Cathode Erosion Performance of Applied-Field Magnetoplasmadynamic Thruster

IEPC-2019-314

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Ge WANG[1], Yong LI[1], Cheng ZHOU[1] , Yanming WEI[1], Yuntian CONG[1], Kun SUN[1], Baojun WANG[1]
Beijing Institute of Control and Engineering, Beijing 100190,China

Abstract: During the operation of the MPD thruster, the cathode will be continuously bombarded by the high temperature plasma, so there will be obvious erosion on the surface of the cathode.And the performance parameters of the cathode have a significant impact on the ignition performance and life of the MPD thruster. Therefore, the cathode erosion test of 100kW MAT-100 MPD thruster of Beijing control engineering institute was carried out, and the cathode erosion was analyzed by SEM. The fundamental way to improve the ablative resistance of the cathode is to improve the high temperature resistance of the cathode or to improve the electron emission ability of the cathode.

I.Introduction

AS we all know, the payload ratio of spacecraft is an important value in space missions. Therefore, reducing the weight of the propulsion system has great practical value to reduce the weight of the spacecraft and increase the payload ratio. With the rapid development of satellite technology and the continuous acceleration of space exploration, traditional chemical propulsion no longer have distinct advantage. On the contrary, people have very strong expectations for new electric propulsion technology, among which the Magnetoplasmadynamic (MPD) thruster is promising type of electric thrusters.

During the operation of the MPD thruster, the cathode will be continuously bombarded by the high temperature plasma, so there will be obvious erosion on the surface of the cathode, which resulting in the decrease of the electron emission performance of the cathode and blocked of the electron emission, and then the thruster failed. At present, large current and high temperature are one of the key factors restricting the cathode life of MPD thruster. Through a large number of experiments, it is found that the performance parameters of the cathode have a significant impact on the ignition performance and life of the thruster, such as the components and the gas supply mode, etc. The cathode surfaces by erosion also present different physical forms.

The 100kW MAT-100 MPD thruster in this paper is developed by Beijing Institute of Control Engineering, with 58-72mm length of cathode. The material of the cathode is tungsten alloy, including pure tungsten, tantalum- tungsten and lanthanum- tungsten. The thruster has two propellant feeding structures: the cusp feeding and the side opening plus the cusp feeding.This paper is consist of four sections: the first section introduces the test system of the thruster, the second section is the structure of the thruster, the third section is the research of the cathode erosion performance of MPD, and the final section is the conclusion and the future research orientation.

A. MPD test Facility

The test system consists of a vacuum system, a ground power processing equipment, and a integrated system with gas supply, water cooling and temperature measurement. The vacuum system provides a vacuum environment for the MPD thruster ignition with the vacuum 10-1 to 10-4Pa. The ground power processing equipment mainly

---

[1] Beijing Institute of Control and Engineering, wangge522@sina.com

provides the power of the trigger, the electromagnetic coil and the anode, and can measure the steady-state operation discharge voltage and current, the voltage and current of electromagnetic coil, arcing voltage and current parameters of the thruster. The integrated system provides argon gas with a flow range of 0-150 mg/s through the cathode of the thruster, which provides deionized water cooling for the anode and cathode of the thruster and the electromagnetic coil, and measures the related temperature parameters of the thruster.

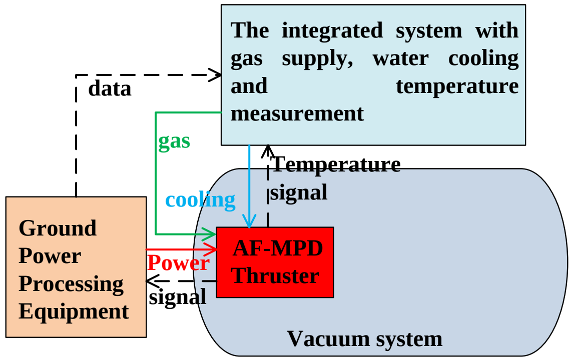


Figure1. Schematic diagram of MPD test system

1 Vacuum system

The test vacuum system for MPD thruster test is consist of a cryopump vacuum system, a Xenon pump vacuum system, a molecular pump vacuum system, a rough vacuum system, a vacuum measurement system, and a vacuum recompression system. All the cathode erosion tests are placed in this vacuum system with stainless steel vacuum chamber of a length of 5 m and 3 m diameter, and the vacuum system is cooled by water.

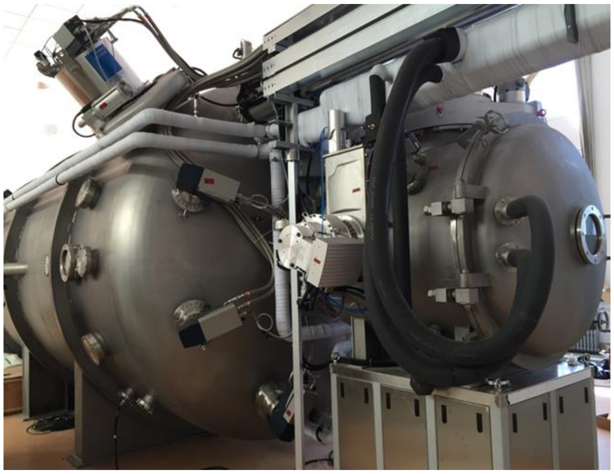


Figure 2. Test vacuum system

2 Ground Power Processing Equipment

The Ground Power Processing Equipment (GPPE) is used to provide high voltage pulses for the start of the MPD thruster and to convert the primary power supply to the appropriate voltage and current during the steady state operation of the thruster. The power supply and the excitation power supply are used to maintain the thruster operation, and at the same time, GPPE is capable of measuring the electrical parameters such as the steady-state working discharge voltage and current of the thruster, the excitation coil voltage and current, and the arcing voltage and current.

The GPPE can provide the voltage and current required by one MPD thruster during operation. The connection relationship between the GPPE and the primary power supply and the MPD thruster is as shown in the Fig. 3:

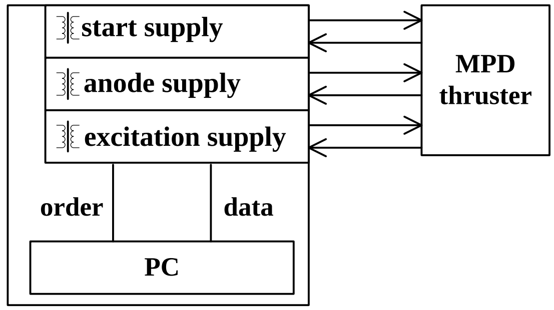


Figure 3. Schematic connection diagram of GPPE and thruster

In order to meet the requirements of starting of arc of MPDT, the high-power MAT-100 MPDT ground power supply is equipped with a maximum power of 1100 kW. The thrust ignition start-up (trigger start-up) voltage is 8000~100000V, and the constant current output is 4000A.

Figure 4. 100kW-power MAT-100 MPDT ground power unit

3 The integrated system with gas supply, water cooling and temperature measurement

The integrated system provides argon gas through the thruster cathode with a flow range of 0-200mg/s, and provides a given flow of circulating cooled deionized water to the anode, cathode and excitation of the thruster. It can measure the temperature of the inlet and outlet pipes, anode casing and cathode. The structure of the gas supply system is shown in the Fig.5.

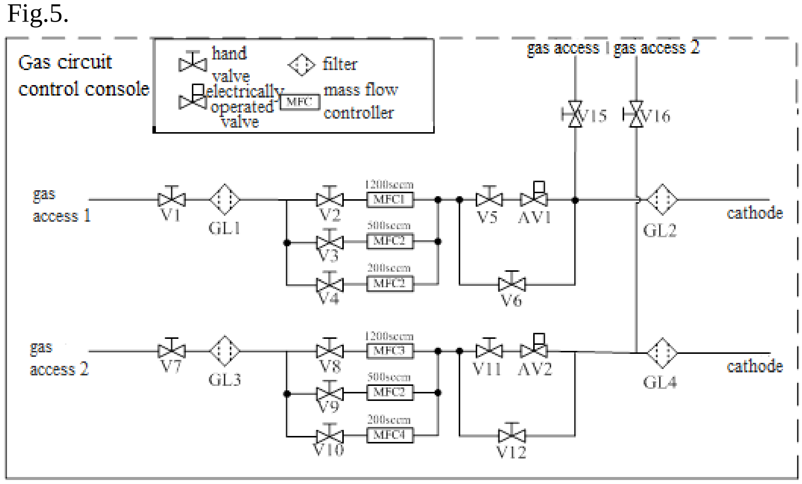


Figure 5. Structure of the gas supply system

B. MAT-100 MPD Thruster

The working principle of B. MAT-100 MPD ThrusterMAT-100 MPD thruster developed by Beijing Institute of Control Engineering.is shown in Fig.6, the MPD thruster consists of anode, cathode and insulator. The anode is made of copper with a cylindrical divergent nozzle, the minimum inner diameter of which is 60 mm. There is an S-shaped cooling channel around the inner wall of the anode. The inlet and outlet of the channel are on the top of the anode, which are separated by a baffle. A slender copper block is employed to connect the anode and electric cable. The junction is on the outer surface of the anode.

The cathode material is tantalum tungsten, with nine propellant channels. The outer diameter of the cathode is 16 mm. The cooling of the cathode is achieved with a water-cooling holder around the cathode base. There is a ring-shaped channel inside the holder. The cold water is injected into the holder from the bottom and flows out from the top. There is a hollow cathode connector on the left side of the cathode. The propellant flows through the center of the connector and into the hollow cathode chamber; there is a large cavity inside the cathode base connecting with nine narrow cylindrical channels. The cavity acts as a buffer to increase the uniformity of the propellant distribution in nine channels. The cathode is connected to the electric cable with an annular copper block, which is installed around the cathode connector.

In addition to the main body of the thruster, an external magnetic coil is also necessary to generate fields for the mechanisms in the MAT-100 MPD thruster; magnetic fields provide a convergent-divergent magnetic field to accelerate the plasma together with the electric field. The field coil consists of 288 turns of circular copper pipes, which act as the passage for both electric current and cooling water. The inner diameter of the coil is 150 mm, while the outer diameter is 500 mm. The highest field strength in the center is 0.25 T with current of 230 A.

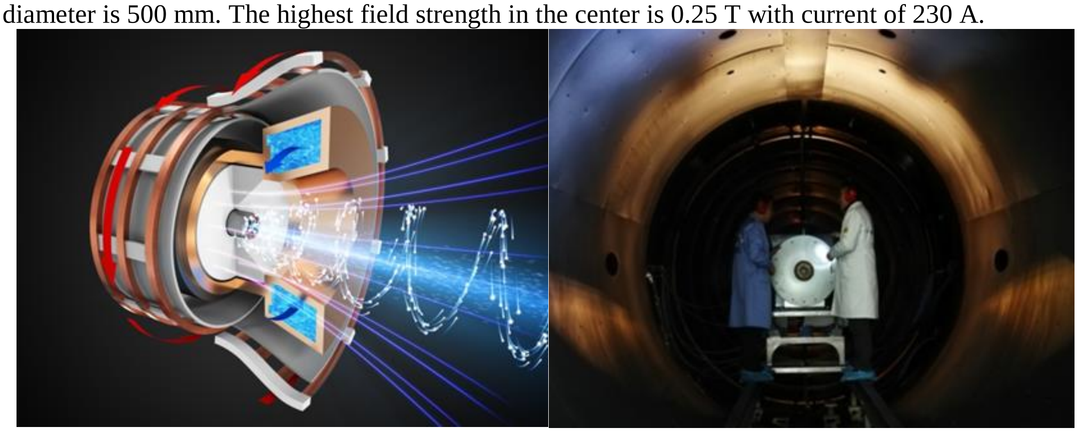


Figure 6. AF-MPD thruster

C. Cathode erosion performance of MAT-100 MPDT

The working principle of MPD leads the cathode to be continuously bombarded by the higher temperature plasma during the operation process, so that the cathode surface will have obvious erosion phenomenon, which resulting in a decrease of the electron emission ability of the cathode, and then the whole thruster. [1-11] Since the service life of the cathode is closely related to its composition and structure, The key to engineering application of the cathode is to achieve the long life cathode through its material composition and structural design. [12,13]

Pure metal cathode is the earliest invented cathode, which has good thermal stability. It is usually processed from refractory metals, such as tungsten (W), molybdenum (Mo), niobium (Nb), tantalum (Ta), rhenium (Re), etc. The metal tungsten cathode is the most representative and the most widely used. The operate at temperature of pure tungsten cathode is typically above 2500 K, and the emission current density of which is about 1 A/cm2, with a low emission efficiency of about 1 mA/W. The pure tungsten cathodes are often used in the detachable systems such as the scanning electron microscopes, the electron spectrometers and the large launch tubes. The work function of metal Ta and metal Mo is slightly lower than W, but the melting point of molybdenum is lower. The metal Ta has a high chemical reactivity and easily to inhale, which requires higher vacuum than W during operation. The metal Re is a metal with excellent chemical stability, low surface adsorption gas, good ion bombardment resistance, high temperature mechanical properties, low evaporation rate and high electrical resistivity. The disadvantage is its expensive cost. It is rarely used alone, which is usually added to tungsten with a small amount formed a W-Re alloy, or the surface of the cathode is coated with a Re coating to improve the electron emission performance of the cathode. Since the pure metal cathode has a single composition and a simple structure, the research on its transmitter has been relatively mature. Formula (1) is the classical Richardson-Deschmann formula for hot cathode electron emission, which indicates that the cathode electron emission current density J mainly depending on the operating temperature T of the cathode and the cathode work function ϕ.

$$J=AT^2e^{-\varphi/kT} \tag{1}$$

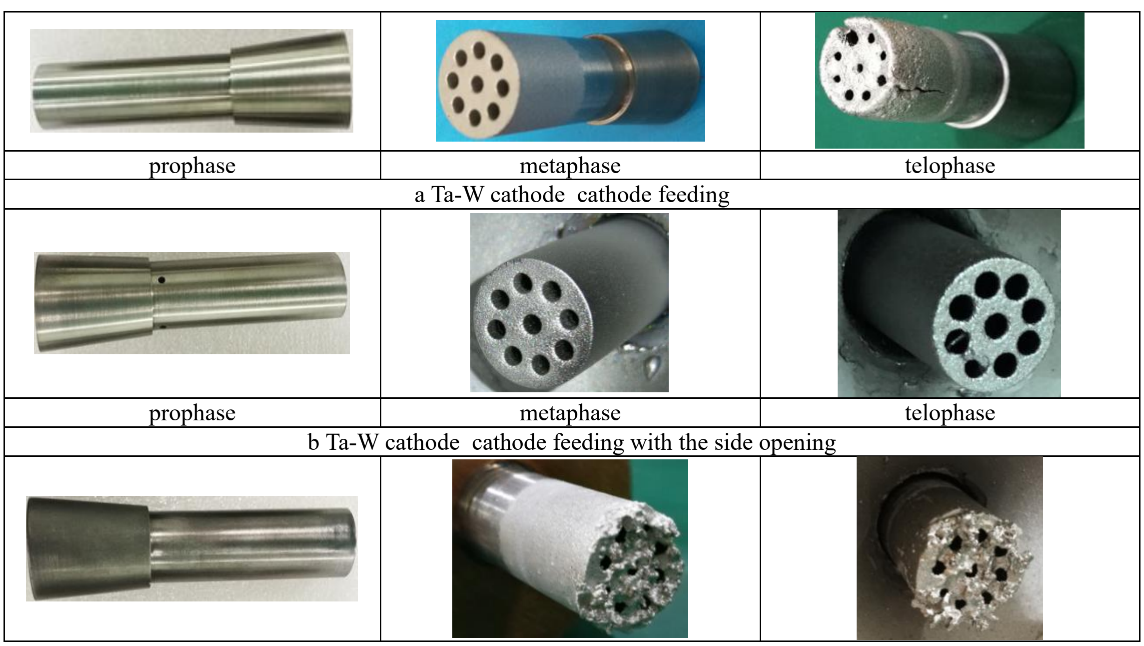
Table 1 shows the work function and emission coefficient of different metals based on the experimental results. Although pure metal cathodes have good stability and resistance to poisoning compared to other cathodes. However, the work function of pure metals is higher. Therefore, in order to obtain a considerable electron emission capability, it is necessary to heat the cathode to a very high temperature, which is a great challenge to the life of the cathode.

Table 1. Some physical properties of common refractory metals

chemical element	melting point/K	$A/(A/cm^2.K^2)$	ϕ/eV	temperature of vapour pressure 1.33×10^{-5}Pa/K
W	3655	60~100	4.52~4.55	2520
Re	3450	50~720	4.72~5.7	2330
Ta	3300	37.2~55	4.1~4.19	2370
Mo	2895	52~115	4.15~4.37	1970
Nb	2770	29~57	3.96~4.01	—

The main problems in the working process of the cathode are the erosion on the surface and the partial melting at extremely high temperature. Figure 7 shows the erosion of the 100kW MAT-100 MPD thruster. Before and after the test, with three different cathode materials and two different structures. It can be found that all the cathodes have melting phenomenon.

As shown in Fig.7(a) cathode failure is the crack appeared on the side surface, running for a long time operation. In Fig.7(b), cathode failure is the hole erosion and expanded to melt for many arced, at the cusp parallel to the side wall. The cusp is severe erosion and melting in Fig.7(c) by arced. And the Fig.7(d) shows the cusp crack leads to erosion and melting at the fissure. Therefore, the failure mechanism can be divided into two kinds: One is because of the large cathode temperature gradient drops (from >3000℃ to 40℃), under the effect of stress, the cathode crack, cathode structure integrity destroyed, thruster failure. Second, the cathodes are deformation due to melting.



prophase	metaphase	telophase
c W cathode cathode feeding		
		
prophase	metaphase	telophase
d La-W cathode cathode feeding		

Figure7. Chart of the cathodes erosion

For the above problem of the cathodes after high temperature erosion, the morphology of the pure tungsten and tantalum-tungsten cathodes were analyzed microscopically. The cathode conducts heat through its metallic properties, therefore, under the high temperature and the constant bombardment of ion current, the cathode surface layer will produce obvious erosion layer. Figure 8 shows the scanning electron microscopy (SEM) morphology images of the front and side of the pure W cathode erosion layer.

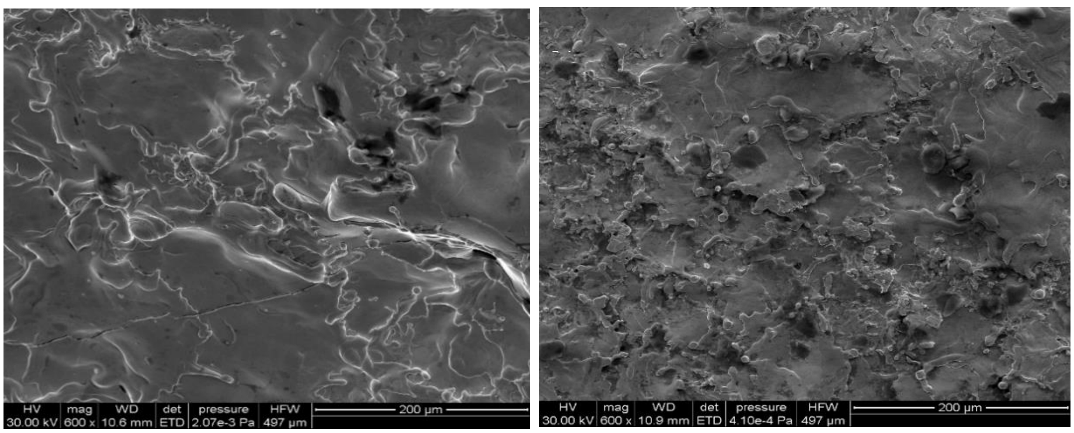


Figure 8. SEM of pure W cathode erosion layer (a) front (b) side

It can be clearly seen from the figure that the ablative layer deforms obviously after high temperature, and the surface roughness is poor. In comparison, the front surface of the erosion layer has better roughness than the side surface. The reason is that the cathode operates at high temperature and a relatively low vacuum degree(10-1-10-2Pa), the severe oxidation takes place on the surface, the cathode front surface is subjected to intense ion bombardment, the ion bombardment strips the oxide layer from the surface, and the side of the cathode has weak ion bombardment where has very thick oxide layer.

For the cathode, the surface oxidation will significantly reduce the cathode emission current density, and at this time, in order to obtain sufficient electron emission ability, the only way is to improve the cathode temperature, but in the condition of poor vacuum degree, the temperature increasing will accelerate the surface oxidation speed, so that the whole cathode goes into a vicious cycle of heating and oxidation. Therefore, improving the working vacuum conditions of the cathode has great significance for improving the life of the MPD cathode.

In addition to surface erosion, the internal structure of the cathode will change obviously at high temperature. As shown in Fig. 9, the erosion layer and the inner unburned region of the W sample were analyzed, the section morphology of the cross-section, the intermediate layer and the unburned layer are showed respectively.

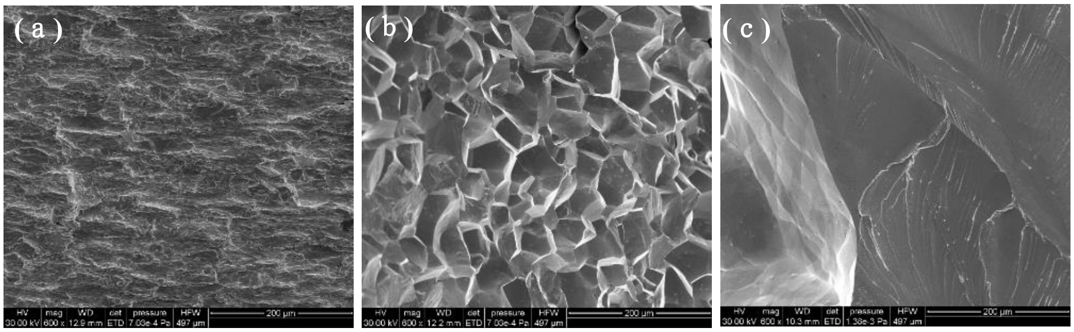


Figure 9. Sectional morphology of different parts of pure W cathode
（a）unburned （b）intermediate （c）erosion

By comparing the ablative conditions of the three areas, it was found that the SEM (FIG. 9 (a)) of the erosion surface section of the cathode showed that the tungsten grains were huge. It was considered that this area was the molten tissue, formed after the rapid solidification of the cathode surface after melting at a high working temperature. The cathode temperature gradually decreases from the end to the bottom, and the cross section of the middle part is analyzed. As shown in Fig.9 (b), the tungsten grain is in an isometric crystal state. Although the melting point of W is not reached of this part, it is higher than the recrystallization temperature of W, leading to obvious recrystallization in this area. Comparing the bottom SEM image of the cathode (Fig. 9(c)), it can be found that the bottom of the cathode is still in a normal tissue state composed of fine W grains due to the relatively timely cooling and relatively low temperature.

Figure 10 shows the morphology of Ta-W cathode after erosion. It can be seen that Ta-W cathode also undergoes the process of melting and resolidification in the erosion process, and the resolidification structure is formed on the erosion surface. The difference between the area without erosion and W matrix is the long grain.

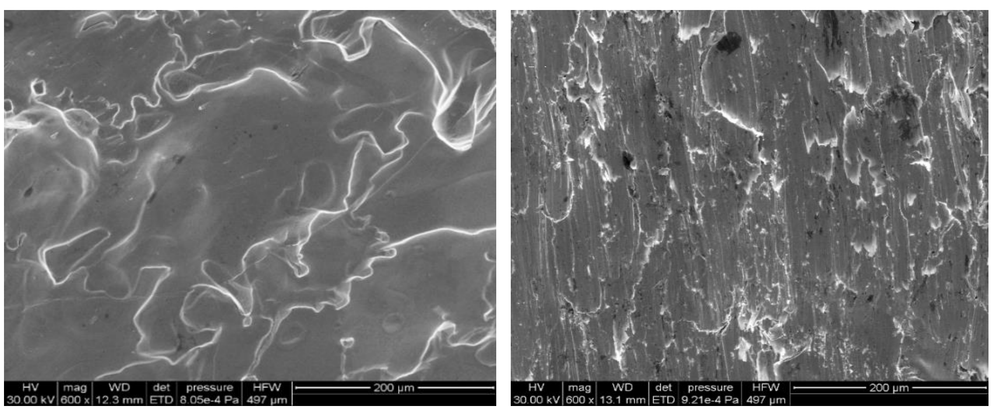


Figure 10. Morphology of erosion and unburned regions of Ta-W cathode after erosion

The oxygen content of the cathode material directly affects the erosion speed of the cathode. The higher the oxygen content is, the faster the erosion speed will be. Therefore, the oxygen content of the cathode material is analyzed,Table 2 shows the test results of element contents in different areas of W cathode and Ta-W cathode.

Table 2. Element contents in different areas of the cathode after erosion

sample	O（%）	W（%）	Ta（%）	average value of O（%）
（W）tip surface erosion area	5.01 4.07	94.99 95.93		4.54
（W）tip surface without erosion area	2.41 3.43	97.59 96.57		2.92

（W）tip lateral surface erosion area	4.81	95.19		4.81
（W-25%Ta）erosion area	3.81 4.15	11.08 9.05	85.11 86.8	3.98
（W-25%Ta）without erosion area	2.64 2.03	10.69 6.53	86.67 91.44	2.335

It can be seen from the composition analysis table that the cathode erosion surface has a higher oxygen content which is caused by exposed to the outside, while the oxygen content inside the cathode ablative surface is slightly higher than that of the non-erosion part, which is caused by the cathode absorbing more oxygen during the molten cooling process, and partial oxidation of this part is occurred of the high temperature. The results of Ta-W cathode analysis show that the Ta content is more than 80%. It is considered that the melting point of Ta is low. At the high temperature, Ta melts and reaches the surface before W, while during the cooling process, the internal W has solidified but Ta with molten state is still on the surface. Therefore, Ta is evenly distributed on the surface of W of the surface layer, finally.

The density of different parts of the sample was analyzed. Table 3 shows the relative density distribution of the different regions of the W cathode and the Ta-W cathode.

The analysis results show that the relative density of the erosion surface area is lower than the original density, because some of the gas is absorbed during the melting and cooling of the surface erosion layer, and the internal oxidation reaction causes the relative density of the whole structure to decrease. The decrease in the density of the Ta-W cathode is more pronounced and is related to the nature of Ta itself. Ta has a strong gas adsorption capacity and is commonly used as a getter in vacuum devices. Therefore, Ta absorbs a large amount of gas under a relatively low vacuum and a high temperature environment, so that the density of the entire cathode is greatly reduced.

Table 3. Relative density distribution of the different regions of the W cathode and the Ta-W cathode

sample	density（%）
W-72-2 erosion surface area	99.14
W-72-2 without erosion bottom area	99.586
W-Ta erosion surface area	85.26
W-Ta without erosion area	98.17

II.Conclusion

In conclusion,the lanthanum tungsten cathode is easy to start arc, but the material has low toughness and prone to fracture. Due to the weak electron emission capacity of the pure tungsten cathode material, the electrode temperature increases, and the erosion melt is serious. Although the tantalum-tungsten cathode are initiation is stable and has the best erosion performance among the three cathodes, but it can only work for 200 hours. The cathode side opening and cusp gas cathode is more resistant to erosion, but has poor thruster performance.

Under the condition of a certain vacuum degree, then imbalance between the cathode electron emission capacity and the working temperature is the main reason for the cathode failure. Therefore, improving the high-temperature resistance performance of the cathode or improving the cathode electron emission capacity are two methods to solve the problem.

Tungsten has the highest melting point as known, the service life of MPD cathode can be extended in the following ways in future studies.

1. According to the requirements of working conditions, the type and quantity of oxides to be added should be reasonably configured, and the oxides should be added in a compound manner, so as to improve the electron emission and antioxidant capacity of the cathode.

2. Reasonably design of the gas supply mode, design the gas supply mode in a compromise between the performance and life of the thruster, and extend the life of the thruster as far as possible on the premise of satisfying ite performance.

3. Improve the heat transfer performance and the high temperature resistance of the cathode.

References

[1]A. I. Morozov, Y. V. Esinchuk, G. N. Tilinin. “Plasma Accelerator with Closed Electron Drift and Extended Acceleration Zone,” Sov. Phys.-Tech. Phys, 1972, vol. 17, No.1, pp.38-45.

[2]B. Duchemin. “An Investigation of Ion Engine Erosion by Low Energy Sputtering,” Thesis for the Degree of Doctor of Philosophy. California Institute of Technology. 2001.

[3]Y. Chiu, B. L. Austin, K. Williams, R. A. Dressler, G. F. Karabadzhak. “Passive Optical Diagnostic of Xe-Propelled Hall thrusters. I. Emission cross sections,” Journal of Applied Physics, 2006, vol.99,pp.1~10.

[4]W. A. Hargus. Jr. “Investigation of the Plasma Acceleration Mechanism within a Coaxial Hall Thruster,” Report NO.TSD-130. 2001, pp. 3~4.

[5]M. H. James. “Low-Perturbation Interrogation of the Internal and Near-Field Plasma Structure of a Hall thruster Using a High-Speed Probe Positioning System,” A Dissertation for the Degree of Doctor of Philosophy, The University of Michigan. 2001.

[6]A. C. Tribble, R. searing, R. Scheps, D. Underwood. “Analysis of Spacecraft-Thruster Interactions for the SPT-70 and SPT-100 Stationary Plasma Thrusters.” AIAA-94- 0330, 30th AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit, Indianapolis, IN, 1994.

[7]G. J. Robert, Y. C. “Edgar. Electric Propulsion. Encyclopedia of Physical Science and Technology,” Third Edition. 2002, vol.5, pp.125-141.

[8]K. N. Kozubskii, V. M. Murashko, Yu. P. Rylov, et, al. “Stationary Plasma Thrusters Operate in Space,” Plasma Physics Reports, 2003, vol. 29, No. 3, pp.277~292.

[9]A. I. Morozov. “The Conceptual Development of Stationary Plasma Thrusters,” Plasma Physics Reports, 2003, vol.29, No.3, pp.235~250.

[10]Lin Zulun, Wang Xiaoju. Cathode Electronics. National Defense Industry Press,2013.

[11]Wang Jinshu, Zhou Meiling, Zuo Tiezhen, et, al. ‘Progress in tungsten-molybdenum hot cathode materials,” Rare metals, 2001,Vol.25, No.1,pp.64-67.