

Experimental Study on The Flashover Characteristics of Typical Medium Materials of Spacecraft Along the Surface

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Abstract: Along the surface flashover is one of the main forms of electrostatic discharge on the surface of the aircraft, the construction of low-pressure electrostatic discharge simulation test system, taking the typical dielectric material commonly used in spacecraft as the research object, simulating the typical structure of the spacecraft surface with the metal-medium structure, simulating the charging process of the spacecraft surface in the operating environment by injecting electrons with an electron gun, starting from the formation process of the electrostatic discharge channel and the theory of the discharge, the change law of the characteristics of the dielectric material along the surface flash discharge is studied. Studies have shown that under vacuum conditions, when the dielectric material is charged with an electron gun, the surface potential of the material is gradually increased, and finally reaches a limit value of dynamic equilibrium (surface charging balance potential); And with the increase of the energy of the electron gun, the balance potential of the surface will also increase; The thicker the dielectric material, the lower the discharge frequency, and the higher the surface dynamic balance potential. The change of material electrical parameters and surface roughness caused by chemical changes in the dielectric material during discharge is an important reason for the influence of the flashover voltage along the surface; Increasing the conductivity and surface roughness of the material, introducing transition substances with a small dielectric constant, and increasing the hydrophobicity of the material can effectively reduce the flashover voltage, which is an effective means of flash network protection for dielectric materials.

Keywords: Spacecraft, Media material, Flashover voltage, Number of discharges, Protective technology.

1. Introduction

In the process of spacecraft operation, surface electrostatic discharge is an important factor affecting its safety and reliability, of which flashover along the surface is one of the main forms of electrostatic discharge on the surface of spacecraft. Due to the rapid conversion of high and low temperatures in the orbital flight environment, the comprehensive action of charged particles and ultraviolet radiation and other factors, the flashover phenomenon will occur under the action of lower DC electric field, and its flashover voltage is much lower than the breakdown voltage of the material itself, which is a key factor restricting the safety of operation, so the study of the flashover discharge characteristics along the surface is of great significance to the safety and protection of the spacecraft.

So far, a systematic and comprehensive study of the characteristics of flashover along the surface has been carried out at home and abroad, and the mechanism model of the flashover discharge of many dielectric materials along the surface has been proposed, among which the secondary electron emission avalanche model (SEEA) and the electron departure polarization relaxation model (ET-PR)[1] are widely recognized and accepted. In the SEA model, a distorted electric field is easily formed at the three junctions (insulating medium, cathode, air or vacuum), which generates initial electrons and generates secondary electrons when they hit the surface of the material under the action of the external field[2]; The movement of the secondary electrons strengthens the electric field in this region, causing the secondary electron emission to collapse and strengthen, resulting in a desorption gas on the surface of the insulating

medium and is ionized [3], forming a conductive channel and flashing networks. In the EPR model, defects in the insulating material cause the charge in the insulation to delaminate and depolarize the medium under the action of the field [4], causing flashovers.

Researchers at home and abroad have studied the influence of factors such as vacuum, temperature, applied voltage waveform, electrode shape, electrode material and surface characteristics of the material on the flashover along the surface through experiments. Among them, Zhang Zhenjun[5] of Xi'an Jiaotong University and others used DC and high voltage as a power source to study the flashover characteristics of polyimide materials under high vacuum conditions. Zhou Lidong[6] et al. applied high DC voltage under different electrode spacing to obtain the voltage and field strength law of flashover along the surface; Hao Zhiyuan[7] et al. used the ion jet method to treat polytetrafluoroethylene (PTFE) materials, and the insulation characteristics of PTFE after treatment were greatly improved; Dong Guojing et al.[8] Through experiments and the establishment of polyimide (PI) along-surface discharge plasma model, the average propagation rate of surface discharge along the surface is positively correlated with temperature and negatively correlated with air pressure; Cui Yuhao et al. [9] designed the epoxy resin (EP)/skin and skin/aluminum plate surface charge scanning measurement device, and studied the dissipation characteristics of the surface charge distribution of the skin after the negative polarity shock voltage was applied. In this paper, three kinds of spacecraft commonly used insulating materials PTFE, EP and PI are selected as research objects, the metal-medium structure is used to simulate the typical structure of the spacecraft surface, the charging process of the aircraft surface

in the flight environment is simulated by means of electron gun injection, the low-pressure electrostatic discharge simulation test platform is built, and the variation law and influencing factors of the flash-line discharge characteristics along the surface are studied during operation, and the research results can provide reference for the electrostatic protection of spacecraft and increase the reliability and safety of spacecraft during operation.

2. Theoretical Analysis of Charging and Discharging of Dielectric Materials

2.1. Equation for Charging and Discharging Current Balance of Spacecraft Surface Materials Under the Action of Space Environment

The charge accumulated by the dielectric material on the

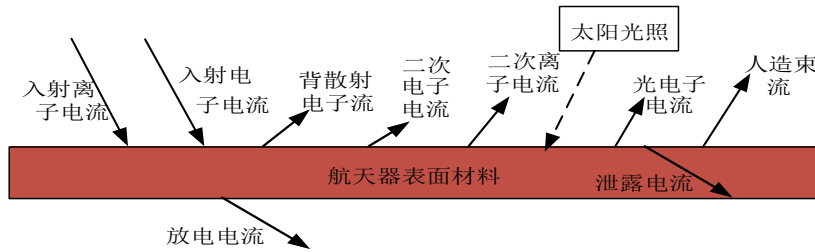


Figure 1. Schematic diagram of charging and discharging current of dielectric material on the surface of the spacecraft

If the spacecraft surface dielectric material is equivalent to a circuit node, the total current at that junction can be expressed as [8]:

$$I_t(U_0) = I_{re}(U_0) - I_{ESD} - [I_n(U_0) + I_{re2}(U_0) + I_{ib}(U_0) + I_s(U_0) + I_{si}(U_0) + I_{sl}(U_0)] \quad (1)$$

Wherein: I_{re} is the current amount of electrons incident into the surface of the dielectric material, I_{ESD} is the current generated by electrostatic discharge, I_{ri} is the current generated by ions on the surface of the dielectric material, I_{re2} is the current generated by the electrons shot out when the electrons are incident on the surface of the material, I_{ri2} is the amount of electron current generated by the ions hitting the surface of the material, I_s is the photoelectron current generated by sunlight irradiating the surface of the material, I_{ib} is the reflected current of the incident electron beam, and I_{sl} is the total leakage current of the dielectric material. Equation (1) is the spacecraft charge discharge current balance equation. When the spacecraft surface potential U_0 reaches equilibrium, the total current $I_t(U_0)$ equals zero, and the spacecraft surface charging charge reaches equilibrium. The charge discharge current balance equation is dynamically variable, and when one of the currents changes, the balance potential U_0 also changes.

2.2. Analysis of Influencing Factors of Dielectric Conductivity

Electron irradiation has a certain effect on the conductivity of the insulating dielectric material, according to the Webber empirical formula to calculate the maximum range of the electron incident dielectric material is:

surface of the spacecraft is mainly due to the irradiation of the electron beam in the space environment and the action of space plasma. Spacecraft in orbit can be seen as an isolated charging probe suspended in a live space environment. The summary of the current on the surface material of the spacecraft is shown in Figure 1, under the impact of the space electron beam and plasma, the medium material on the surface of the spacecraft receives the electron beam and plasma charge at the same time, in addition to reflecting a part of the electrons, it will also emit secondary electrons under the impact. Sunlight shines on the surface medium material of the spacecraft, and after the low-energy electrons are stimulated, they emit photoelectrons. The spacecraft surface dielectric material is connected to other conductors or materials due to leakage resistance will generate leakage current. When the surface potential of the spacecraft exceeds its breakdown threshold, an electrostatic discharge current is also generated [10].

$$R = \frac{\alpha E}{\rho} \left(1 - \frac{\beta}{1 + \gamma E}\right) \times 10^2 \quad (2)$$

where R is the range of the electron incident material medium; α , β , γ are constants; E is the energy of the incident electron; ρ is the material density. As can be seen from Equation (2), the greater the energy of the incident electron, the greater the range of the electron entering the material medium.

According to Equation (2) it is possible to calculate the transferred energy within the electron incident material:

$$w = \frac{1.544E}{R} \exp\left[-7.5\left(\frac{d}{R} - 0.3\right)^2\right] \quad (3)$$

where w is the electron transfer energy; d is the spacing between the material and the electron irradiation source. According to Equation (2) (3), after electron irradiation, the energy transferred inside the electron incident material increases, that is, the energy deposited in the material increases. The deposited energy triggers the ionization of the atoms of the material, forming a large number of electron-hole pairs, forming a radiation-induced conductivity.

The expression for radiation-induced conductivity [11-13] is:

$$\sigma_r = jm\mu\tau_r g_f = \frac{j\tau_g(D)GE\tau_r g_f}{100} \mu_n + \mu_p \quad (4)$$

where j is the beam density; $\tau_g(D)$ is the rate at which electron-hole pairs are produced; G is the yield of chemical radiation, that is, the number of ion pairs produced after each

100 eV of radiant energy absorbed; E is the energy of the incident electron; τ and g_f indicate that the resulting electron-hole pairs are recombined at g_f with odds after the average time τ ; μ_n is the electron mobility; μ_p is the cavity mobility.

According to formula (4), the radiation-induced conductivity increases with electron irradiation incident electron energy. According to the research of Zhang Zhenjun et al., the induced conductivity of material irradiation caused by high-energy electron irradiation is far greater than the intrinsic conductivity of the material itself. Therefore, as the number of tests increases, the electron irradiation makes the electron-hole pair in the material increase, and in the positive charge deposition area of the flashover surface, the increase of the carrier can effectively discharge the positive charge, reduce the surface potential of the material, and then reduce the degree of distortion of the electric field at the three junctions, so that the flashover voltage of the material increases [5].

2.3. Analysis of Influencing Factors of Dielectric Material Relative Dielectric Constant

According to the Secondary Electron Emission Avalanche Model (SEEA), when a dielectric material is hit by an electron when it flashes along the surface, in addition to reflecting a part of the electron, it also emits secondary electrons, leaving a positive charge on the surface of the material. On the one hand, the presence of a positive charge on the surface attracts electrons to hit the material, inducing the formation of a secondary electron collapse, and the positive charge effect is more obvious at the beginning of the flashover; On the other hand, the positive charge on the surface of the medium makes the surface potential of the medium positive, which indirectly increases the distortion field strength at the three junctions of the insulating material, the vacuum and the metal cathode, and promotes the formation of flashovers along the surface. However, the charge in the process of material flashover discharge is not infinite accumulation, when the surface charge reaches a certain limit, the electron hit the surface of the material after being bound by the electric field can not produce secondary electrons, at this time the positive charge on the surface of the material will tend to be balanced.

For different materials, due to the relative dielectric constant of the material, the degree of accumulation of the surface charge and the release rate are also different, according to the bektas S I et al. on EP, PTEF, nylon three kinds of insulation materials found that the larger the relative dielectric constant of the material, the higher the degree of surface charge accumulation, the slower the discharge rate. As an important parameter, the dielectric constant has a great influence on the occurrence of flashovers along the surface of the material, and Akahance, Kofoid, Suzuki et al. used different materials to conduct flashover experiments along the surface, and concluded that the discharge voltage along the surface flashover and the dielectric constant of the material show a negative correlation [14-16].

2.4. Analysis of Influencing Factors of Media Roughness

Flashover along the surface is easier to occur than breakdown discharge, although the single or several times will not burn the breakdown medium material, but the flashover current has a certain burning and destructive effect on the surface of the material, before and after the flashover,

the surface roughness of the specimen changes greatly.

When no flashover along the surface occurs, the surface of the PTFE sample as a whole is relatively uniform, and the surface appears to be slightly defected during processing and transportation, mostly uniform bumps, as shown in Figure 2, at this time, the surface roughness is the smallest, and the flashover voltage is low; With the increase of the experimental test, the flashover current burns on the surface of the PTFE sample, and when the flashover is 20 times, a large number of obvious burned deep indentations appear on the surface of the sample, as shown in Figure 3, at this time, the roughness of the sample surface increases, and the flashover voltage increases.

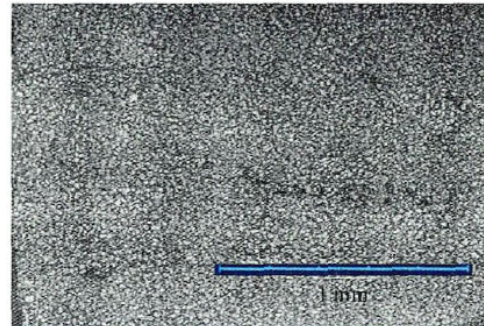


Figure 2. Surface of a PTFE specimen when no flashover occurs

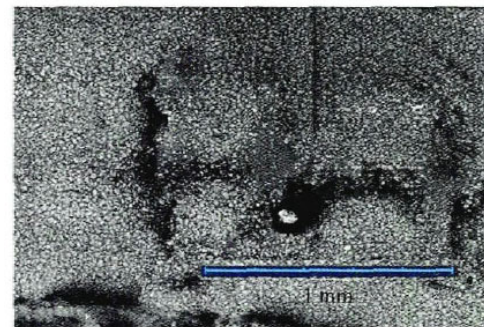


Figure 3. Surface of PTEF specimen after 20 flashovers

The surface roughness of the material hinders the flashover voltage, and the analysis includes the following points: (1) the flashover current makes the surface of the medium material appear gully of different shapes and sizes, which directly increases the passage distance of the secondary electrons, hinders the formation of the secondary electron collapse and the generation of the flashover channel, resulting in an increase in the flashover voltage; (2) The dents on the surface of the medium material that have been ablated can play a role in binding electrons, resulting in a relatively small number of electrons participating in the next flashover; (3) The surface roughness of the medium after the flashover increases, and the diffuse reflection effect of the incident electron is increased, which will change the direction of secondary electron emission, and will also reduce the number of secondary electrons along the surface after participation; (4) Due to the change in the direction of secondary electron emission, the energy obtained under the acceleration of the electric field is reduced, and when it is re-incident to the surface of the medium, there is not enough energy to strike out new secondary electrons, resulting in a larger flashover voltage on the surface of the medium; (5) However, when the number of flashovers continues to increase, due to the

increase of the flashover voltage, the flashover current becomes larger, which further deepens the degree of ablation of the discharge current on the surface of the medium, and the new flashover current will melt the dents of the old flashover ablation into pieces to form a new larger dent. The inner surface of the new larger dent is relatively flat, and the roughness of the material surface through which the flashover passes is reduced, resulting in a final stable trend of the flashover voltage [17]. Song Manqing[18] et al. of North China Electric Power University showed that the rough surface was in the center and the texture orientation was out of order when the surface flashover voltage appeared to be extreme.

3. Experimental Design

The flashover along the surface is a complex gas discharge process, due to the large number of influencing factors, it is difficult to simulate the flashover characteristics of the simulation software, and in addition, the cost of establishing an experimental platform during the operation of the spacecraft is too high and the feasibility is not large. Therefore, according to the experimental requirements, this paper builds a low-pressure experimental platform to systematically study the flashover along the surface of spacecraft medium materials in low-pressure environments.

The test bench mainly includes two parts: a discharge system and a measuring system, as shown in Figure 4. The ultimate vacuum degree of the vacuum system can reach 4.1×10^{-4} Pa, which is better than the technical requirements of 10^{-3} Pa, and meets the test requirements of simulating a low-pressure environment, as shown in Figure 5.

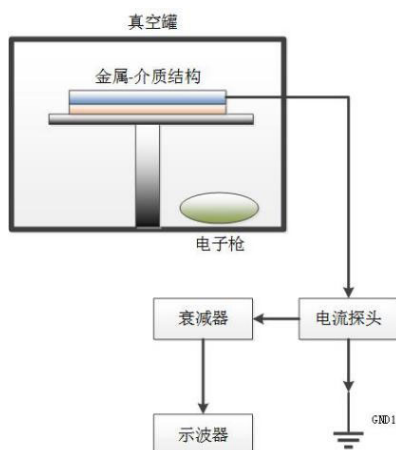


Figure 4. Low-pressure electronic irradiation test platform



Figure 5. Vacuum system of low-pressure along-surface flashover test platform

The structure of the medium-metal electrode designed in

the test is shown in Figure 6, which selects three kinds of media commonly used in spacecraft, PI, EP and PTFE, for testing; At the same time, the dielectric film is set to different thicknesses, which can realize the study of the flashover discharge law along the surface under the conditions of different materials and different media film thicknesses.



Figure 6. Structure of a dielectric-metal ground electrode

The measurement system adopts Tektronix's CT-1 current probe, with a frequency band of 25kHz to 1GHz, a rise time of 350ps, a sensitivity of 5mV/1mA, a maximum peak pulse current of 12A, and a propagation delay of 3.25ns. The oscilloscope uses the TektronixTDS7404B digital oscilloscope, the test bandwidth is 4GHz, the maximum sampling rate is 20GS/s, and the specifications meet the test requirements. To prevent the measured electrostatic discharge current from damaging the oscilloscope, a 30dB attenuator is added between the oscilloscope and the current probe, with a frequency band range of DC to 2000MHz, to protect the oscilloscope. The test sample was charged using an electron gun and the surface potential of the medium was measured using the EST102 vibration capacitive electrometer; At the same time, the CT-1 current probe is used to collect the current signal on the ground circuit of the electrode discharge, and the attenuator is connected to the oscilloscope input to observe and record the dielectric discharge. In addition, the Agilent 34460A nanoampere connection probe is used to monitor the electron beam irradiation current intensity of the electron gun. The test site is shown in Figure 7.

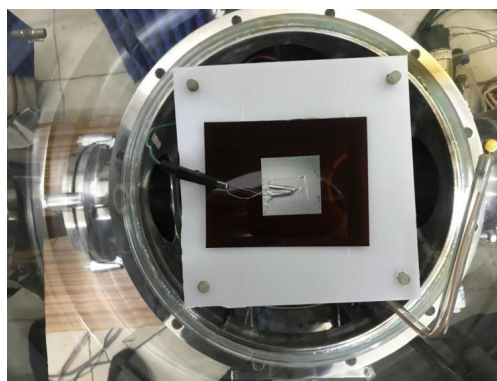


Figure 7. Sample connection in a vacuum tank

Before the test, first place the test material according to the test schematic, and connect the instrument and equipment, pump the vacuum tank to a vacuum state below 10^{-3} Pa, and then adjust the electron gun high voltage source voltage, set the electron beam energy flow density to a fixed value, use the electron beam to irradiate and charge the surface of the material, a total of 300s, and use the vibration capacitive electrometer to observe and record the surface potential of the

material every 10s; At the same time, the oscilloscope is used to observe and record the discharge of the material to the ground electrode, and record the discharge frequency and current waveform. During the test, the electron beams with different energy flow densities were used to irradiate the test samples, and the influence of the electron beam energy and the thickness of the dielectric film on the electrostatic discharge of the material was analyzed and studied.

4. Test Results and Analysis

4.1. Effect of Electron Beam Energy on The Charging Potential on The Surface of Dielectric Materials

When the vacuum degree is less than 10^{-3} Pa, the beam density of $5\text{nA}/\text{cm}^2$ electron beam is used to irradiate the PI, PTFE and EP films with a back-grounded aluminum-platinum area of $5\times 5\text{cm}^2$ and a thickness of 0.2mm , respectively, the irradiated medium surface is $10\times 10\text{cm}^2$ square, and the surface potential of the specimen is measured every 10s, and the surface potential change trend in the 300s time is shown in Figure 8.

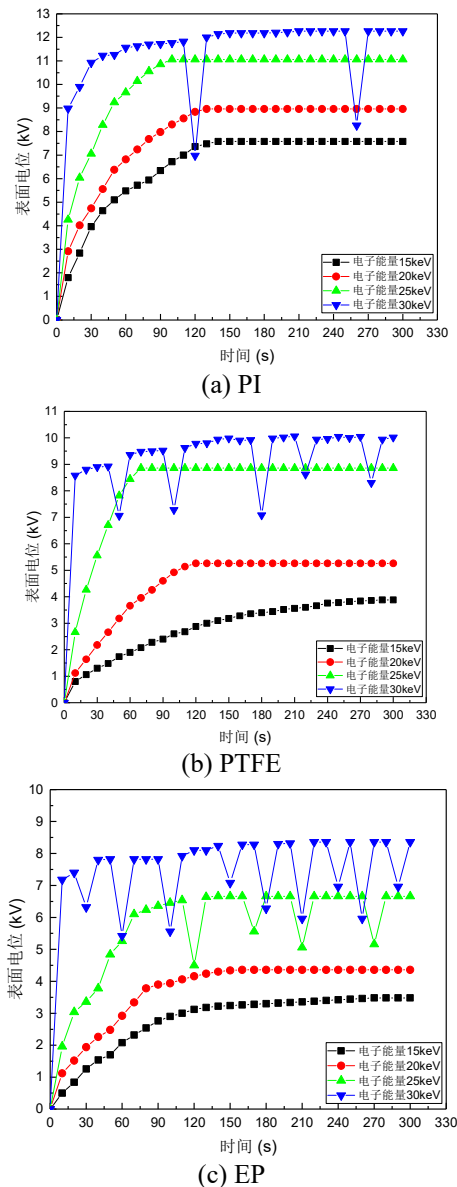


Figure 8. The change law of charging potential on the surface of the three media

As can be seen from Figure 8, when using an electron gun to irradiate and charge the three materials of PI, PTFE and EP, the surface potential of the three materials is gradually raised in the process, although the surface potential of the material will decrease due to electrostatic discharge, resulting in charge discharge, but the potential on the surface of the medium will still gradually increase, and finally reach a limit value of dynamic equilibrium (surface charging balance potential); And as the energy of the irradiated electron beam increases, the equilibrium potential of the surface also increases. Since the secondary electron emission coefficient of PI and other dielectric materials is less than 1 [10], when irradiating PI, PTFE and EP with an electron gun, the surface of the three materials will gradually accumulate electrons, so that the negative potential on the surface of the surface will gradually increase, at this time, a gradually increasing electrostatic field is established between the surface of the medium and the grounding layer on the back side, and the direction is pointed to the surface of the medium by the ground electrode. On the one hand, under the action of this electric field, a dark current will be generated inside the medium, and when the dark current is less than the charging current of the electron beam on the surface of the medium, the surface charge of the medium will show a gradual upward trend [19]. On the other hand, due to process problems in the production process of dielectric materials, some click-through field strengths inside the medium are lower than other parts, and these points may first establish discharge channels in the process of gradually increasing the electrostatic field E_c ; At the same time, the surface roughness of the medium is not uniform, resulting in the potential of some parts of the surface of the electron beam on the charging process of the dielectric material is higher than other places, and the electrostatic field E_e established under the action of the adjacent ground electrode is higher than that of other places, and these places may become discharge channels during the process of surface potential increase. When these discharge channels produce electrostatic discharge, it will cause the surface charge of the medium to be discharged and the surface potential of the medium will decrease; When the charge-discharge process occurs repeatedly and the dynamic equilibrium is reached, the maximum potential of the surface of the medium will correspondingly reach a limit value (surface charging balance potential).

Theoretically, due to the blocking effect of the surface potential of the medium on the electron beam, when the electron beam charges the medium, the maximum potential that can be achieved on the surface of the medium is numerically equal to the energy of the electron beam [20-22]. Under the action of electron beam irradiation with the same beam density, the increase in electron energy will lead to a decrease in radiation-induced conductivity [23], so in the dynamic balance process of charge-discharge of the electron beam irradiation medium material, with the increase of electron energy, the leakage current of the medium decreases, and when the equilibrium potential is reached, the amount of electron charge accumulated on the medium will increase, resulting in an increase in the balance potential of the surface.

4.2. Comparative Analysis of Charging Potential on The Surface of Different Thickness Media

When the vacuum degree is less than 10^{-3} Pa, the beam

density is 5nA/cm² and the energy is 30keV electron beam, and the PI, PTFE and EP materials with thicknesses of 0.1mm, 0.2mm and 0.5mm are irradiated and charged respectively, the irradiated medium surface is 10×10cm² square, the back side is 5×5cm² square aluminum platinum grounding, and the surface potential is tested every 10s, monitoring a total of 300s. The relationship between the surface potential of the specimen over time is shown in Figure 9.

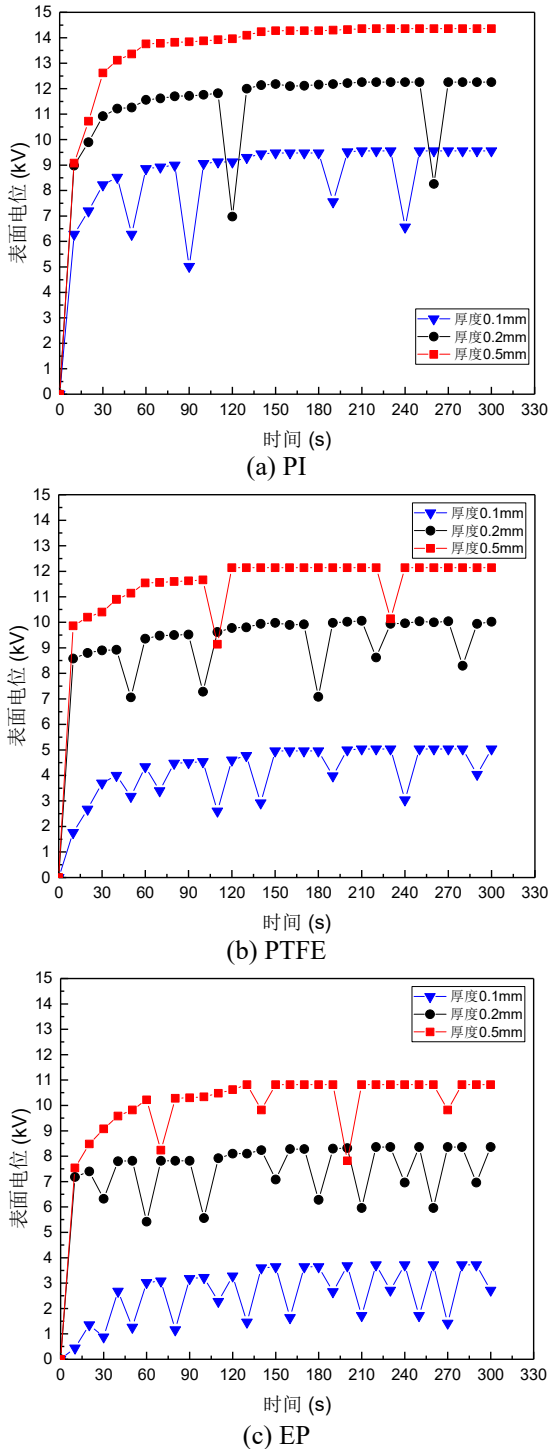


Figure 9. The surface charging potential of different thickness medium changes

As can be seen from Figure 9, during the charging of the medium using a high-energy electron beam, the final equilibrium potential reached increases as the thickness of the medium increases; Among the three materials of the same thickness, under the same conditions, the PI charging

potential is the highest and the number of discharges is the smallest. For the same kind of dielectric film of different thicknesses, under the premise of the same surface roughness, the surface charge distribution is similar during the charging process of using the electron beam; However, due to the different thickness of the material, the dielectric properties of the material are different, that is, the thicker the material, the better the dielectric properties. As a result, in the process of dynamic balancing of charging-discharging of the dielectric material using electron beam, as the thickness of the dielectric material increases, the dielectric properties increase, the smaller the leakage current inside the dielectric material, and the surface of the material can eventually reach a higher dynamic equilibrium potential.

4.3. Comparative Analysis of Charging Potentials on The Surface of Different Dielectric Materials

Comparing the discharge characteristics of different materials in Figures 8 and 9, it can be found that in the three materials, the frequency of EP discharge is higher under the same conditions, and the dynamic charging potential that can be achieved on the surface of the material is the lowest; PI discharge frequency is the lowest, and the highest dynamic charging potential can be achieved on the surface of the material

Among the three materials, due to the smallest pi surface roughness and the largest EP surface roughness [24,25], the surface charge distribution of the EP material under the same electron beam irradiation charging conditions is the most uneven, and there may be more discharge channels inside and current leakage

The rate is faster, the surface accumulated charge ability is poor, and the (dynamic) charging potential that can be achieved on the surface of the material is the lowest; The surface charge distribution of PI material material is more uniform, the internal discharge channel of the material is less, the current discharge rate is slower, and the dynamic charging potential that can be achieved on the surface of the material is the highest. In addition, the dielectric constant can reflect the energy loss and storage capacity of the medium to the electrostatic field, the PI relative dielectric constant is 4.8 [26], the EP relative dielectric is usually between 3 and 4, the PTFE relative dielectric constant is usually between 1.8 and 2, for the 0.5mm PI film, because its own dielectric properties are better than the other two materials, so under the same charging conditions, the leakage current inside the medium is relatively small, and the surface equilibrium potential achieved is higher than that of the other two materials.

5. Conclusion

Taking the three typical dielectric materials commonly used in spacecraft as the research object, a test research platform for charging and discharging typical dielectric materials of spacecraft is established, the typical structure of the surface of the spacecraft is simulated by metal-dielectric structure, the charging process of the spacecraft surface in the operating environment is simulated by means of electron gun injection into the electron, the influence of electron beam energy and dielectric film thickness on the material charge and discharge discharge is analyzed, and the change law and influencing factors of flash-line discharge along the surface are experimentally studied, and the following conclusions are

obtained:

(1) Under vacuum conditions, when using a high-energy electron beam to irradiate and charge the three materials of PI, PTFE and EP, the surface potential of the three materials is gradually increasing, although the surface potential of the material will decrease due to electrostatic discharge, resulting in charge discharge, but the potential on the surface of the medium will still gradually increase, and finally reach a limit value of dynamic equilibrium (surface charging balance potential); And as the energy of the irradiated electron beam increases, the equilibrium potential of the surface also increases.

(2) Under vacuum conditions, comparing the same charging method with the three media, it is found that the discharge frequency of PI is the lowest, and the surface dynamic balance potential is the highest; PTFE centered; EP discharge has the highest frequency and the lowest surface dynamically balanced potential. The thicker the dielectric material, the lower the discharge frequency, and the higher the surface dynamic balance potential.

(3) The surface properties of the material have an important impact on the flashover along the surface, and the surface of the material is treated by introducing a transition medium with a relatively small dielectric constant, increasing the surface roughness and conductivity of the material, increasing the hydrophobicity of the material, etc., reducing the flash network voltage is not only obvious, but also simple and easy, and gradually becomes an effective means of today's flash network protection.

References

- [1] Lei Yangjun, Xiao Dingquan. The phenomenon of along-surface flashover of ceramic insulators in vacuum and its research progress[J]. *Functional Materials*, 2003, 34 (6): 630-637.
- [2] Chang Liang, Ma Kui, Wang Jinzhong. Research status of flashover phenomenon along solid dielectric in vacuum[J]. *Ningxia Electric Power*, 2009(3): 20-23.
- [3] Xiao Li, Wang Yu, Yan Ping. Research and analysis of gas generated by vacuum side discharge[J]. *Insulating Materials*, 2011, 44 (6): 56-64.
- [4] Chen Chengwei, Cai Xinjing. Development of experimental system for flashover of insulating materials along surface under atmospheric pressure[D]. Jilin: Northeast Dianli University, 2015.
- [5] Zhang Zhenjun, Zheng Xiaoquan, Wu Wenbin, et al. Characteristics of polyimide vacuum DC along the surface at different temperatures[J]. *Journal of Xi'an Jiaotong University*, 2014, 48 (4): 48-51.
- [6] Zhou Lidong, Sun Yongwei, Yuan Qingyun, et al. PTFE flashover voltage law along the surface[J]. *Strong Laser and Particle Beam*, 2017, 29(8): 1-4.
- [7] Hao Zhiyuan, Ji Changsheng, Song Ying. Study on surface modification of PTFE by argon plasma jet[J]. *Journal of Yan'an Jiaotong University*, 2014, 48(4): 59-67.
- [8] Dong Guojing, Liu Tao, Li Qingmin. Numerical simulation of air-polyimide insulation along-surface discharge process under pulsed electrical stress[J]. *Transactions of China Electrotechnical Society*, 2020, 35(9): 2006-2019.
- [9] Cui Yuhao. Study on discharge characteristics of surface of metamaterial skin under the action of impulse voltage[D]. Hefei: Hefei University of Technology, 2020.
- [10] Xu Bin. Research on the surface charging law and protection method of spacecraft[D]. Shijiazhuang: Ordnance Engineering College, 2013.
- [11] Du B X, Li J, Du Q, Fu M L. Surface charge and flashover voltage of EVA/CB nanocomposite under mechanical stresses[J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2016, 23(6): 3734-3741.
- [12] Li F, Jiang J H, Xu L, Kang J J, et al. Investigation on surface flashover characteristics of the insulator with different transformer oil coating conditions in vacuum[C]. // 2016 27th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), 2016(1): 1-4.
- [13] E.K. Her, T.J. Ko, B. Shin, et al. Superhydrophobic transparent surface of nanostuctured poly(methyl methacrylate) enhanced by a hydrolysis reaction[J]. *Plasma Process Polym*, 2013(10): 481-488.
- [14] Blaise G, Le Gressus C. Charging and flash over induced by surface polarization relaxation process[J]. *Journal of Applied Physics*, 1991, 69(9): 6334-6339.
- [15] Chalmers I D, Lei J H, Yang B, et al. Surface charging and flashover on insulators in vacuum[J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 1995, 2(2): 225-230.
- [16] De Tourreil C H, Srivastava K D. Mechanism of surface charging of high-voltage insulators in vacuum[J]. *IEEE Transactions on Electrical Insulation*, 1973, 8(1): 17-21.
- [17] ZHANG Jianping. Study on electrostatic discharge effect of typical material components of spacecraft under strong field action[D]. Shijiazhuang: Army Engineering University, 2021.
- [18] Song Manqing. Effect of roughness modification on flashover and surface charge characteristics of epoxy resin materials[D]. Baoding: North China Electric Power University, 2021.
- [19] Wang Yan, Zhang Zhenlong, Quan Ronghui, et al. Research on Satellite Dielectric Conductivity Measurement Technology for Deep Charging Evaluation[J]. *Spacecraft Environmental Engineering*, 2012, 29(4): 425-429.
- [20] Wang Dan, He Yongning, Li Yun. Analysis of charged phenomenon caused by electron beam impacting the surface of medium[J]. *China Space Science and Technology*, 2017, 37(02): 1-10.
- [21] Bedingfield K L, Leach R D. Spacecraft system failures and anomalies attributed to the natural space environment[R]. NASA RP-1390, 1996.
- [22] Mandell M J, Davis V A, Cooke D L, et al. Nascap-2K spacecraft charging code overview[J]. *IEEE Transactions on Plasma Science*, 2006, 34(5): 2084-2093.
- [23] Yao Hong, Zhang Zhanwen, Huang Yong, et al. Influencing Factors of Surface Roughness of Polyimide Thin Films[J]. *Strong Laser and Particle Beam*, 2011, 23(7): 1861-1866.
- [24] Wang Yunying, Meng Jiangyan, Wang Yunping. Effect of low temperature plasma treatment on surface properties of PTFE[J]. *Journal of Aeronautical Materials*, 2009, 29(05): 77-81.
- [25] Wang Tao, Zhou Kaifeng, Li Zhilei, et al. Study on the surface morphological characteristics of epoxy resin and silicone rubber before and after DC side flashover[J]. *Insulation Materials*, 2020, 53(11): 6-11.
- [26] Meng Zhicheng. Study on the influence of ambient temperature on the charging characteristics of spacecraft dielectric materials[D]. Shijiazhuang: Ordnance Engineering College, 2017.
- [27] Yu Kaikun, Zhang Guanjun, Zheng Nan, et al. The effect of laser treatment on the flashover characteristics of alumina

- ceramics in vacuum[J].Transactions of China Electrotechnical Society, 2009,24 (1): 28-34.
- [28] GUO Yuewen. Surface treatment of alumina ceramics and its influence on the performance of vacuum along the surface[D].Xiangtan:Xiangtan University,2020.
- [29] Yan Jiyuan, Liang Guishu, Kang Yuchan, et al. Study on Gradient Etching and Flashover Properties along the Surface of Plasma of Epoxy Resin[J]. High Power Laser and Particle Beams, 2021,33 (6): 065016.
- [30] Ding Ziyu, Xing Zhaoliang, Huang Xuwei, et al. High-frequency side-side discharge characteristics of silicon-oxygen-containing polyimide films[J].Proceedings of the CSEE, 2021,41 (1): 211-221.
- [31] Wang Ruixue,Gao Yuan,Zhang Shuai,et al. Study on the influencing factors of methane conversion in pulsed dielectric barrier discharge[C].//Abstracts of the 18th National Plasma Science and Technology Conference. Xi'an, Shaanxi,2017.
- [32] Shen Wei,Li Qiu,Li Shengtao. Improvement of Flashover Performance and Mechanism of Epoxy Nanocomposites in Electron Beam Irradiation Treatment[J]. Proceedings of the CSEE, 2020,40 (22) : 7144-7152.
- [33] Li Yasha,Xia Yu,Liu Shichong,et al. Discussion on the phenomenon of surface discharge along the surface of bulk materials from the change of charge trap characteristics of polyimide single-molecule chain[J].Acta Physica Sinica, 2022,5 : 052101.