GROUND-BASED EXPERIMENT OF ELECTRIC BREAKDOWN OF SPACECRAFT INSULATOR SURFACE IN AMBIENT PLASMA ENVIRONMENT

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Abstract

In the future, LEO spacecraft will be larger and higher powered. Because of the balance of leakage currents through ambient space plasma, their main conductive body will have a higher negative potential without plasma contactor operation. When spacecraft operate with a higher voltage, more intensive arcing is suspected to occur on the surface. In this study, ground-based experiment was carried out to understand the arcing phenomenon and to examine influences of ambient space plasma on the arcing process. Simulating plasmas were generated by electron cyclotron resonance discharge. When arcing occurred on negatively-biased anodized aluminum sample (AAS) plates in the plasma environment, the time variations in arc current and bias voltage were measured. Arc spot diameter was also measured. The single arcing characteristics showed that both the peak arc current and the total charge emitted by arcing increased with initial charging voltage and neutral particle number density. The diameter of arc spots increased with initial charging voltage although it was almost constant regardless of neutral particle density. The repetitive arcing characteristics showed that the arc rate gradually increased with arcing number. Lots of overlapping arc spot were observed after 1,000 arcings, and its number increased with arcing number. Accordingly, arc tends to occur at a same location as increasing arcing number. Influences of initial charging energy on arcing characteristics were also examined by widely changing capacitance and initial charging voltage. The arc spot diameter widely increased with initial charging energy, and the fitting line could be evaluated. Accordingly, high voltage operation of LEO spacecraft might bring drastic degradation of AAS by arcing, depending on ambient plasma conditions and spacecraft capacitance.

1. Introduction

Spacecraft are in a severe environment in space. Their surfaces are exposed to energetic and reactive particles, such as electrons, ions, protons and oxygen atoms and ultraviolet light, including particles exhausted from plasma thrusters, during space missions. The environmental effect plays a crucial role in determining the spacecraft's reliability and lifetime [1]. Although the number density of ions such as oxygen and nitrogen is smaller than that of atomic oxygen in LEO, electrostatic interactions between the surface materials and the ambient plasma, such as negative or positive sheath creation, and charging and arcing phenomena, frequently occur. The ions are accelerated in a negative potential sheath on a solar array, and the current generated by the solar array is leaked by impact of the ions; the solar array is still degraded by sputtering and arcing due to the collected ions [2],[3]. Accordingly, the environmental factors cause changes of chemical structures of spacecraft materials and their optical and/or electrical properties [4],[5]. In GEO satellites, it is well-known that the electrical breakdown of negative charging on their insulating surfaces causes intensive damages in the systems. In plasma contactor operations, the negative charging is expected to be mitigated by ions attracted from the plasma, resulting in surface degradation as well as in cases with high voltage solar arrays [6]-[8]. The mechanism of the material degradation, the structure of electrical sheaths and the charging and arcing processes must be understood.

In Osaka University, the structure of an ion sheath created around a high voltage solar array and the degradation of surface materials near the array due to high energy ion bombardment have been investigated [2],[3],[5]. The mitigation of negative charging by plasma flow, i.e. the feature of plasma contactor operations, has also been studied [6]-[8].

In the future, LEO spacecraft will be larger and higher powered. Because of the balance of leakage currents through ambient space plasma, their main conductive body will have a higher negative potential without plasma contactor operation. When spacecraft operate with a higher voltage, more intensive arcing is suspected to occur on the spacecraft surface. In this study, ground-based experiment is carried out to understand this phenomenon and to examine influences of ambient space plasma on the arcing process. Simulating plasmas are generated by electron cyclotron resonance (ECR) discharge. Arcing characteristics of negatively-biased anodized aluminum sample (AAS) plates in the plasma environment are investigated. When arcing occurs on the plate, the time variations in arc current and bias voltage are measured. Arc spot diameter is also measured.

2. Hazard of Drastic Destruction of Spacecraft Surface Materials by Arcing in Plasma Environment

In general, the spacecraft conductive body, as shown in Fig.1, has a negative potential, near solar array voltage, on potential of

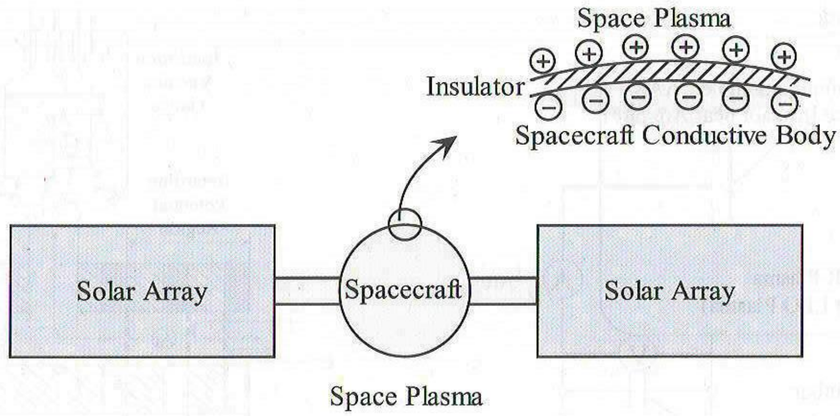


Fig.1 Feature of charging on spacecraft surface insulators.

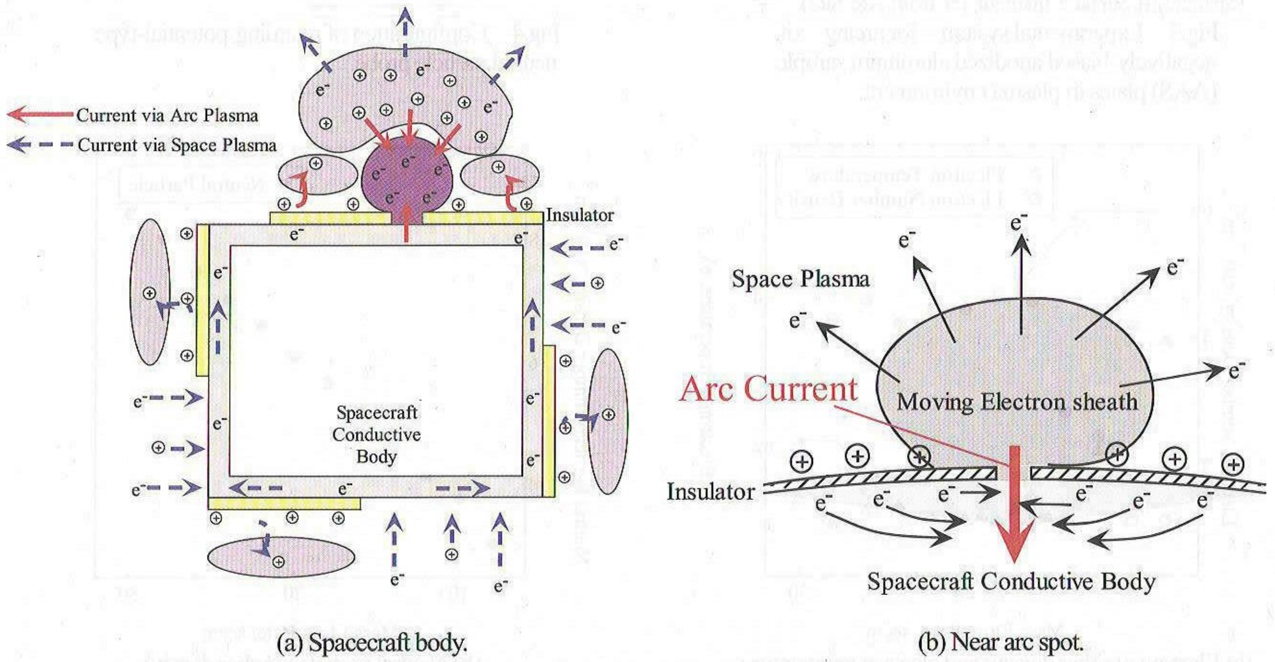


Fig.2 Current paths for arcing on surface insulator between spacecraft conductive body and space plasma.

space plasma. It is called absolute negative charging. Then, positive charging occurs on an insulator of the spacecraft surface. The large insulator works as a capacitor with a high capacitance. As shown in Fig.2(a), if electric breakdown occurs between the spacecraft conductive body and space plasma, i.e. destruction of the insulator by arcing, arc currents flow through several paths until neutralization of charge is finished. As a result, the arc current flowing from space plasma to the arc point of the spacecraft conductive body, as shown in Fig.2(b), is very high because of the high capacitance of the insulator. The arcing is suspected to intensively degrade insulator materials of spacecraft surface, specially with a high voltage solar array. Furthermore, the arcing characteristics are considered to depend on feature of space plasmas near spacecraft surface because interaction between electrons extracted from the arc spot and the ambient space plasma is expected to occur. Intensive arcing is suspected to occur in some ambient plasma environment.

3. Experimental Apparatus

Figure 3 shows the experimental system for arcing of negatively-biased anodized aluminum sample (AAS) plates in plasma environment. The experimental facility developed in Osaka University mainly consists of a vacuum tank, a vacuum pump system, a plasma source and an AAS plate [9],[10]. The electron cyclotron resonance (ECR) plasma source is set on a flange of the large stainless vacuum tank 0.7 m in diameter x 1.5 m long. The main vacuum pump is an oil-free turbo-molecular pump with a high

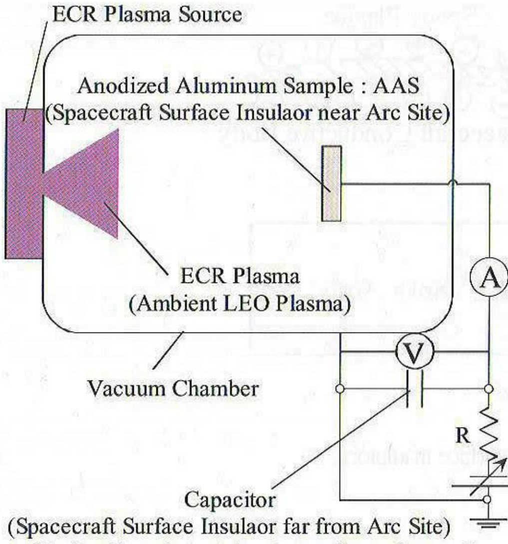


Fig.3 Experimental system for arcing of negatively-biased anodized aluminum sample (AAS) plates in plasma environment.

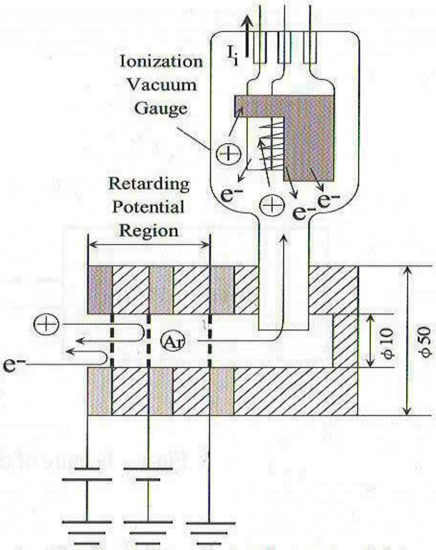
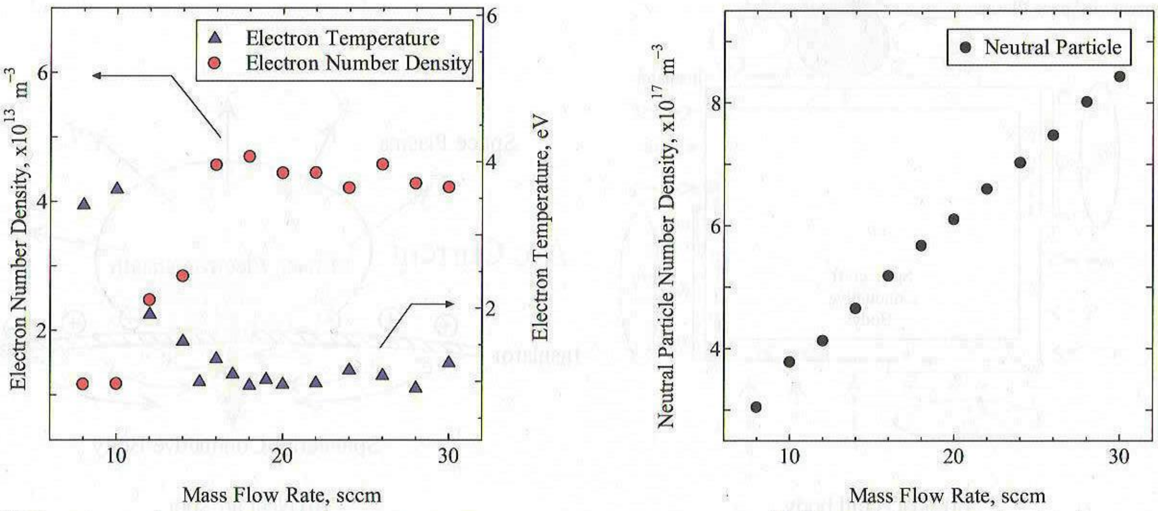


Fig.4 Configuration of retarding-potential-type neutral particle probe.



(a) Electron number density and electron temperature. (b) Neutral particle number density.

Fig.5 Plasma properties measured at center of AAS plate located 660 mm downstream from plasma source exit. The microwave input power is 300 W.

pumping speed of 5 m^3/s. The tank pressure is kept some 10^{-3} Pa during all experiments.

Argon plasmas simulating spacecraft ambient plasma are produced by ECR discharge. Microwaves of maximum 1 kW and 2.45 GHz are introduced into the ECR discharge chamber. An orifice is set to the downstream exit of the discharge chamber to produce a low-density plasma. Electron number density and electron temperature are measured with a Langmuir probe. Neutral particle number density is also measured by a retarding-potential-type neutral particle probe shown in Fig.4.

Figure 5 shows the plasma properties measured at the center of the AAS plate located at 660 mm downstream from the plasma source exit. The microwave input power is 300 W. When the argon flow rate increases from 8 sccm, the electron number density increases from $1.2 \times 10^{13} m^{-3}$ and the electron temperature decreases from 4.0 eV. Over a flow rate of 16 sccm, they saturate with $4.5 \times 10^{13} m^{-3}$ and 1 eV, respectively. The neutral particle number density linearly increases from $3.0 \times 10^{17} m^{-3}$ with a flow rate of 8 sccm to $8.5 \times 10^{17} m^{-3}$ with 30 sccm.

As shown in Fig.6, an AAS plate 50 mm x 50 mm square is used in this experiment. The plate made from Al2017 is prepared with MIL-A-8625-TYPE I, and the anodized layer is 1.3 um thick as well as those of Japanese Experimental Module in International Space Station. To simulate some surface area of spacecraft, a capacitor of 0.1 uF is mainly connected between the AAS and a vacuum chamber, i.e. the ground. Just after arcing, charging to the capacitor begins; then charging is finished after a few sec, and arcing occurs again; that is, repetitive arcing is observed. When arcing occurs, the time variations in arc current and charging voltage are measured. The diameter of arc spots also is measured.

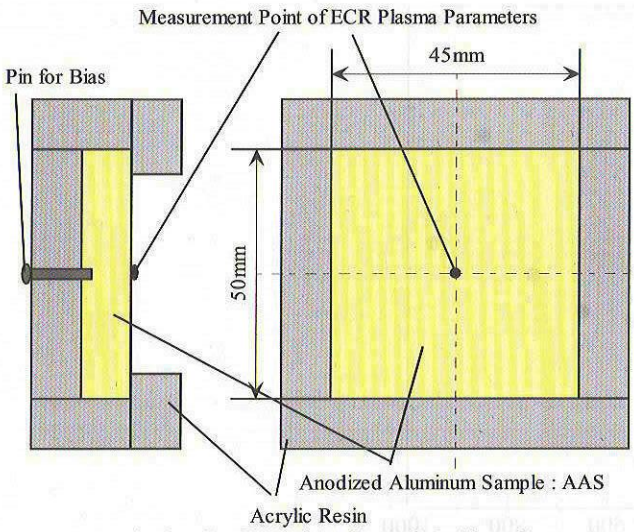


Fig.6 Configuration of sample holder of negatively-biased AAS plates.

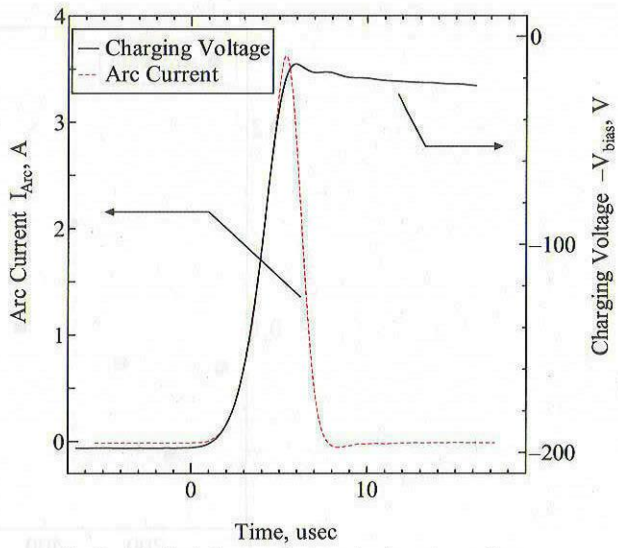
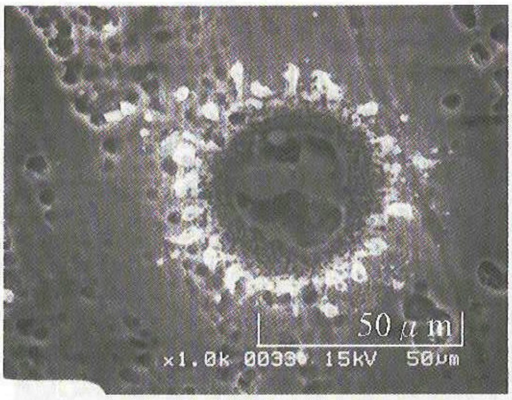
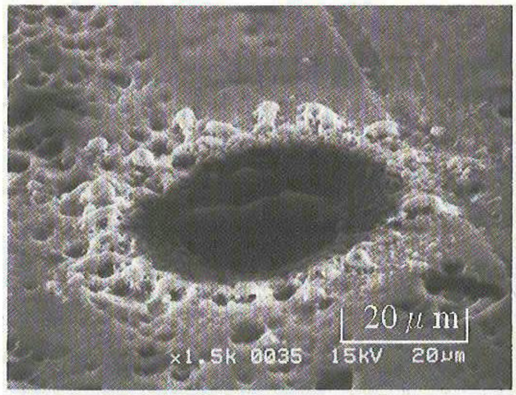


Fig.7 Typical time variations in charging voltage and arc current for arcing of AAS plate in plasma environment.



(a) Front.



(b) Sideways.

Fig.8 Typical photograph of arc spot for arcing of AAS plate.

4. Results and Discussion

4.1 Single Arcing Characteristics

Figures 7 and 8 show typical time variations in charging voltage and arc current, and a photograph of arc spot, respectively, for arcing on an AAS plate. The charging voltage rapidly changes from an initial charging voltage to zero, and then the arc current also rapidly changes up and down. The peak arc current is the order of ampere. As shown in Fig.8, a large hole with some ten um is created by arcing. The anodized layer is eroded, and the main aluminum part appears. Accordingly, degradation of material properties by arcing is suspected.

We examined the time variations in charging voltage and arc current, and the characteristics of peak arc current, arcing impedance, total emitted charge, total emitted charge ratio and arc spot diameter, dependent on initial charging voltage at constant plasma parameters of neutral particle density, plasma density and electron temperature of $3.0x10^{17}$ m^{-3}, $1.2x10^{13}$ m^{-3} and 4 eV. The arc impedance is defined as a value of peak arc current divided into initial charging voltage. The total emitted charge is a value integrating arc current in time. Since the value does not equal the charge initially stored in the capacitor, the total emitted charge ratio can be defined as a ratio of total emitted charge to initial charge in the capacitor. The charging voltage rapidly approached zero from each initial charging voltage. At -400 and -500 V, the charging voltage transiently increased above zero. This is considered because a large amount of ions created by intensive ionization of an eroded and evaporated AAS, and/or neutral particles in the ambient plasma enters the arc spot [10],[11]. The arc current rapidly increased and had a peak; then decreased. The peak arc current and the arc impedance increased and decreased, respectively, with an increase in initial charging voltage from 100 to 500 V, and the duration time of arcing became short. A higher density plasma is considered to be created with increasing initial charging

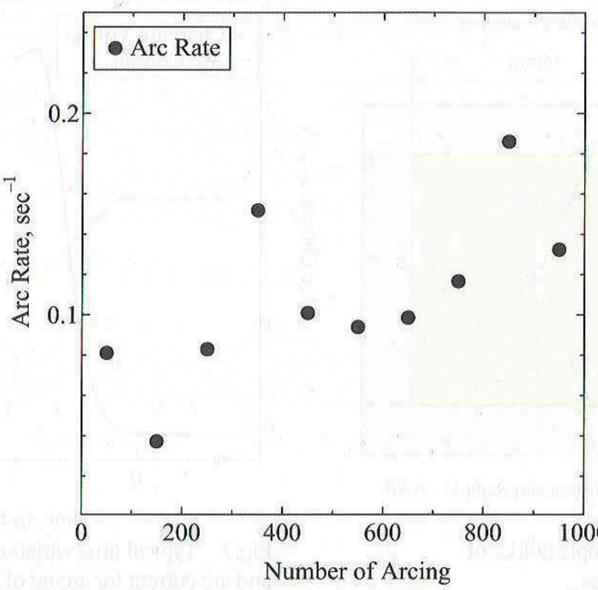
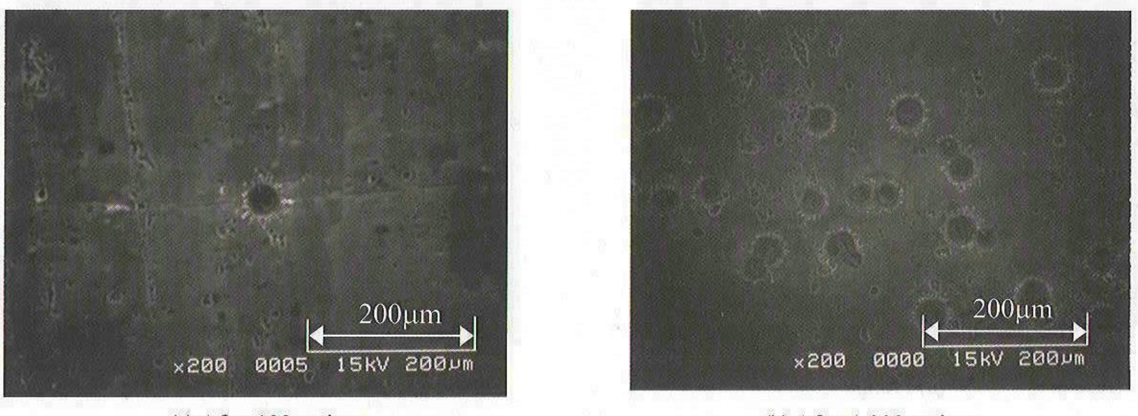


Fig.9 Arc rate vs arcing number characteristics for repetitive arcing test at constant plasma parameters of neutral particle density and plasma density of 1.5×10^{19} m^{-3} and 2.4×10^{13} m^{-3} with a constant initial charging voltage of -200 V. The total arcing number is 1,000.



(a) After 100 arcings. (b) After 1,000 arcings.

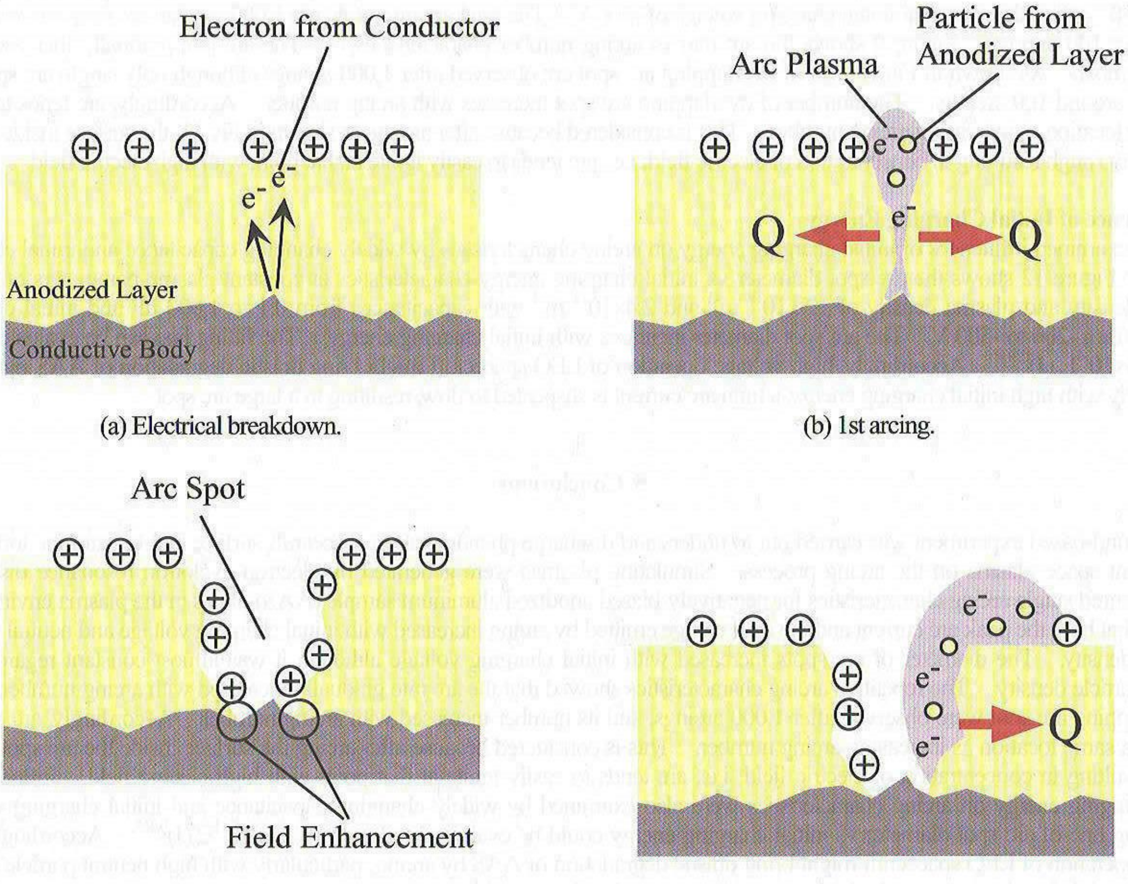
Fig.10 Typical photograph of arc spots for repetitive arcing of AAS plate.

voltage. As a result, both the total emitted charge and the total emitted charge ratio linearly increased with initial charging voltage. Because the total emitted charge ratio above 1.0 was achieved, an additional current flew from the ambient plasma. The additional current is considered to be an ion current created by intensive ionization in the ambient plasma as mentioned above. The diameter of arc spots was almost constant at charging voltages up to 350 V and increased with above it. This shows that a large volume of the AAS was eroded and evaporated with a high initial charging voltage, resulting in creation of a dense plasma around the arc spot by intensive ionization.

We examined the time variations in charging voltage and arc current, and the characteristics of peak arc current, arcing impedance, total emitted charge, total emitted charge ratio and arc spot diameter, dependent on neutral particle number density at plasma parameters of 1.2-4.5x10^{13} m^{-3}, 1-4 eV and constant initial charging voltage of -200 V. Both the charging voltage and the arc current showed rapider and more intensive changes with increasing neutral particle density. This is considered because of ionization enhanced with high-density neutral particles as well as cases with high initial charging voltages [10],[11]. The characteristics of peak arc current, arcing impedance, total emitted charge and total emitted charge ratio agreed with those of charging voltage and arc current. The total emitted charge ratio also reached above 1.0 at high neutral particle densities. On the other hand, the arc spot diameter was almost constant regardless of neutral particle density because the energy stored in the capacitor was constant.

4.2 Repetitive Arcing Characteristics

Repetitive arcing test was carried out at constant plasma parameters of neutral particle density and plasma density of 1.5×10^{19} m^{-3}



(a) Electrical breakdown.

(b) 1st arcing.

(c) Field enhancement.

(d) 2nd arcing inside arc spot.

Fig.11 Arc spot formation for repetitive arcing including initial electrical breakdown.

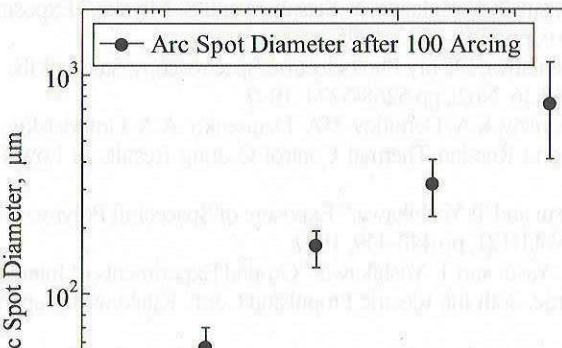


Fig.12 Arc spot diameter vs initial charging energy characteristics at constant plasma parameters of neutral particle density and plasma density of 1.5×10^{19} m^{-3} and 2.4×10^{13} m^{-3} with capacitances from 0.1 to 1,000 uF and initial charging voltages from -200 to -500 V.

and $2.4x10^{13}$ m^{-3} with a constant initial charging voltage of -200 V. The total arcing number is 1,000, and an arc rate was estimated every after 100 arcings. Figure 9 shows the arc rate vs arcing number characteristics. The arc rate gradually increases with arcing number. As shown in Fig.10, lots of overlapping arc spot are observed after 1,000 arcings although only single arc spots are observed around 100 arcings. The number of overlapping arc spot increases with arcing number. Accordingly, arc tends to occur at a same location as increasing arcing number. This is considered because after arcing, as shown in Fig.11, the surface inside the arc spot is very rough resulting in concentration of electric field; i.e., arc tends to easily ignite at that point with high electric field.

4.3 Influence of Initial Charging Energy

We examined influences of initial charging energy on arcing characteristics by widely changing capacitance and initial charging voltage. Figure 12 shows the arc spot diameter vs initial charging energy characteristics at constant plasma parameters of neutral particle density and plasma density of $1.5x10^{19}$ m^{-3} and $2.4x10^{13}$ m^{-3} with capacitances from 0.1 to 1,000 uF and initial charging voltages from -200 to -500 V. The arc spot diameter increases with initial charging energy. The fitting line can be evaluated to be $d(m)=2.5x10^{-4}E_0(J)^{0.368}$. Accordingly, high voltage operation of LEO spacecraft might bring drastic degradation of AAS by arcing; particularly with high initial charging energy, a high arc current is suspected to flow, resulting in a large arc spot.

5. Conclusions

Ground-based experiment was carried out to understand discharge phenomena on spacecraft surface and to examine influences of ambient space plasma on the arcing process. Simulating plasmas were generated by electron cyclotron resonance discharge. The measured single arcing characteristics for negatively-biased anodized aluminum sample (AAS) plates in the plasma environment showed that both the peak arc current and the total charge emitted by arcing increased with initial charging voltage and neutral particle number density. The diameter of arc spots increased with initial charging voltage although it was almost constant regardless of neutral particle density. The repetitive arcing characteristics showed that the arc rate gradually increased with arcing number. Lots of overlapping arc spot were observed after 1,000 arcings, and its number increased with arcing number. Accordingly, arc tends to occur at a same location as increasing arcing number. This is considered because after arcing the surface inside the arc spot is very rough resulting in concentration of electric field; i.e., arc tends to easily ignite at that point with high electric field. Influences of initial charging energy on arcing characteristics were also examined by widely changing capacitance and initial charging voltage. The fitting line of arc spot diameter vs initial charging energy could be evaluated to be $d(m)=2.5x10^{-4}E_0(J)^{0.368}$. Accordingly, high voltage operation of LEO spacecraft might bring drastic degradation of AAS by arcing; particularly with high neutral particle density and high initial charging energy, a high arc current is suspected to flow, resulting in a large arc spot.

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