Endurance Test of PTFE-sheet-fed Pulsed Plasma Thruster

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Abstract: An electrothermal-acceleration-type PPT has the problem that its performance decreases rapidly with increasing in shot numbers. The degradation is caused by the increase in the volume of the cavity by the sublimation of PTFE. A PTFE-sheet-fed PPT (PSF-PPT) was proposed to solve the above problem at previous work. However, the PSF-PPT also had three problems. To solve those problems, the new PTFE-sheet-fed PPT was designed. This paper shows the results of 300 shots test of the new PSF-PPT for a future endurance test.

Nomenclature

A	=	amplitude of the theoretical dumped vibration
I_{bit}	=	impulse bit
Δm	=	mass shot
I	=	moment of inertia
ω_n	=	natural frequency of the theoretical dumped vibration
ζ	=	dumping ratio of the theoretical dumped vibration
K	=	spring constant of the thrust stand
L_{PPT}	=	distance between rotation center of the thrust stand and a PPT
$\Delta\theta$	=	angular displacement of the thrust stand
g	=	acceleration of gravity

Ⅰ. Introduction

A. Electrothermal-acceleration-type PPTs

A pulsed plasma thruster (PPT) is one of the electric propulsion thrusters, which generally uses polytetrafluoroethylene (PTFE; generally called Teflon®) as solid propellant. The PPT is small and light, and has a simple structure. For these reasons, The PPT is considered as an attractive candidate for propulsion system of small satellites. There are two main types of PPTs. One is an electromagnetic-acceleration-type PPT, and the other is an electrothermal-acceleration-type PPT. The electrothermal-acceleration-type can generate a larger impulse bit, or thrust, than an electromagnetic-acceleration-type. However, the electrothermal-acceleration-type has the problem. As shown in Fig.1, its performance is decreasing rapidly with increasing in shot numbers. The degradation is caused by the increase in the volume of the cavity as shown in Fig.2. This phenomenon indicates that PTFE which compose the cavity's inner wall is sublimated by a discharge current as a propellant.

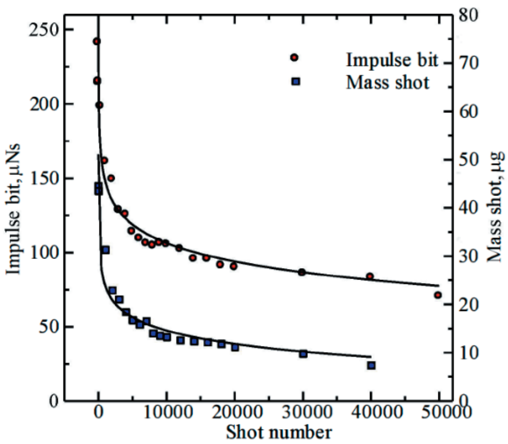

Figure.1 Rapidly degradation of electrothermal-acceleration-type PPT's performance.

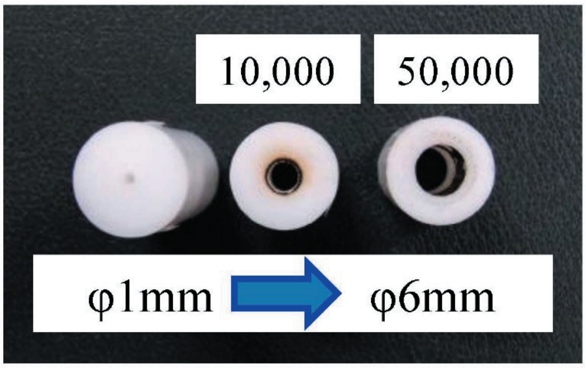

Figure.2 Feature of cavity's volume enlarged by increasing in shot numbers.

B. PTFE-sheet-fed PPTs

In previous work, PTFE-sheet-fed PPT (PSF-PPT, shown in Fig.3) was proposed to solve the above problems. The PSF-PPT consists of electrodes and a cavity made of ceramic. The PTFE-sheet is prepared as a propellant and supplied to the ceramic cavity. Since the ceramic cavity is not sublimated as a propellant and not enlarged by the discharge current, the maintenance of the initial performance is expected. The previous work showed that the PSF-PPT achieved a recovery of the impulse bit by supplying of PTFE-sheet into the ceramic cavity at 800th shot.

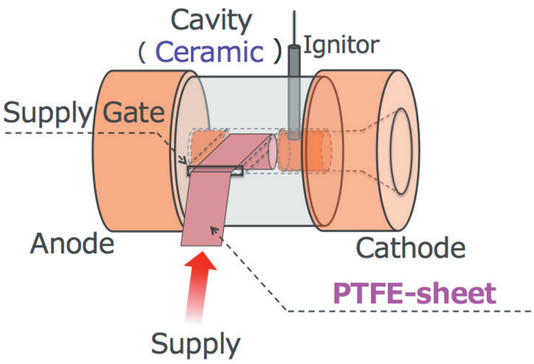

Figure.3 PSF-PPT.

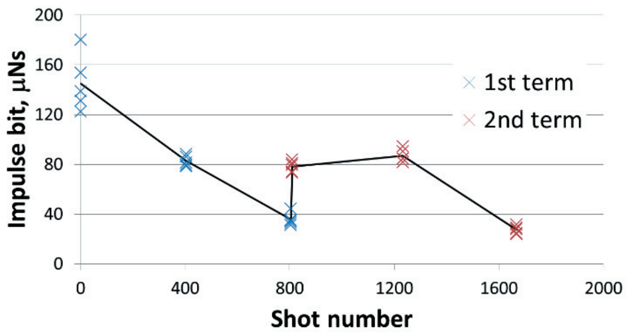

Figure.4 remained PTFE-sheet and carbonization of the cavity.

However, there are still three problems to be solved for the PSF-PPT. The first problem is that a part of the supplied PTFE-sheet remained in the ceramic cavity without being sublimated. The remained propellant prevented the additional supply and caused abnormal discharge. The second is that the ceramic cavity wall is carbonized and an electrical connection occurs between anode and cathode. When the carbonization happens, charging the capacitor became impossible. The remained propellant and the carbonization of the ceramic cavity is shown in Fig.5.

The third is leakage of PTFE gas from the supply gate. This phenomenon causes a loss of the impulse bit.

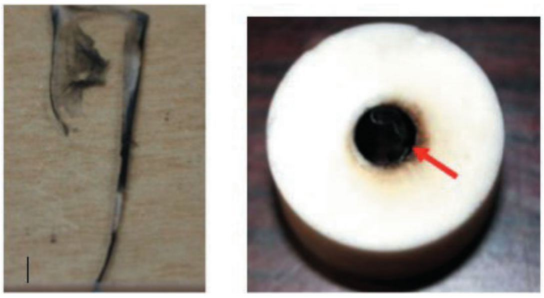

Figure.5 Remained PTFE-sheet (left) and carbonization of ceramic cavity (right).

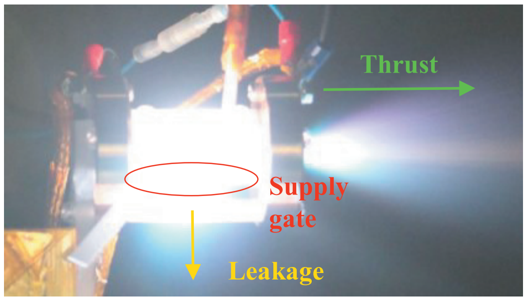

Figure.6 Leakage of PTFE gas from supply gate.

C. Purposes of this study

When the above three problems are solved, PSF-PPTs would be one of the effective methods for solving the decline in the performance of the electrothermal-acceleration-type PPT. Thus, the purposes of this study were decided as following.

【Phase 01】
– Removing the remained PTFE-sheet
– Preventing the carbonization of the ceramic cavity
– Preventing the leakage of PTFE gas

The above three purposes were regarded as Phase 01. In addition, another purpose as Phase 02 were also decided.

【Phase 02】
– Indicating ability to maintain the performance of the PSF-PPT by endurance test.

Ⅱ. Design of new PSF-PPT

To achieve the above purposes, a new PSF-PPT were designed as shown in Fig.7.

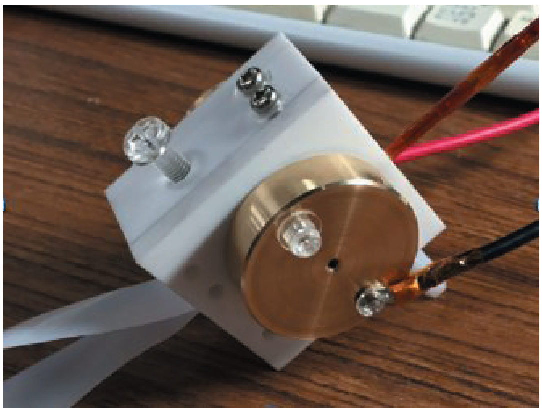

Figure.7 The new type PSF-PPT

The new PSF-PPT includes some ideas for achieving the three purposes of Phase 01.

A. Supply and discharge system

Fig.8 indicates the new PSF-PPT's supply and discharge system.

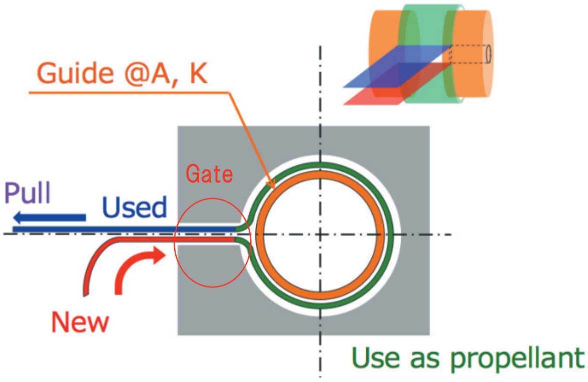

Figure.8 Supply and discharge system for PTFE-sheet.

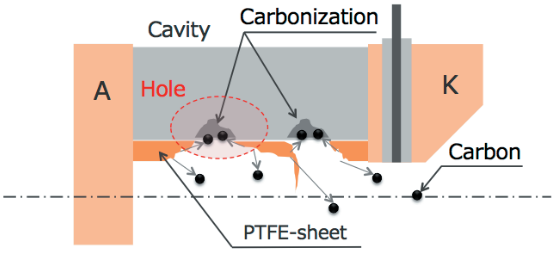

Figure.9 Mechanism of carbonization of ceramic cavity.

The PTFE-sheet is inserted from a gate and wound along the guide in the cavity. And it is also discharged through the same gate. A part of the PTFE-sheet in the cavity is used as propellant. The PTFE-sheet are used as propellant under a restriction. The restriction is the number of operation of the PSF-PPT. The PTFE-sheet is discharged through the gate before its mechanical strength is lost by overuse.

B. Prevention of the carbonization

The abovementioned supply and discharge system is effective for the prevention of the carbonization of ceramic cavity. Fig.9 indicates a mechanism of carbonization. This mechanism was clarified by the previous work. The carbonization occurs from holes on the PTFE-sheet. The holes appear by overuse of the PTFE-sheet. When the inner wall of cavity is covered by the PTFE-sheet fully, the carbonization does not occur. For this reason, a restriction of using the PTFE-sheet (discharge timing of PTFE-sheet) was decided as the following.

– An operation of the discharge is carried out before the holes appear on the PTFE-sheet or the sheet's mechanical strength is lost by overuse.

C. A solution for the leakage of PTFE gas

For solving the leakage of the PTFE gas, a valve such as Fig.10 was manufactured and set between the gate and the cavity. The valve plays a role in sealing a gap between the gate and the cavity. Thus, it is expected to prevent the leakage.

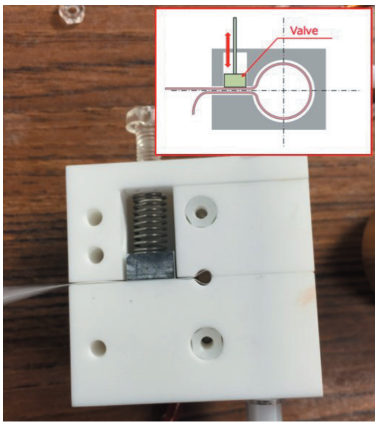

Figure.10 A valve for sealing the PTFE gas.

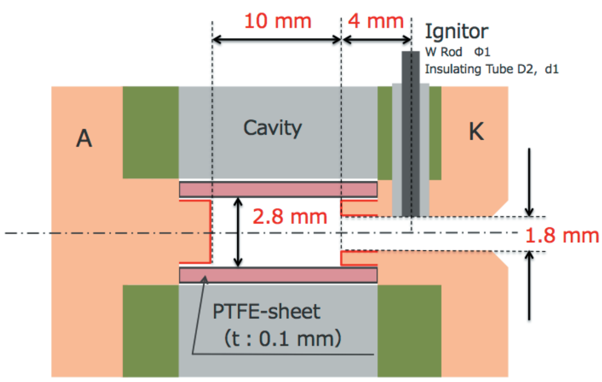

Figure.11 Geometry of the new PSF-PPT.

Ⅲ. 300 shots test and results

A. Geometry of the new PSF-PPT

Fig.8 shows measures of the new PSF-PPT. The inside diameter of the ceramic cavity is 3 mm. Thickness of the PTFE-sheet is 0.1 mm. Thus the actual inside diameter of this PPT is 2.8 mm. The distance between electrodes is 10 mm. The shortest distance between PTFE-sheet and center of the ignitor is 4 mm.

B. 300 shots test

As the preparation of endurance test, 300 shots operational test. The purposes of this test are showed as below.

- Operational confirmation
- Comparison of performance with conventional electrothermal-acceleration–type PPT
- Listing up of problems of the new PSF-PPT

This test was carried out with the procedure as below.

1st. The new PSF-PPT is mounted on a thrust stand in a vacuum chamber for measurement of an impulse bit and a mass shot.
2nd. The pressure is kept below 1.0 mPa.
3rd. The new PSF-PPT is operated 100 shots and performance measurements are done at 20 shots interval.
4th. Supply and discharge of the PTFE-sheet is conducted after the new PSF-PPT is taken out from the vacuum chamber.
5th. Procedures 1st ~ 4th are repeated 2 times.

Procedures 1st ~ 4th are designated as Operation-01. Thus, Opration-01, Opration-02, and Operation-03 in this test was tried.

C. Thrust stand

Fig.12 shows the thrust stand in the vacuum chamber. This stand conducts dumped vibration when the PPT generates impulse bit. The impulse bit and the mass shot are measured by observing the dumped vibration using a laser displacement sensor. An oscillatory waveform obtained by the sensor is fitted to a theoretical dumped vibration. The impulse bit is shown using an amplitude *A* of the theoretical dumped vibration as following.

$$I_{bit} = \frac{AI\omega_n\sqrt{1-\zeta^2}}{L_{PPT}} \qquad (1)$$

On the other hand, the mass shot is shown using the displacement of the balance position $\Delta\theta$ as following.

$$\Delta m = \frac{K\Delta\theta}{gL_{PPT}} \qquad (2)$$

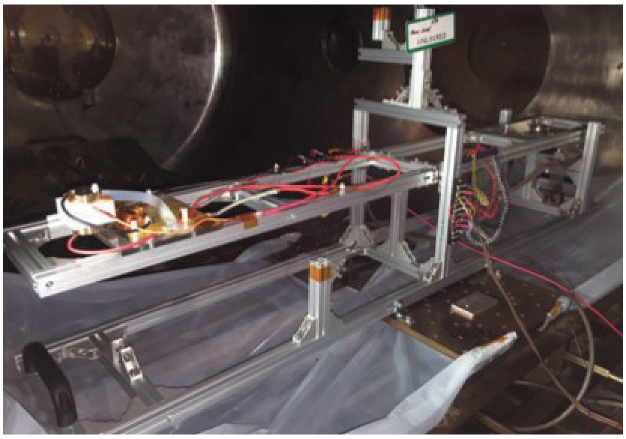

Figure.12 Thrust stand

D. Experimental results

The new PSF-PPT was successfully operated during the 300 shots test. The PTFE-sheet was easily supplied and discharged between the operations. Fig.13 shows the discharge feature of the new PSF-PPT operation. The leakage of the PTFE gas such as Fig.6 was not observed visually.

The shot number history of impulse bit is shown in Fig.14. This figure indicates the impulse bit of the new PSF-PPT is less than the half of the impulse bit of the conventional PPT.

On the other hand, Fig.15 shows the shot number history of mass shot. The results of t of the new PSF-PPT approximately shows the same tendency as that of the conventional PPT. However, the average mass shot of the new PSF-PPT (19 μg) is slightly smaller than that of the conventional PPT (22 μg).

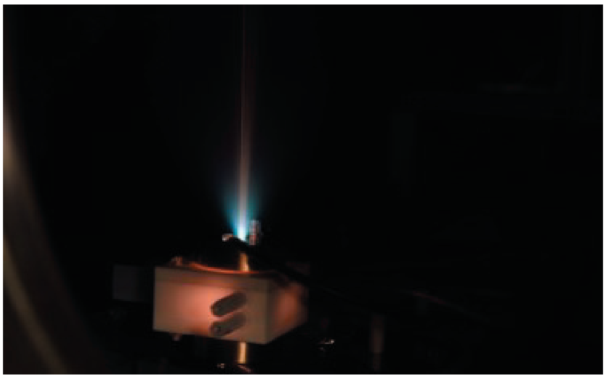

Figure.13 Feature of operation of the new PSF-PPT

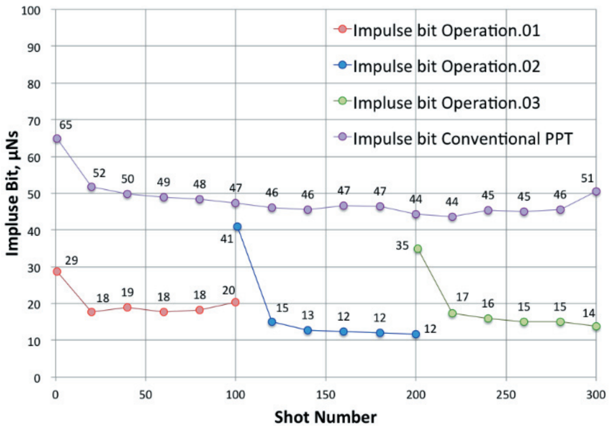

Figure.14 The shot number history of impulse bit.

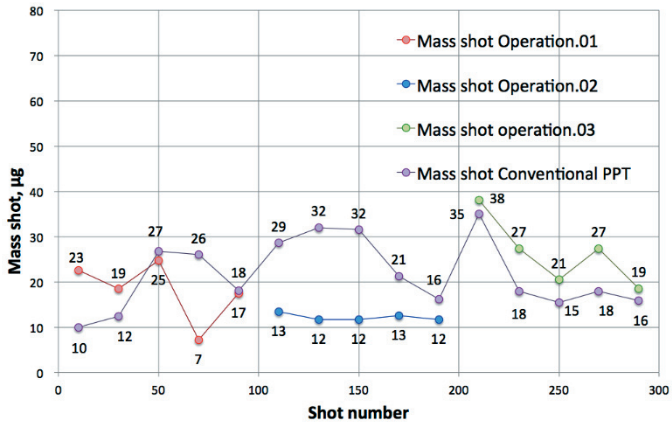

Figure.15 The shot number history of mass shot.

Table 1 shows amounts of change of the cavity parts. Red numbers in Table 1 indicate the increase in mass of each part. After Operation-02, most of the mass of the parts increased.

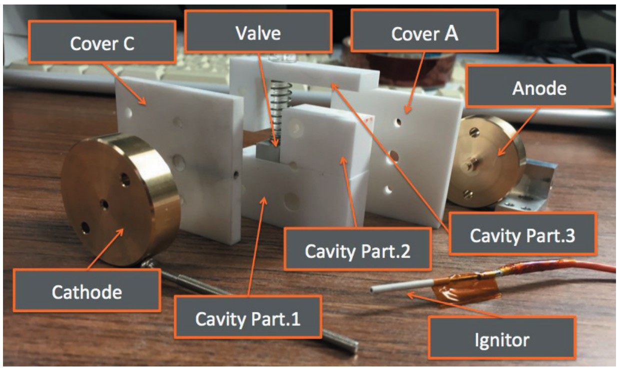

Figure.16 Parts of the new PSF-PPT

Table 1. Amounts of change of the cavity parts

		before Operation	after Operation.01	after Operation.02	after Operation.03
		[g]	[g]	[g]	[g]
Anode	AVE	79.7889	79.7885	79.7881	79.7879
	ΔM		0.0004	0.0004	0.0001
Cathode	AVE	78.6174	78.6169	78.6166	78.6164
	ΔM		0.0005	0.0003	0.0002
Cover A	AVE	24.3293	24.3287	24.3334	24.3321
	ΔM		0.0006	0.0047	0.0013
Cover C	AVE	24.1652	24.1645	24.1666	24.1695
	ΔM		0.0007	0.0021	0.0030
Cavity part.1	AVE	32.9244	32.9243	32.9267	32.9257
	ΔM		0.0001	0.0024	0.0011
Cavity part.2	AVE	13.5967	13.5965	13.5973	13.5963
	ΔM		0.0002	0.0008	0.0010
Cavity part.3	AVE	12.8728	12.8725	12.8739	12.8733
	ΔM		0.0003	0.0014	0.0006
Valve	AVE	2.6733	2.6732	2.6728	2.6727
	ΔM		0.0001	0.0004	0.0001
Ignitor	AVE	5.0146	5.0143	5.0144	5.0140
	ΔM		0.0003	0.0000	0.0004
Total	SUM(AVE)	274.3157	274.2801	274.2868	274.2808
	ΔM		0.0355	0.0067	0.0061

Ⅳ. Problems of the new PSF-PPT for an endurance test

A. Leakage of the PTFE gas

The leakage of the PTFE gas occurred from the cavity after the 300 shots test. Fig.17 and 18 show carbonization of the covers and cavity parts by solidification of the PTFE gas, respectively. The carbonized spots are junctions of parts and sidewalls where the valve moves. The phenomenon indicates the matters as below.

- The PTFE gas leaked from the cavity to the valve's space and a gap between parts.
- The leaked PTFE gas escaped from the gate or was solidified at the gap.
- The mass of the parts increased by the solidification.

In Table 1, only the results of Operation-02 can explain the above mentions. Therefore, it is inferred that the leakage mainly occurred after the Operation-02 because jointing force between the parts at the time was less than the others. However, this inference lacks the reliability. The reason is that the total mass shot of Operation-02 is only 3.5 mg although the total amount of change of the parts is 10 mg. The total mass shot normally has to be smaller than the total mass shot. The reason is considered that water in the air was stuck in the surface of the parts when the new PSF-PPT is taken out in the vacuum chamber.

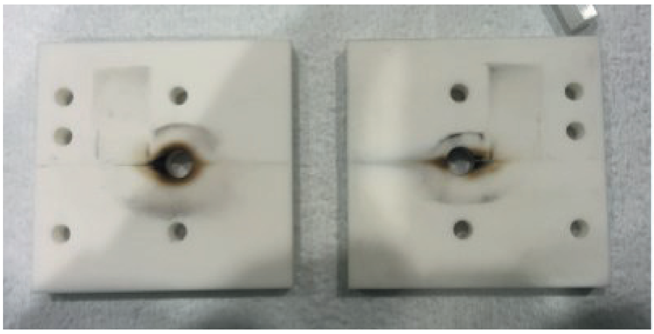

Figure.17 Covers of the new PSF-PPT after 300 shots.

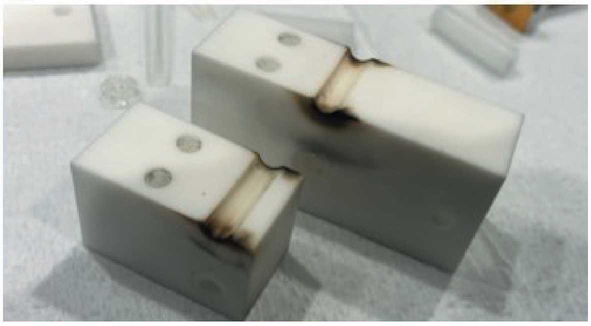

Figure.18 Cavity parts of the new PSF-PPT after 300 shots.

B. Low impulse bit and small mass shot

As shown in Fig.14 and 15, the impulse bit and the mass shot of the new PSF-PPT were lower than the conventional electrothermal-acceleration-type PPT. The results are caused by the above-mentioned leakage of the PTFE gas. In other words, because the amount of the leaked PTFE gas is not exhausted from a nozzle as a propellant, the mass shot is become smaller and the impulse bit is become lower. Additionally, there is a small space between the cavity and the valve in the new PSF-PPT. Due to this small space, the volume of cavity of the new PSF-PPT is larger than that of the conventional PPT. Therefore, the pressure in the cavity is lower than the conventional and as a result, the impulse bit declines.

C. Prospect for endurance tests

From the above, it was found that the new PSF-PPT has the problem of the leakage of the PTFE gas. Moreover, its impulse bit and mass shot of the new PSF-PPT were smaller than that of the conventional PPT. As a result, the endurance tests of the new PSF-PPT were insufficiently carried out. However, the following information from this study was obtained.

- Steady supply and discharge of the PTFE-sheet was achieved.
- Preventing the carbonization between electrodes was achieved for 300 shots operation.

In other words, at present, the problem that should be solved for endurance tests is only the prevention of the leakage of the PTFE gas. In order to strengthen the sealing of the PTFE gas, the further improvement of the new PSF-PPT was conducted. Fig.19 is a picture of the improved new PSF-PPT. Main improvement points are as below.

- The number of tightening points between parts was doubled compared with the former one.
- Tightening force between parts was reinforced.
- Sealing performance of the valve was improved.
- Distance between the valve and the cavity was shortened.

Two of the above are methods for getting rid of clearance between parts, and will prevent the leakage of PTFE gas at junction of parts. The others of the above will bring about not only prevention of the leakage but also improvement of the pressure in the cavity. Since the way of closing the valve changed using a spring into using screws, the valve can seal the PTFE gas stronger. On the other hand, as shown in Fig.20, the distance between the valve and the cavity was change to be zero. The distance of the former was 3 mm. The space caused low pressure in the cavity. The pressure would be better than the former by the improvement.

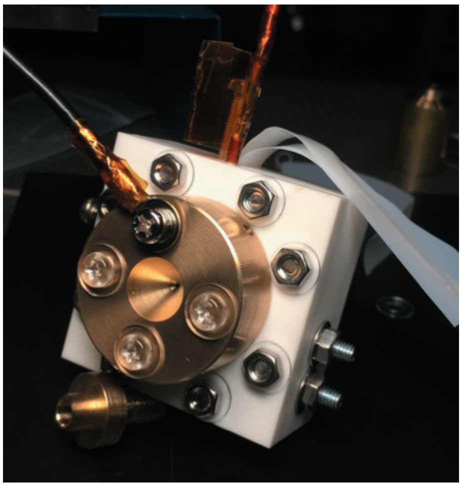

Figure.19 Improved new PSF-PPT.

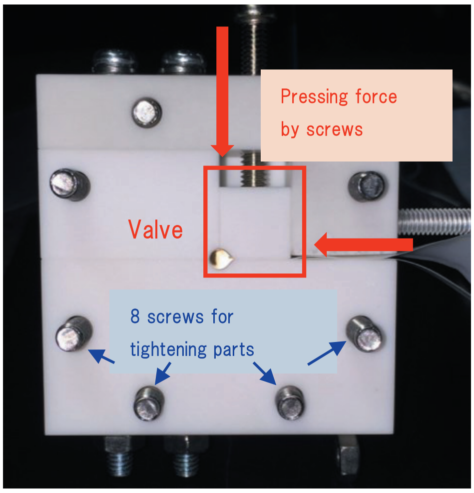

Figure.20 Tightening points of parts and valve closed by screws

V. Conclusions

Conclusions of this study are listed up as below.

- To solve the problems of electrothermal-acceleration-type PPTs and to achieve maintaining performance of PSF-PPTs, the new PSF-PPT was designed.
- 300 shots test of the new PSF-PPT achieved by discharging used PTFE-sheet for removing the remained sheet.
- The new PSF-PPT also achieved prevention of the carbonization between electrodes for 300 shots operation.
- The leakage of the PTFE gas was not prevented in spite of using the valve.
- The performances of the new PSF-PPT are lower than those of the conventional PPT caused by the leakage.
- Solutions of the leakage were proposed.

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