Plasma and solar array arcing caused by space debris impact

Shinya FUKUSHIGE[1], Yasuhiro AKAHOSHI[1], Keiko WATANABE[2],
Toshikazu NAGASAKI[1], Kenshou SUGAWARA[1],
Takao KOURA[1], Mengu CHO[1]

1.Department of Mechanical Engineering, Faculty of EngineeringKyushu Institute of Technology
1-1, Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka, 804-8550, Japan
Phone & Fax: +81-93-884-3151
E-mail: e584102s@tobata.isc.kyutech.ac.jp
2. Osaka University

Abstract

There is high possibility that space debris impacts to a solar array paddle in spacecraft parts, because the solar array paddle has large area. Space debris impact to the solar array causes not only mechanical damage but also electrical damage such as arcing on the solar array through local high density plasma created by hypervelocity impact. In the worst case, Joule heating of this arcing carbonizes insulation layer and permanent short-circuit path is created. This is permanent sustained arc. However, no permanent sustained arc caused by space debris impact in orbit has been reported. Purpose of this study is evaluation of possibility of permanent sustained arc through the plasma created by debris impact. Hypervelocity impact tests to solar array coupons in the condition of pseudo power generation were conducted. We ascertained that space debris impact can lead to permanent sustained arc on the solar array due to plasma created by hypervelocity impact

Key Words: Space Debris, Solar Array, Plasma, Discharge

1. INTRODUCTION

In recent years, a solar array of a spacecraft has become larger with the voltage higher because a spacecraft has a large amount of power in requests from an advanced mission. Therefore the risk of a space debris impact and discharge on the solar array is increasing. Space debris impact to the solar array causes not only mechanical damage such as destruction of a solar cell and insulation layer but also generation of local high density plasma due to impact energy[1]. This plasma can lead to arcing between solar cells or cell and substrate on the solar array[2]. In the worst case of this event, Joule heating of this arcing can carbonize insulation layer and create permanent short-circuit path. This is permanent sustained arc (PSA). Purpose of this study is evaluation of possibility of PSA through the plasma created by debris impact. It is considered that micro debris which has high probability of impact cannot trigger PSA because no PSA caused by hypervelocity impact on the actual solar array of spacecraft in orbit has been reported. Therefore we conducted hypervelocity impact tests using comparatively large size projectile which was 3 [mm] Al sphere. Target was solar array coupon in the condition of pseudo power generation. Temperature and density of plasma created by hypervelocity impact as well as current and voltage of external circuit which connected to the solar array coupon were measured. We ascertained that space debris impact can lead to permanent sustained arc on the solar array due to plasma created by hypervelocity impact.

2. EXPERIMENTAL SETUP

The hypervelocity impact tests were carried out using the two-stage light gas gun, installed at Laboratory of Spacecraft Environmental Interaction Engineering (La SEINE) in Kyushu Institute of Technology. The experimental setup is shown in Fig. 1. The projectile was Al2017 sphere which was 3 [mm] in diameter. This projectile is accelerated in a launch tube with sabot. The sabot separation section and the test chamber are partitioned out by the polyester film which is 25 [μm] in thickness. The ambient pressure of sabot separation section is 10 [kPa] and that of the test chamber is 4 x 10^{-2} [Pa] because the separation of projectile from sabot needs air drag. The magnet detector, which consists of a permanent magnet and a pick up coil, was set up in the blast tank, and the signal of the projectile was used as oscilloscope trigger to record data.

Solar array coupon is shown in Fig. 2. The solar cell is silicon cell. The cell and coverglass are 100 [μm] in thickness. The substrate is CFRP Al honeycomb sandwich.

Solar array coupon can simulate the condition of power generation with connection to the external circuit, which is shown in Fig. 3. The external circuit consisted of quick response constant current (CC) power supply, resistor and constant voltage (CV) power supply[3]. The resistor simulates load resistance of a spacecraft. The output of CC power supply simulates that of a string of solar array. The CV power supply simulates the voltage which maintained by the other strings of solar array when discharge occurs on the string. The voltage of the CV power supply was set 1 [V] lower than that of CC power supply. CRD power supply which consisted constant current regulation diodes and voltage source was used as quick response CC power supply. The current probe 1 (Cp_1) measured current of circuit which

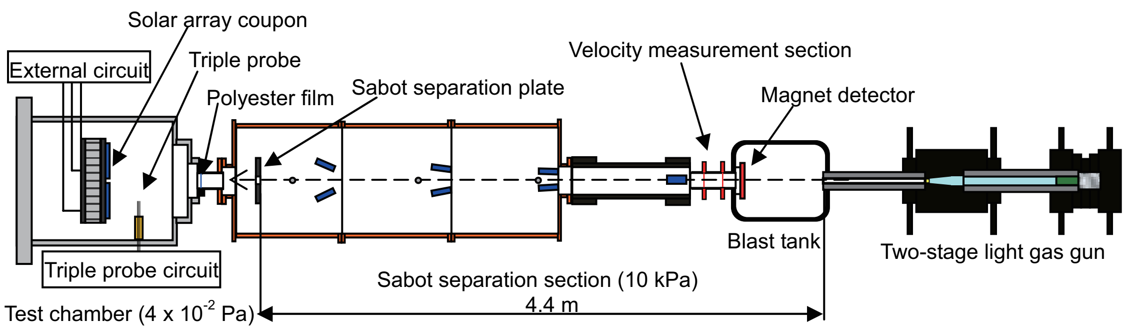
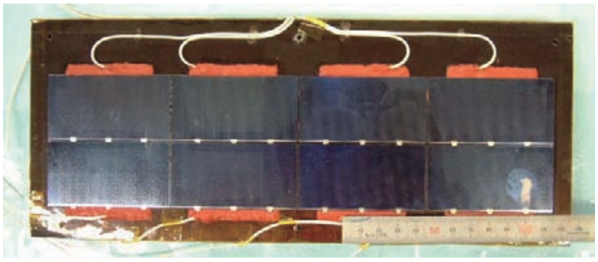
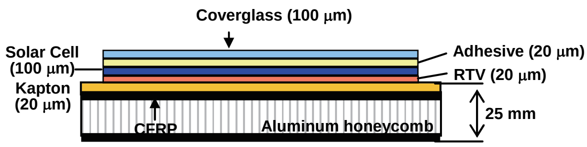


Fig. 1 Experimental setup of hypervelocity impact test



(a) Front view



(b) Cross section

Fig. 2 Solar array coupon

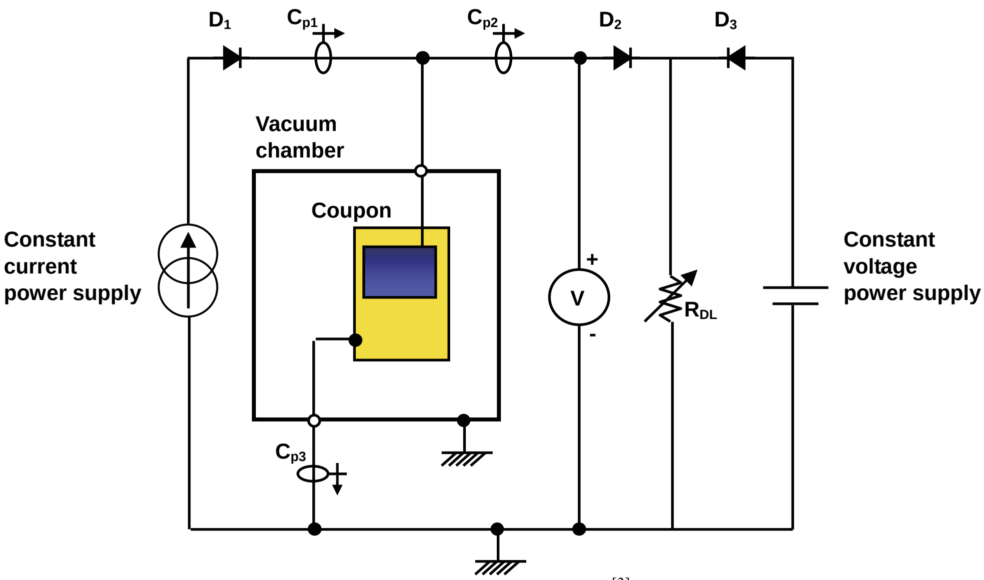


Fig. 3 External circuit[3]

simulate the output of a string of the solar array. The current probe 2 (Cp_2) measured current which flow to resistance. The current probe 3 (Cp_3) measured discharge current between the cell and substrate. The voltage probe measured string voltage.

Triple probe[4] was set at a distance of 100 [mm] from the front of the solar array coupon to measure electron temperature and density of plasma created by hypervelocity impact. The configuration of the triple probe is shown in Fig. 4. The probe was made of coated copper wire. The diameter was 2 [mm] and the exposure length was 20 [mm]. The near part of the tip of the probe was insulated by Kapton tape. The electron temperature Te [eV] and density N_e [m^{-3}] can be calculated by V_2, V_3 and following equations. The electron temperature is obtained from equations (1) and (2);

$$\frac{I_1+I_2}{I_1+I_3}=\frac{1-\exp(-\phi_{d2})}{1-\exp(-\phi_{d3})} \quad (1)$$

$$I_1 = I_2 + I_3 \quad (2)$$

where $\phi_{d2} = eV_{d2}/\kappa Te$, $\phi_{d3} = eV_{d3}/\kappa Te$, e is elementary electric charge and κ is Boltzmann constant. Finally, electron density can be calculated by following equations.

$$I_i=\frac{I_3-I_2\exp(-\phi_{\Delta V})}{1-\exp(-\phi_{\Delta V})} \quad (3)$$

$$N_e = [(M)^{1/2} / S\,]\, I_i\, f_1(V_{d2}) \quad (4)$$

$$f_1(V_{d2}) = 1.05 \times 10^{15} (Te)^{-1/2} [\exp(\phi_{d2}) - 1]^{-1} \quad (5)$$

Here M [g] is ion mass, S [mm^2] is surface area of the probe and I_i [μA] is ion current. In this study, V_{d2} = 3 [V], V_{d3} = 18 [V] and the resistance was 0.25 ~ 10 [kΩ].

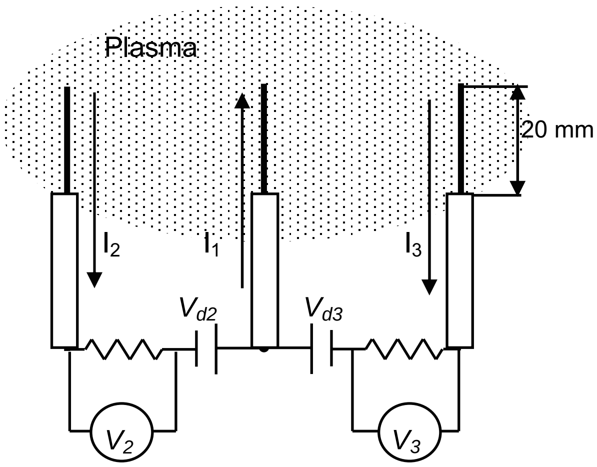


Fig. 4 Triple probe circuit

The measurement results of electron density and temperature depend on measurement point and time because plasma created by impact diffuses from impact point. Therefore, the solution of the advection-diffusion equation was defined as fitting curve to time history of electron density at the measurement point on the assumption that plasma diffusion can be represented by that solution, which is following formula.

$$N_e = \frac{n_e}{(4\pi Dt)^{3/2}} \exp\left(-\frac{(r-Ut)^2}{4Dt}\right) \qquad (6)$$

where t is elapsed time since impact, N_e is electron density, and r is distance from impact point to measurement point of the triple probe. The fitting parameters, which are electron number n_e, diffusion coefficient D, and advection velocity U can be obtained by the curve fitting.

The electron temperature at the time when the electron density is maximum value on the fitting curve is adopted as a representative value of electron temperature because diffusion into vacuum is isothermal expansion.

3. TEST RESULTS

Test results about discharge are distinguished by the following definitions. Primary arc (PA) is discharge just after impact. Temporary sustained arc (TSA) is discharge that discharge current measured by C_{p3} equals to circuit current measured by C_{p1} for over 2 [μsec]. Permanent sustained arc (PSA) is that there is permanent short-circuit path after hypervelocity impact test. Hypervelocity impact test were conducted in the impact velocity of mainly approximately 4 [km/s] and several different velocity. The test results are shown in Table 1. The results of discharge which are arranged on voltage and current condition of external circuit are shown in Fig. 5. The results of a longer duration of discharge are shown in Fig. 1, where there are various results in the same condition of voltage and current setting.

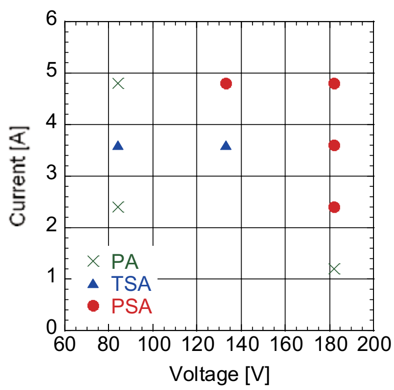


Fig. 5 Test results about discharge

These results confirm hypervelocity impact causes PSA on a solar array. In the case that impact velocity was around 4 [km/s], PSA occurred under the conditions that voltage was 182 [V] and current was 2.4 [A] and more. In the other impact velocity, although there were few tests conditions of voltage and current, PSA occurred under 133 [V] – 4.8 [A] and 182 [V] – 4.8 [A] with the impact velocity of about 2.1 [km/s] and under 182 [V] – 4.8 [A] with the impact velocity of around 4.7 [km/s].

The typical example of the voltage and current waveforms of the external circuit is shown in Fig. 6. Applied voltage and

Table 1 Test results of hypervelocity impact test

Voltage [V]	Current [A]	Impact velocity [km/s]	Discharge	Electron number x10^{13}[electrons]	Electron temperature [eV]	Diffusion coefficient [m^2/s]	Advection velocity [km/s]
84	2.4	3.78	PA	180	1.74	64.7	5.81
	3.6	3.68	TSA	45.4	2.63	15.9	4.14
	4.8	3.52	PA	163	1.77	54.1	4.74
133	3.6	3.72	TSA	194	1.71	53.9	5.50
		4.02	TSA	295	2.07	58.3	4.52
	4.8	2.08	PSA	3.74	1.04	6.18	2.12
		2.85	PA	30.8	1.06	27.2	3.63
		3.74	TSA	350	1.85	74.2	4.14
		3.85	TSA	154	1.46	57.8	5.52
		4.82	PA	892	2.86	104	6.14
182	1.2	3.95	PA	259	2.10	54.7	5.46
	2.4	3.81	PSA	129	1.50	42.3	5.78
	3.6	3.74	PSA	185	2.37	39.0	4.55
	4.8	2.14	PSA	3.08	1.37	5.15	1.95
		3.76	PSA	233	1.76	51.3	5.72
		4.65	PSA	643	2.93	95.3	6.23

current were 133 [V] and 3.6 [A], respectively, and impact velocity was 4.02 [km/s].

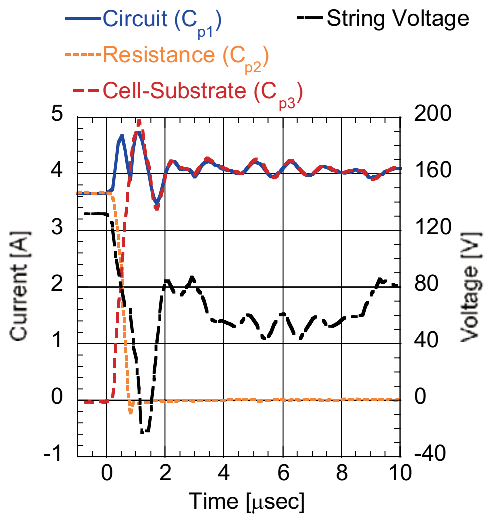


Fig. 6 Current and voltage of onset of arcing

The contact between the cell and substrate through the Al sphere cause short circuit, in the penetration process of the Al sphere into the solar array coupon. The time at the voltage drop due to short-circuit between the cell and substrate was set to 0 [sec] in Fig. 6. It took the circumference of largest dimension of the Al sphere approximately 400 [μsec] to pass through the cell. The plasma created by hypervelocity impact sustained discharge between the cell and substrate after the perforation. Collision of ions into substrate, which is cathode, generates neutral gas and secondary electrons while plasma diffuses. Thermionic emission occurs due to local temperature rise of the substrate caused by ion collision depending on conditions. The electrons generated by those processes ionize the neutral gas and the arcing can be sustained by the new ions and electrons after diffusion of plasma created by impact. If the arcing stops before insulation layer is carbonized by Joule heating, this arcing is TSA, if not, PSA occurs. Therefore, ion current density which is collected by the substrate at the impact point plays a vital role in the occurrence of TSA or PSA. This ion current density can be calculated by equation (6) and (7) using the number of electrons, electron temperature, diffusion coefficient and advection velocity, which were shown in Table 1.

$$i_i = \exp\left(\frac{1}{2}\right) e N_e \sqrt{\frac{\kappa Te}{m_i}} \qquad (7)$$

Here i_i is ion current density and m_i is ion mass. The calculation results at 1 [nsec] after impact are plotted on Fig. 7 as a function of impact velocity. These results can be fitted by power law with index of 2.0. Therefore, the ion current density is proportional to kinetic energy of the projectile. In the tests, the impact velocities were low in comparison with that of debris in low earth orbit, which is 10 [km/s] on an average. However, because the ion current density which is collected by the substrate at the impact point is proportional to kinetic energy, it is considered that higher velocity impact can trigger PSA.

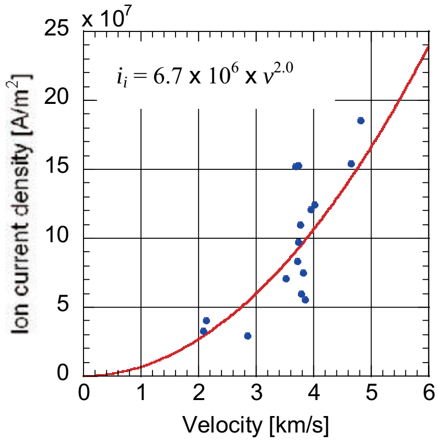


Fig. 7 Ion current density at impact point

4. CONCLUSION

In this study, hypervelocity impact tests using comparatively large size projectile which was 3 [mm] Al sphere were conducted to evaluate possibility of PSA due to the plasma created by debris impact. As a result, we concluded that hypervelocity impact can lead to PSA on a solar array. The plasma created by hypervelocity impact was measured by triple probe and the electron number, electron temperature, diffusion coefficient and advection velocity were obtained using the solution of the advection-diffusion equation. The ion current density which is collected by the substrate at the impact point can be calculated from these parameters. The calculation results shows that the ion current density is proportional to kinetic energy of projectile.

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