co} is obtained.

If there are n craters on a cover glass sample (with area of A) all together, and each crater has an averaged transmittance of T_{co}, then the total transmittance for the sample is

$$T = \frac{T_{\mathrm{co}}\sum_{i=1}^{n} A_i + T_0(A - \sum_{i=1}^{n} A_i)}{A} = T_{\mathrm{co}}\beta + T_0(1-\beta) \tag{7}$$

This result indicates that the transmittance of the damaged solar cell cover glass is determined by its surface damage ratio and the crater transmittance. In the calculation, no overlapping of craters is assumed.

The transmittances for an amount of typical microcraters were measured by a series of $0.6 \sim 2$ mm test light spots with a spectrum of $300 \sim 900$ nm. The averaged transmittance T_{co} was obtained and is displayed in Fig. 8; the original transmittance of the cover glass T_0 was also plotted for comparison. The result showed that the averaged crater transmittance varies with wavelength and decreases by more than 50% in the range of 400 to 800 nm.

By application of earlier result and damage ratio calculation in Eq. (7), the transmittance degradation in space can be evaluated. The calculation was made for the case of the earlier mentioned SSO

Table 1 The surface damage ratio of solar cell due to integrated space microimpacts, (altitude: 800 km, inclination: 98 deg, duration: 10 yr)

	debris + meteoroids	Meteoroids
Averaged	0.61%	0.31%
Severe	2.30%	1.16%

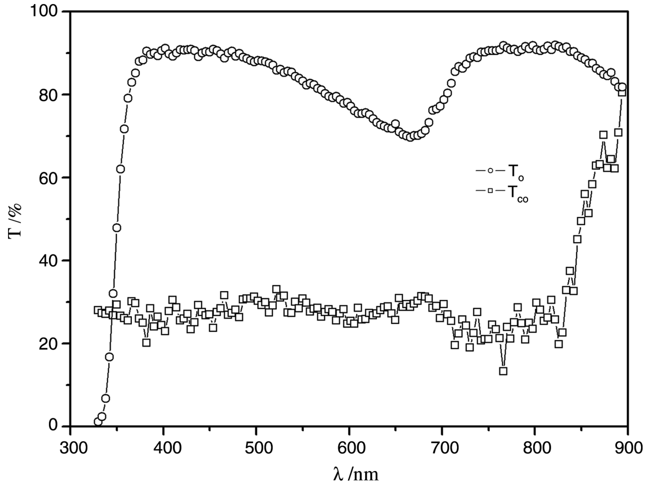

Fig. 8 Transmittance of crater region on cover glass in comparison with the original transmittance.

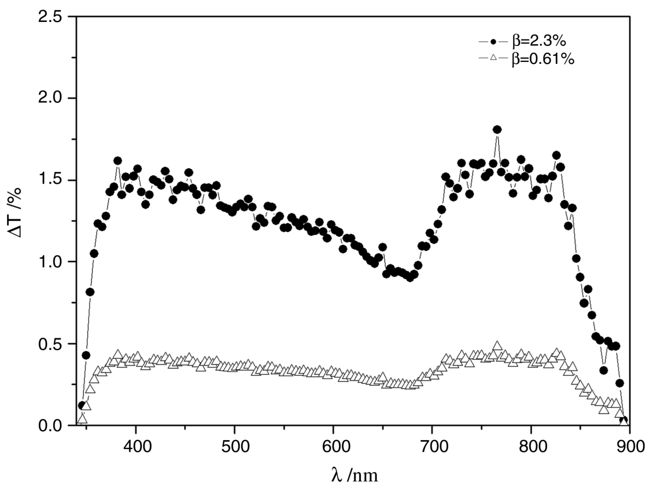

Fig. 9 Degradation of the transmittance of solar cell cover glass, (altitude: 800 km, inclination: 98 deg, duration: 10 years).

spacecraft and is displayed in Fig. 9. The solar cell transmittance degradation for a lifetime of 10 years is below 0.5% on average (corresponding to $\beta = 0.61\%$) and amounts to between 1 and 1.5% in the worst case ($\beta = 2.3\%$).

IV. Conclusions

The space microdebris effects to solar cells were simulated on a newly developed coaxial plasma accelerator. The experiments showed that the hypervelocity impact induced enlarged craters on cover glass, with the conchoidal zone diameter about $2 \sim 10$ times the central pit, while the central pit size is around $0.5 \sim 2$ times the incident particle. The damage equation was obtained, on the basis of which surface damage ratio for cover glass was evaluated for both averaged and worst possible cases. For a typical SSO spacecraft, the surface damage ratio for solar cell is approximately 0.61% on average and amounts to 2.3% in the worst case during a lifetime of 10 years, and the resultant transmittance degradations are approximately 0.5% and 1.5%, respectively.

The contribution of penetrations was not considered here, since their probabilities are very low. The retrieved solar panels from LDEF, HST and EUDERA also indicated that most penetrations were caused by debris of millimeters, for which the fluxes were much lower and had trivial contribution to net result.

It has to be considered that the accuracy of the space debris models is quite unknown. The models are permanently updated and calibrated from impact craters on retrieved satellites. In some experts' opinion, the models may underestimate the actual fluxes by about 1 order of magnitude [10,11].

Based on the surface damage ratio and transmittance degradation predictions, it is possible to further evaluate the degradation of functional parameters such as output power, short circuit current, and open circuit voltage, etc., according to solar cell principle and the theoretical model for the parameters, which will be investigated in future studies.

Acknowledgments

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