Multi-hour Test of Tungsten Anodes for a Low Power DC Arcjet

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A multi-hour life test of a low-power DC arcjet anode was conducted using a 500 W-class laboratory model arcjet. In order to investigate the anode deterioration process, which is considered to be the most critical life-limiting issue for DC arcjets, three tungsten anodes were fabricated and compared. One was made of conventional pure tungsten, consisting of multiple fine grains of several tens of micrometers in diameter. A second one was also made out of tungsten but consisting of four coarse grains and the last one was single-grain tungsten. After 90 hours of accumulated operation, all these materials showed anode degradation as a result of the so-called constrictor closure phenomenon, although the number and state of cracks were very different depending on the anode type. In the case of the multiple-grain anode and the four-grain anode, cracks were found only along the grain boundaries. However, contrary to our expectations, in the single-grain anode two large cracks appeared in the grains. Also, it was found that crack formation begins in the arcjet start-up phase due to thermal shock by the arc column.

Introduction

Recently, kilowatt-class DC arcjet thrusters have become available for use in commercial satellites, such as the devices manufactured by PRIMEX Aerospace Company (PAC), which has developed 600 s nominal mission average thrusters for communication satellites.[1] However due to limited power availability, such thrusters are not feasible for their use in small satellites. Consequently, arcjet thruster systems are currently applicable only for large satellites. Since low-power arcjet thrusters are greatly beneficial to power-limited satellites for missions such as LEO orbit raising and North-South stationkeeping in GEO, it is desirable to develop a low-power arcjet thruster system featuring a power level of around 500 W as well as adequate operational lifetime.

Due to these considerations, the Institute of Space and Astronautical Science (ISAS) has been attempting to develop a low-power arcjet thruster for several years.[2] Scaling down of the thruster has already been successfully conducted, and a specific impulse ($I_{sp}$) range of 300-400 s has also been demonstrated for an input power regime from 400 to 500 W. In the course of such tests, several major thruster life-limiting issues...
were identified: 1) insulator degradation, 2) cathode degradation, and 3) anode degradation. They are all thermally related.

Furthermore, anode degradation is classified into two types: 1) reduction of the constrictor cross-sectional area or, in other words, constrictor closure, and 2) erosion of the convergent anode surface. During long thruster operation for several hundred hours and multiple firing cycles, together with resultant high thermal stresses to the thruster, the anode constrictor diameter considerably decreases and the surface is eroded. PAC solved this anode lifetime issue by using a special alloy called W-4Re-HfC, which increases the tensile strength at high temperature and improves the endurance properties after accumulated operation periods of around a hundred hours.\[3\]

However, the degradation by the constrictor closure phenomenon is severe and, for that reason, the lifetime of several-kilowatt class arcjets is limited to approximately 1,000 hours. Looking at sub-kilowatt class low-power arcjets, for which electrical power is restricted, the constrictor closure issue will clearly be critical because the arcjet operation is drastically affected by the constrictor diameter, and their operation cannot be stabilized by increasing the discharge power.

Therefore, it is imperative that the problem of anode degradation is resolved. In the case of PAC, higher strength materials have been adopted to overcome such problem. Another way to cope with this issue, which we propose in this paper, is by using materials with few or no grain boundaries, due to the fact that the existence of grain boundaries and grain embrittlement under severe thermal cycles during the arcjet operation is considered to be the major cause of anode degradation.

**Experimental Apparatus**

**Arcjet Thruster**

The so-called SAGAMI-II arcjet thruster used in this study is shown in Figure 1. This thruster was originally designed for operation in a pulsed mode.\[4\] A small size thruster head was adopted so that it may reach thermal equilibrium in a short time. The anode consists of a pure tungsten insert in a molybdenum housing. An expansion nozzle follows the 0.5 mm diameter with a 0.5 mm long cylindrical constrictor.

The cathode consists of a 2 % thoriated tungsten rod that is 2.0 mm in diameter, with a 30 deg half-angle conical tip. Details of the electrode configuration are shown in Figure 2. As for the propellant, a gas mixture simulating decomposed hydrazine, which is basically 67 % hydrogen and 33 % nitrogen by mole fraction, was utilized.

**Anodes**

Three different anodes were employed in order to compare anode degradation and thrust performance. Images of the three anodes as seen from downstream are depicted in Figure 3. One consisted of ordinary (multiple fine) grains of several tens of micrometers in...
diameter (Anode-A). Another was made up of four coarse grains (Anode-B) and the last one was a single-grain (Anode-C). Since it is technically unattainable to make single-grains out of tungsten for arcjets of such size (down to the centimeter level), the portion including the constrictor of Anode-C was made of a single-grain tungsten with an external diameter of 7 mm, and the outside of this was made of multiple fine grains, same as for Anode-A. The joint boundary between the single-grain and ordinary (the multiple fine) grains was brazed with a material consisting of Molybdenum 43 % mass Ruthenium.

Performance Measurement Facility
Two different test facilities were used to conduct arcjet performance measurements and lifetime testing. Thrust performance measurements were conducted in a vacuum tank. Its dimensions are 0.8 m in diameter and 2.0 m in length, being equipped with a swing-arm thrust stand constructed of steel and featuring a water-cooling jacket (Tank-A), as shown in Figure 4. During thrust measurements, the ambient pressure was maintained at approximately 10⁻¹ Torr, using a rotary pump and a mechanical booster pump.

The discharge power was supplied by a switching regulator DC power supply with a maximum operating voltage of 155 V and a maximum current of 10 A. The current ripple was rated at about 10 % at 10 A operation. The start-up was accomplished with a separate circuit using a high-voltage pulse igniter in order to initiate breakdown. High voltage pulses of around 1.5-2.0 kV were generated from one to ten times per second until an arc current was initiated and then the pulses were automatically turned off. In the cases when the thruster did not achieve ignition or the arc extinguished suddenly, the open-voltage was limited to 200 V.

The thrust was measured using a swing-arm thrust stand.[5] Due to the thermal drift, the accuracy of the thrust measurements was within 2 % in the few hundred-milliNewton range. Discharge current and discharge voltage were measured using a Hall type current sensor and a 40:1 voltage divider, with each sensor providing an accuracy of ±0.5 %. Besides these values, the static pressure of the propellant passage was monitored instead of the stagnation pressure at the plenum chamber.

Continuous Test Facility
For continuous thruster operation, a 1.0 m diameter and 2.0 m long steel vacuum tank, with a water-cooling jacket (Tank-B) and without a thrust stand, was employed. Tank-B is shown in Figure 5. It provided an ambient pressure of about 1.0 Torr for a mass flow rate of 25 mg/s. A DC power supply, tuned for low-power arcjet operation, provided a maximum current of 6 A with a 20 % current ripple. The continuous firing was controlled with a personal computer system, which regulated the propellant flow rate and input power to the thruster.[6] The current, voltage, mass flow rate, tank and plenum pressure, and temperature of the anode were recorded every 10 sec.
Experimental Procedure

Continuous Test
A three-step process was followed for the examination of the anode life-test as shown in Figure 6. In the first step, visual examination with a Scanning Electron Microscope (SEM) was carried out. In the second step, arcjet performance measurements were conducted in Tank-A, keeping the propellant mass flow rate at 25 mg/s. In the last step, the arcjet was operated continuously for a 30-hour period in Tank-B. These steps were repeated until the total operational time reached 90 hours for each anode. The selected operational parameters for the continuous test are given in Table 1. The input power and the mass flow rate were kept constant.

![Figure 6. Continuous test procedure.](image)

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SEM Micrography</td>
</tr>
<tr>
<td>2</td>
<td>Measure Thrust Performance</td>
</tr>
<tr>
<td>3</td>
<td>Continuous Operation for 30 Hours</td>
</tr>
</tbody>
</table>

Table 1. Continuous test condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Rate</td>
<td>25 mg/s</td>
</tr>
<tr>
<td>Discharge Power</td>
<td>480 W</td>
</tr>
<tr>
<td>Vacuum</td>
<td>&lt; 1 Torr</td>
</tr>
<tr>
<td>Propellant</td>
<td>N₂+2H₂</td>
</tr>
<tr>
<td>Operation Time</td>
<td>90 hours</td>
</tr>
</tbody>
</table>

Crack Formation Test
An experiment to investigate the timing at which cracks appeared in the constrictor was conducted in Tank-A using Anode-D, which was exactly the same as Anode-C, adopting the following procedure: 1) the arcjet was operated for 10 seconds, and then cooled down for 5 minutes. This procedure was repeated 12 times. After that, SEM micrographs of the constrictor were taken (Crack Test 1). 2) The thruster was operated for 30 minutes, and then cooled down for 15 minutes. Such procedure was repeated 3 times. After that, SEM micrographs of the constrictor were taken (Crack Test 2).

Results and Discussions

Continuous Test
The discharge voltage, current profiles and plenum pressure profiles during the 90-hour operation are shown in Figure 7. There are large notches in the voltage and current graphs about every 7-8 hours corresponding to daily turn on/off of the continuous operation. Also small notches at higher frequency are observed, and these correspond to the so-called low-voltage mode. Although the reason is not clear, for Anode-C these low-voltage modes are mitigated compared to the other anode types. The discharge voltage gradually changed, which may be attributed to shape degradation of the constrictor. Hence, the discharge current automatically changed to keep the input power roughly constant. The plenum pressure gradually increased during the 90-hour continuous test. The anode temperature stayed approximately constant at about 1000 K during operation for all anode cases, as obtained from the thermocouple attached to the outer wall of the anode.

Anode Degradation
Figure 8 shows micrographs of three constrictors taken from the upstream direction before and after continuous operation. Figure 9 shows the change in normalized constrictor area \( \frac{A}{A_0} \) that was measured with the SEM; here A is the constrictor area and \( A_0 \) is the initial constrictor area. It was observed that all three anodes showed constrictor closure during the operation, this being particularly severe in Anode-C. This phenomenon proceeded rapidly for the first 30 hours, and then gradually changed with time in all cases. The number of cracks did not change after the 30-hour period of operation. The increase of plenum pressure is due to this closure. Anode degradation including this constrictor closure is clearly observed in these micrographs. Radial cracks were found for all materials. Anode-A had a large number of cracks and Anode-B had only three. These cracks were along the grain boundaries. The grain boundaries in Anode-B are four, but one of them does not appear in the SEM micrograph. However, Anode-C has no grain boundaries so cracks appeared inside the grain and two of them located along the same line were rather large. Hence, Anode-A and Anode-C were more severely eroded than Anode-B.
Figure 7. Operational profiles for 90-hour continuous test.
Anode-A: initial condition.

Anode-A: after 90-hour operation.

Anode-B: initial condition.

Anode-B: after 90-hour operation.

Anode-C: initial condition.

Anode-C: after 90-hour operation.

Figure 8. Micrographs of constrictors.
Figure 9. Constrictor cross-sectional area variation.

Figure 10. Constrictor of Anode-D after Crack Test 1.

Figure 11. Constrictor of Anode-D after Crack Test 2.

The micrographs of the Anode-D constrictor as taken from upstream after Crack Test 1 and 2 are shown in Figure 10 and Figure 11 respectively. Figure 10 shows the constrictor condition after the arcjet start-up phase, and Figure 11 shows its condition after the steady-state period. One long crack appeared from the edge of the constrictor. This shows that cracks in the constrictor are caused by thermal shock in the arcjet start-up phase. The micrographs in Figure 10 and Figure 11 only differ in terms of the shifting of the “hill” near the root of the crack. This is because the arc column attaches at this point and melts this “hill.” This phenomenon shows that the low-voltage mode arc attaches easily to a root of cracks. As for Anode-C, during the start-up phase rather large cracks appear in the grain so as to relieve the strong thermal stress. It may be possible that the Molybdenum & Ruthenium brazing was partly responsible for the appearance of these large cracks.

**Performance Change**

In order to discuss the performance variation, the total efficiency \( \eta_{\text{total}} \) and the arc efficiency \( \eta_{\text{arc}} \) were calculated from the following expressions,

\[
\eta_{\text{total}} = \frac{F^2/2m}{mH_0 + VI}
\]

\[
\eta_{\text{arc}} = \frac{mH}{mH_0 + VI}
\]

where \( m \) is the mass flow rate, \( H \) is the enthalpy, \( H_0 \) is the enthalpy for the case with no arc discharge, \( V \) is the discharge voltage, and \( I \) is the discharge current. The enthalpy is written as,

\[
H = \left( \frac{A^* P_C}{m} \right)^2 \frac{\gamma^2}{\gamma - 1} \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}
\]

where \( A^* \) is the throat area, \( P_C \) is the plenum pressure and \( \gamma \) is the ratio of specific heats. In our experiments operational parameters were kept basically constant, so the frozen-flow efficiency should not change significantly and we can define nozzle efficiency as follows,

\[
\eta_{\text{nozzle}} = \frac{\eta_{\text{total}}}{\eta_{\text{arc}}} = \frac{F^2/2m}{mH}
\]

Graphs in Figure 12 show the variation in thruster performance, \( I_{\text{sp}} \) and total efficiency, before and after the continuous test. In Figure 13, arc efficiency and nozzle efficiency are shown. The variation of thrust performance can be interpreted with respect to the arc and nozzle efficiency values.
Figure 12. Specific Impulse (data accuracy = ±9 sec) and Total Efficiency variation of three anodes.
Figure 13. Arc Efficiency and Nozzle Efficiency variation of three anodes.
In the case of Anode-A, considering that the arc efficiency stays almost unchanged compared with nozzle efficiency, the \( I_{sp} \) variation can be explained as follows. Analyzing the results for the first 30-hour testing period, it is evident that as time passed the constrictor shape degradation (which may produce shock waves, turbulences and so on, decreasing nozzle efficiency) varied only slightly, producing just a slight decrease in \( I_{sp} \). However, the nozzle efficiency was seen to increase greatly with time because of plenum pressure rising due to constrictor closure, thus producing a large increase in \( I_{sp} \). From these observations, it is concluded that an overall increment in \( I_{sp} \) is realized after a 30-hour operation period using Anode-A. For the rest of the 90-hour period, the pressure stayed basically constant, although the constrictor shape degradation continued its course, resulting in a gradual decrease in \( I_{sp} \).

In the case of Anode-B, the nozzle efficiency stayed constant. However, a slight amount of constrictor closure took place in the 0-60-hour period. Since there was a small amount of shape degradation and just a slight amount of closure, these two processes balanced resulting in no significant variation in nozzle efficiency. Also, since neither nozzle efficiency nor arc efficiency changed, the \( I_{sp} \) did not vary. In the subsequent 60-90-hour period, the arc efficiency and nozzle efficiency remained unchanged, thus yielding no variation in \( I_{sp} \).

As for Anode-C results, the arc efficiency decreased rapidly for the first 30-hour period. This may be due to the appearance of two large cracks, as well as to the rapid increase in nozzle efficiency in the most severe constrictor closure case. These two factors balanced and, as a result, \( I_{sp} \) stayed basically constant. In the 30-60-hour period, arc efficiency and nozzle efficiency showed no variation, and the constrictor closure and anode degradation stopped, thus yielding no change in \( I_{sp} \). For the last 60-90-hour period, the plenum pressure increased slightly again with constrictor closure and, as a result, \( I_{sp} \) showed a minor increase.

Of all three cases, in Anode-B the material erosion was not severe and thrust performance variation was almost unchanged. It is concluded that Anode-B is preferable to the other two anodes within the scope of our experiments.

**Constrictor Closure**

Figure 14 shows the constrictor edge of Anode-C after 90-hour operation. Two surfaces overlap each other like a sort of “strata fault,” which may show the mechanism of constrictor closure. In the arcjet start-up phase, cracks appear or grow and in the arcjet steady operation phase their width becomes narrow due to compressive thermal stress around the constrictor. If the compressive thermal stresses reach the yield stress of the anode material, the constrictor deforms plastically and permanent strain takes place to decrease constrictor area.

![Figure 14. Close up view of the Anode-C constrictor edge after 90 hours.](image)

In the past it has been stated that high-temperature creep processes occur predominantly in 1.8 kW-class arcjet constrictors and closure proceeds as a function of time due to creep.[8] However, in our case we can neglect this phenomenon based on results from our previous study.[9] Thus, for the 500 W-class arcjet, short term plastic deformation causes the closure and, after this, the closure seems to be saturated as shown in Figure 9.

In the case of Anode-A, multiple grains recrystallize under high temperature and the yield stress becomes lower, thus the material develops a tendency to deform plastically. In addition, Anode-A has a large number of cracks, causing closure. As for Anode-B, the yield stress is lower than that of Anode-A because the size of the grain is larger, and there are a few, but long cracks. Thus, constrictor closure was observed. The cracks in Anode-C are the largest of all for any of the three types and the yield stress of the single-grain...
material is lower, and so the constrictor closure was most severe. Also, since constrictor closure may occur even in the Crack Test 2 (Figure 11), the width of the crack shown in this figure is slightly narrower than those from Crack Test 1 (Figure 10).

Conclusions

As for 500 W-class low-power DC arcjet, it was found that constrictor closure takes place due to physical processes related to the occurrence of radial cracks in the constrictor, as well as the existence of thermal stress. To this respect, cracks appear in the arcjet start-up phase due to thermal shock, and constrictor closure and crack generation are observed for the first 30-hour operation. Three tungsten anodes of different crystal structures were compared. All of them showed constrictor closure, but the amount of erosion was found to be very different depending on the material type. From the thrust performance and erosion features, it is concluded that the arcjet thruster anode material should be made of tungsten with few coarse grains, instead of ordinary (multiple and fine grains) tungsten, in order to improve erosion and performance stability. However, a single-grain anode met the difficulty of larger-size materialization and turned out to be a disappointing result due to the incidence of initial cracks by thermal shock at the arcjet start-up phase.

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References


