Surface Modification of Pyrolytic-Graphite Grids for an Ion Thruster

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Abstract: This paper describes surface treatments to reduce the frequency of high voltage breakdowns between pyrolytic graphite grids of an ion thruster. The frequency is usually higher than that with molybdenum grids and lowering it is desirable for not losing effective thrust and not damaging the grids. Three methods--sandblasting, laser, and ion etching—were tried using test coupons, and we chose a combination of sandblasting and ion etching as the best. A set of real grids were treated using the method, installed on the ion thruster, and run. The result was compared with that acquired in a previous run using a set of untreated grids. Since the run time was very short, we have not yet confirmed that the method is effective.

Nomenclature

I = current
$\dot{m}$ = propellant flow rate
V = voltage

Subscripts

a = accelerator grid
b = beam
ck = main hollow cathode keeper
d = discharge
nk = neutralizer hollow cathode keeper
MHC = main hollow cathode
MPF = main propellant feed
NHC = neutralizer hollow cathode

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I. Introduction

Japan Aerospace Exploration Agency (JAXA) has developed ion thrusters for ETS-Ⅵ, COMETS, and ETS-Ⅷ and a 20-mN ion thruster for ETS-Ⅷ was applied to Super Low Altitude Test Satellite (SLATS)[1]. We started planning of a successor of SLATS and it requires ion thrusters of longer lives. The endurance test of the ETS-Ⅷ ion thrusters showed that their lives were determined by the erosion of their grids, which were made of molybdenum and coated with ceramic. Lowering discharge voltage is effective to extend the life of a thruster; however, it will be accompanied with lowering the performance of the thruster. We kept this method as a trump card and chose to change the material of the grids at first.

Graphite is known as a material that has higher sputter yields than that of molybdenum; however, it is not usually stiff enough to form grids as fine as ones made of molybdenum. High density graphite is stiffer than normal one but still not stiff enough. Carbon-carbon composite is further stiffer by embedded carbon fibers, but the fibers are scraped off in forming apertures in grids. In addition, there are many voids, which should be filled with matrix, in the body and short-cut fibers, which are not well held by matrix, can slip out into the apertures. Both the existence of voids and slip-outed fibers are not desirable for both long life and suppressing high voltage break downs (HVBD).

Pyrolytic graphite (PG) is a better material than those stated above due to the characteristics as follows[2]:

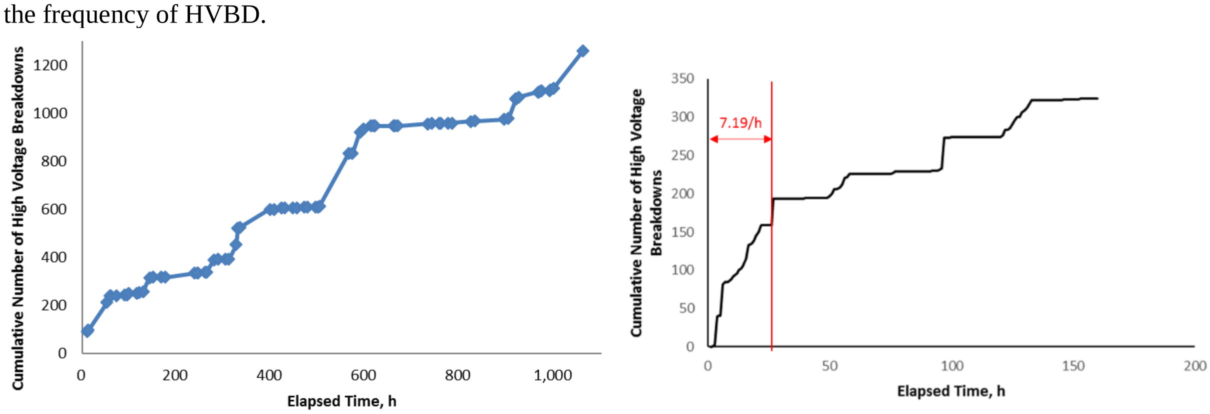
1. Denser than other graphite and C/C; desirable for long life;
2. Stiffer than other graphite and relatively fine grids can be formed.

PG is produced by heating hydrocarbon to its decomposition temperature threshold and permitting the graphite to crystallize.

We have made sets of grids made of PG for an ETS-Ⅷ type ion thruster and run it using them[3]. The longest run time of the grid set was 1,061 hours and the number of HVBD occurred during the period was 1,260. Figure 1 shows the cumulative number of HVBDs as a function of run time and Fig. 1 (b) is a magnification of Fig. 1 (a). The frequency of HVBD in average during the entire period was 1.19 h^{-1}; even though it seemed much higher than those of molybdenum grids, it is not seriously high and it might be lowered by some means. The entire period falls into three categories: initial stage (more specifically first 25 hours), calm periods, and frequent periods. In the calm periods, HVBDs were rare and we can find frequent periods around 100 hours and 130 hours after the start for example. The initial stage is defined as a frequent period before the first calm period and there was an especially frequent period in the initial stage. Frequent HVBDs implies effective thrust loss and could seriously damage the grids at worst. Even though we may leave the initial stage, we want to remove especially frequent periods as much as possible.

Goebel assumed that the edges of the grid surface and fine irregularities locally generated strong electric field and caused HVBD. He sandblasted PG test coupons to round its edges and improved voltage threshold[5]. Martinez et al. improved the threshold voltage by intentionally causing breakdowns; weak arc limited by the power supply rounded edges and removed impurities on the surface[6].

We try three methods including sandblasting in this study to dull edges and to remove fine irregularities to reduce the frequency of HVBD.



(a) (b)

Figure 1. Cumulative number of high-voltage breakdowns[4].

II. Methods

First, we apply three kinds of surface treatment: (1) sandblasting, (2) laser, and (3) ion etching to test coupons made of PG. Second, we observe the coupons using an SEM (Scanning Electron Microscope) and find out which treatment looks the most effective to smooth the surface. Finally, we apply the treatment that looks the most effective to real girds made of PG, operate a thruster with them, and the frequency of HVBD is compared with that obtained in the previous 1,061-hours running.

A. Test coupons

Each test coupon is 5cm x 5cm square and imitates a screen or an accelerator grid in its thickness, hole diameter, and hole center-to-center distance, which grid was used in the 1,061-hour running (see Fig. 2). The SEM photographs of untreated test coupons are shown in Figs. 3 and 4. In Fig. 3, there are numerous sharp white ridges on the perimeter of the aperture and white winding lines on the plane; they correspond to the lines of cleavage. Figure 4 (a) shows a side of a coupon and Fig. 4 (b) shows the other side of the coupon. Both sides do not appear the same because a drill comes in from a side (a) and goes out from the other (b). No burrs, which were usually produced on the drill output side in making a hole in metal body, were found because carbon would rather be cleaved off than stick to the body unlike metal.

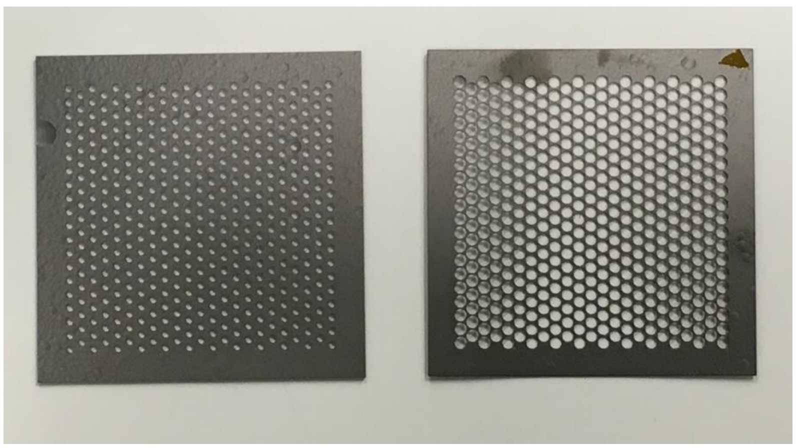


Figure 2. Accelerator-grid type test coupon(left) and screen-grid type test coupon(right).

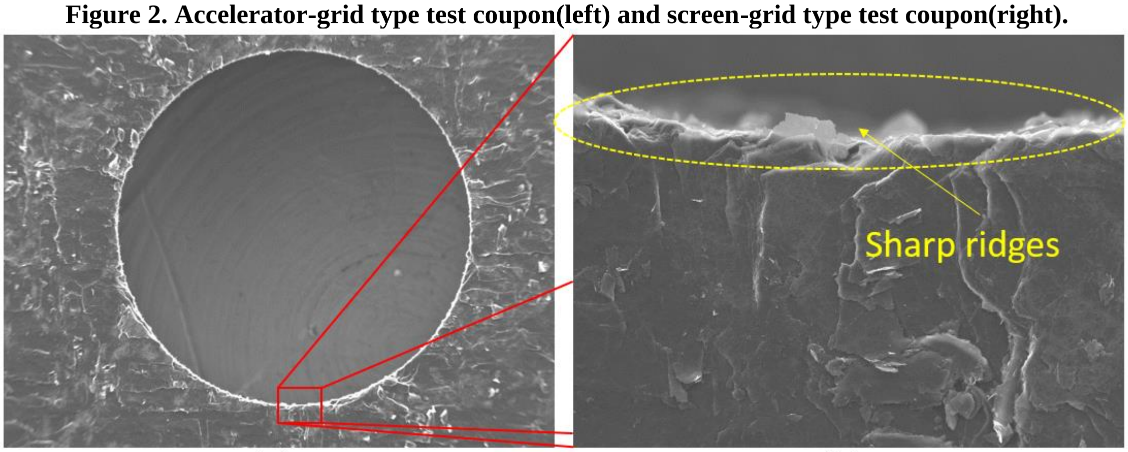


Figure 3. SEM photo of untreated accelerator-grid type test coupon.

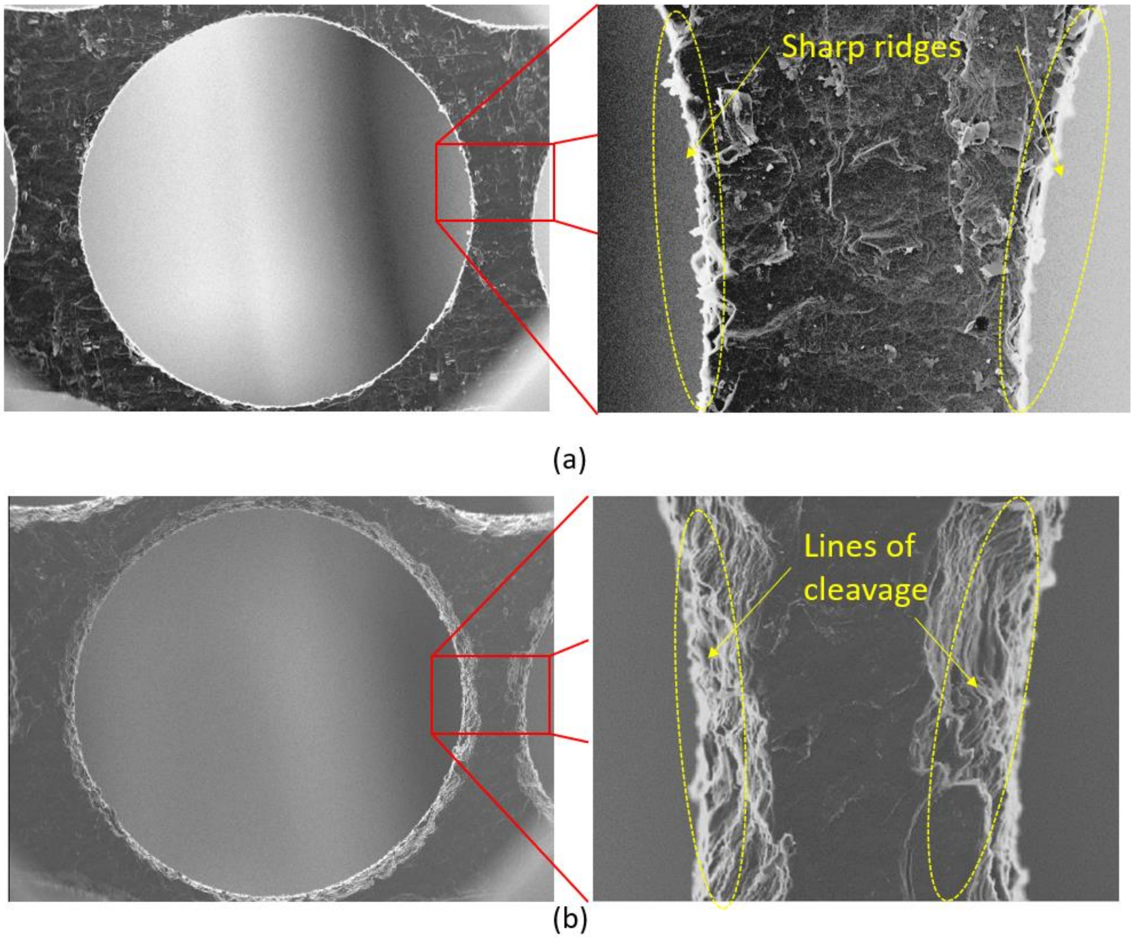


Figure 4. SEM photo of untreated screen-grid type test coupon.

B. Surface treatment

(1) Sandblasting is an operation of letting abrasive grains impinge on the target surface to treat it and was used to smooth grid surfaces by Goebel and Martinez et al.[5,6]. The abrasive grains used in this study are a mixture of 200-μm diameter polymer and diamond grains and is generally used to remove fine burrs on a precision tool[7]. Figure 5 shows the sandblasting equipment and a test coupon. An injection nozzle is set at a fixed angle over the test coupon. The nozzle scans over the test coupon and the table is rotated 90°after every scan to heighten uniformity. Sandblasting setting the nozzle perpendicular to the test coupon did not result better.

(2) Laser is widely used in the removal of particulates or thin extended contamination layers from solid surface[8]. In this study, we use a laser of 1,070-nm wave length and the maximum output power of 20W. Since a finite number of pulsed laser spots cover a plane, the intensity of laser light is lacking in uniformity. We can control the size of the spots by controlling the focus length and the pitch of the spots to acquire appropriate uniformity.

(3) The ion etching equipment used in this study is mainly used in removal of coating or burr on the surface of tools. In this study, argon and oxygen are used[9].

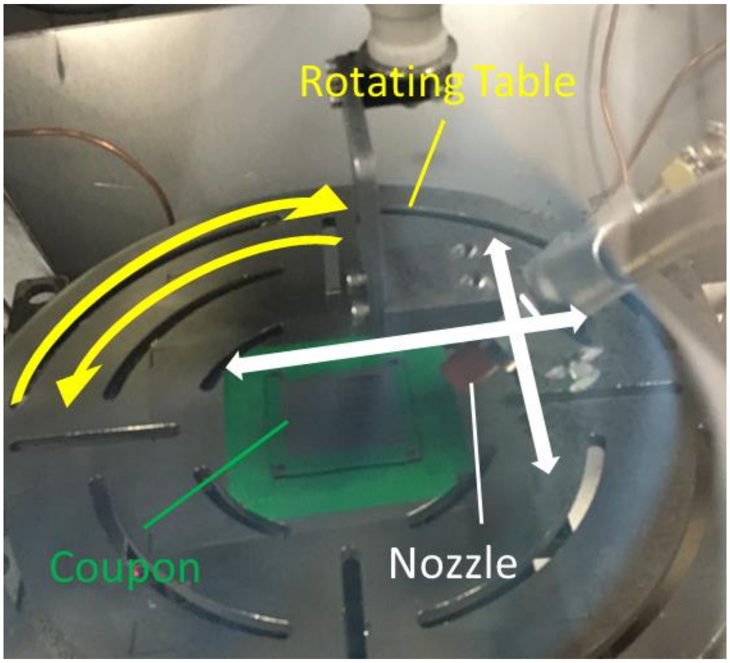


Figure 5. Sandblasting equipment.

C. Ion thruster

A schematic view of the 12-cm diameter ion thruster is shown in Fig. 6 though the decelerator grid is not installed in this study. This is of modified Kaufman type and characterized by its magnetic circuit, which includes cascades of magnet bars. Operating parameters are shown in Table 1 and correspond to those used in the 1,061 hours running.

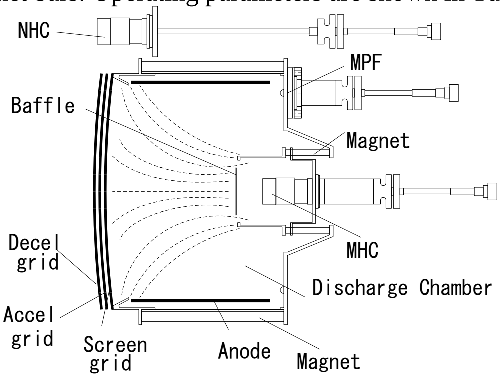


Figure 6. Schematic view of original thruster.

Table 1. Operating parameters.

Parameter	Value
V_b, V	900
V_a, V	-300
I_d, A	3
I_{ck}, A	0.5
I_{nk}, A	0.5
$\dot{m}_{MPF}$, sccm	6.5
$\dot{m}_{MHC}$, sccm	2
$\dot{m}_{NHC}$, sccm	2

III. Results

Parameters in sandblasting and the reduction in thickness of the coupons are shown in Table. 2. Sandblasting was conducted under four conditions: combinations of two injection pressures (0.15 and 3 MPa) and two processing time (2.5 and 5 minutes). Figure 7 shows a sandblasted test coupon for Case 4. Even the combination of the lower injection pressure and the shorter processing time—that is, Case 4—rounded sharp edges sufficiently; any other combinations did not make the surface smoother than that in Case 4 though they made the coupon thinner than that in Case 4. Even lower injection pressure and even shorter processing time than those in Case 4 may result the same smoothness and leave more thickness.

In laser processing, each coupon was irradiated under one of 24 conditions; output power, degree of overlapping of the laser spots, and degree of the spot focusing were changed. In most conditions, many circular marks, each of which was corresponding to a lase spot, were distinguishable (see Fig 8. (a)) and they could be erased by irradiating again with lower output power and larger spots (see Fig 8. (b)). Sharpe ridges after irradiation looked the same as they had been, and this fact means that laser acts only on very shallow extent from the surface. Even though we could burn out the ridges by raising output power or focusing better, it might damage in the non-ridge area. If laser were effective for this purpose, it would be powerful against the ridges and gentle against the other area. This seemed very difficult and we discarded laser.

In ion etching, fine cracks were observed on the plane of the coupon treated using argon as shown in Fig. 9 (a) and (b) but were not on the plane treated using oxygen as shown in Fig. 9 (c). The cracked surface is undesirable and we chose to use oxygen only thereafter. We tried two processing time: four and eight hours; however, no distinguishable differences were found between them. The surface of the coupon shown in Fig. 9 (c) was treated for four hours. Ion etching removed small edges from the entire surface except those on the barrels.

Table 2. Parameters in sandblasting and thickness reduction

Case	Injection pressure[MPa]	Processing time[min]	Thickness reduction[%]
1	0.2	5	5
2	0.3	5	8
3	0.2	2.5	3.5
4	0.15	2.5	3

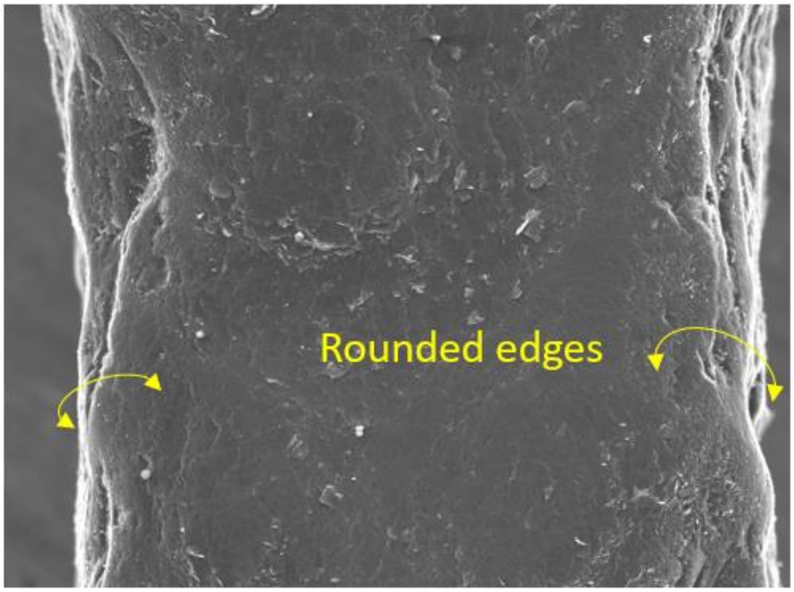
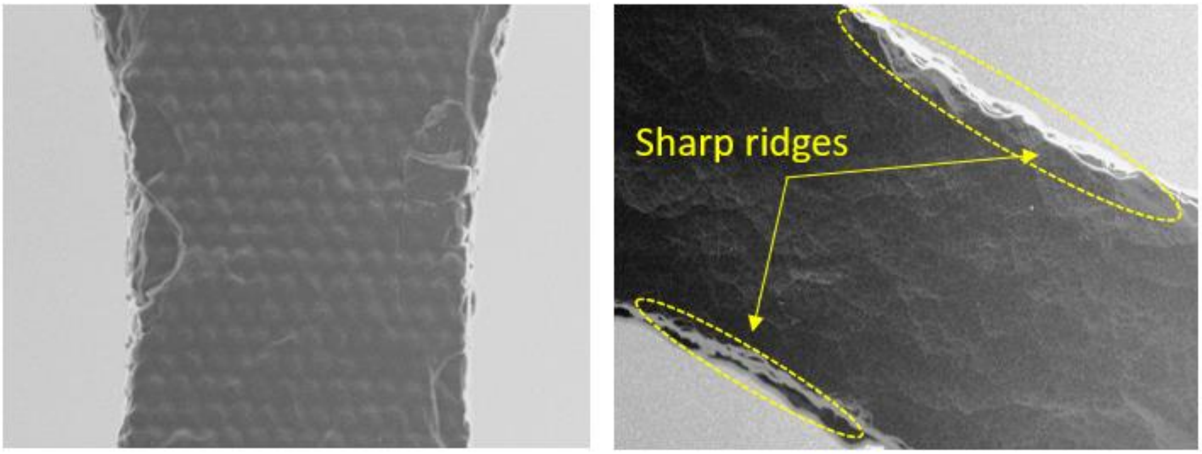
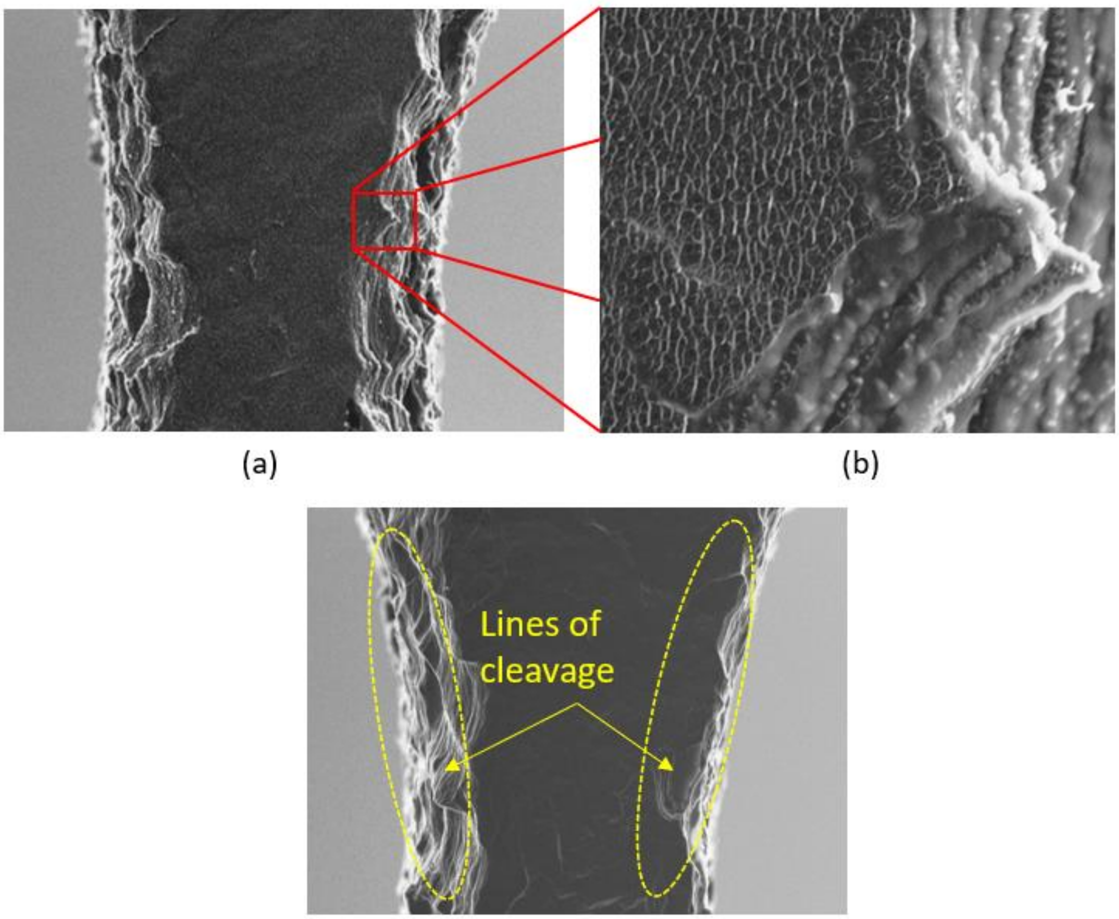


Figure 7. SEM photo of sandblasted screen-grid type test coupon (Case 4).



(a) (b)

Figure 8. SEM photo of laser irradiated screen-grid type test coupon: (a)After primary irradiation and (b) After secondary irradiation.



(a) (b) (c)

Figure 9. SEM photos of ion-etched test coupons: (a) and (b) argon, (c) oxygen.

The results are summarized in Table 3 and we chose a surface treatment procedure to apply to real grids as follows:

1. sandblasting to round the ridges on the perimeters of the apertures,
2. ion etching using oxygen to smooth the entire surfaces.

Figures 10 and 11 show the test coupons treated using this procedure before applying to real grids. The ridges on the perimeters disappeared and the entire surfaces were smoothed sufficiently. The maximum reduction in thickness of the coupons was 3% and the real grids to be treated were made about 3% thicker than they should be. Only the upstream surface of the accel grid and the downstream surface of the screen grid were treated; both surfaces faces each other and were drill incident.

Table 3. Effectiveness of methods.

Method	dull sharp ridges	smooth surface	remarks
Sandblasting	◎	△	Caution needed in thickness reduction
Laser	×	○	
Ion etching	×	◎	

◎: excellent ○: good △: fair ×: poor

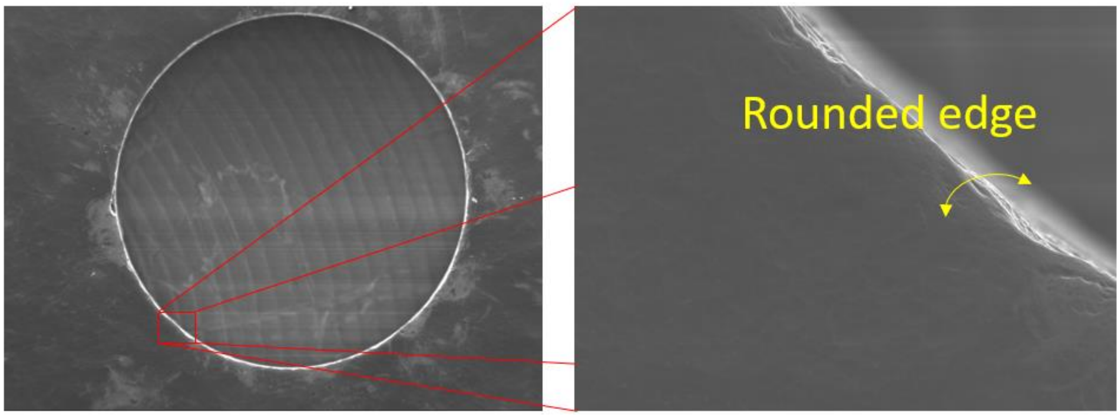


Figure 10. SEM photo of accel-grid type test coupon after treatment.

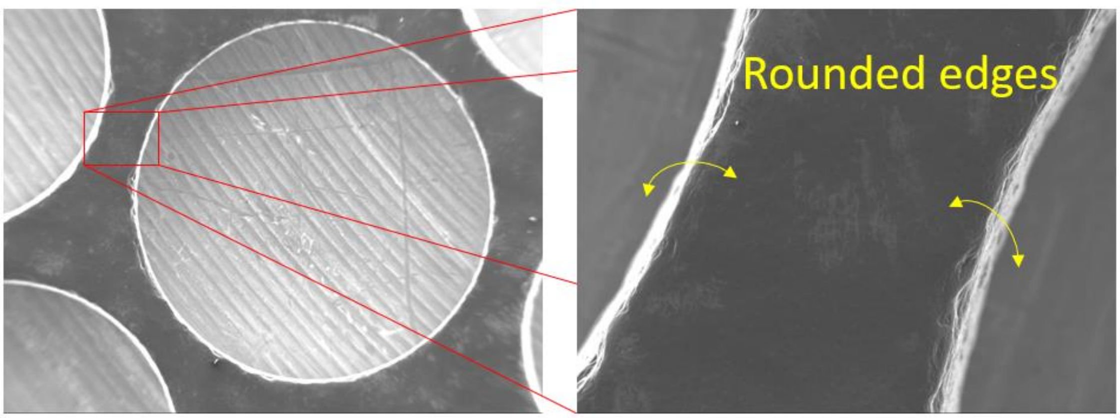


Figure 11. SEM photo of screen-grid type test coupon after treatment.

Figure 12 shows a photograph of the thruster with treated PG grids. This thruster was run for 16 hours and HVBDs recorded is shown in Fig. 13. HVBDs in the first 16 hours in the previous 1,061-hour run are also shown in the figure for comparison. The followings are concluded:

(1) The initial stage did not end by 16-hour run and the frequency in this period was close to that of the initial stage in the previous 1,061-hour run ignoring the especially frequent periods.

(2) No especially frequent period appeared in the first 16 hours.

(3) Longer run is required to judge the effectiveness of the method for HVBD reduction.

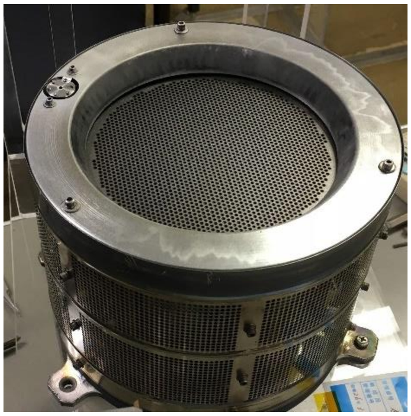


Figure 12. Photograph of thruster with treated PG grids

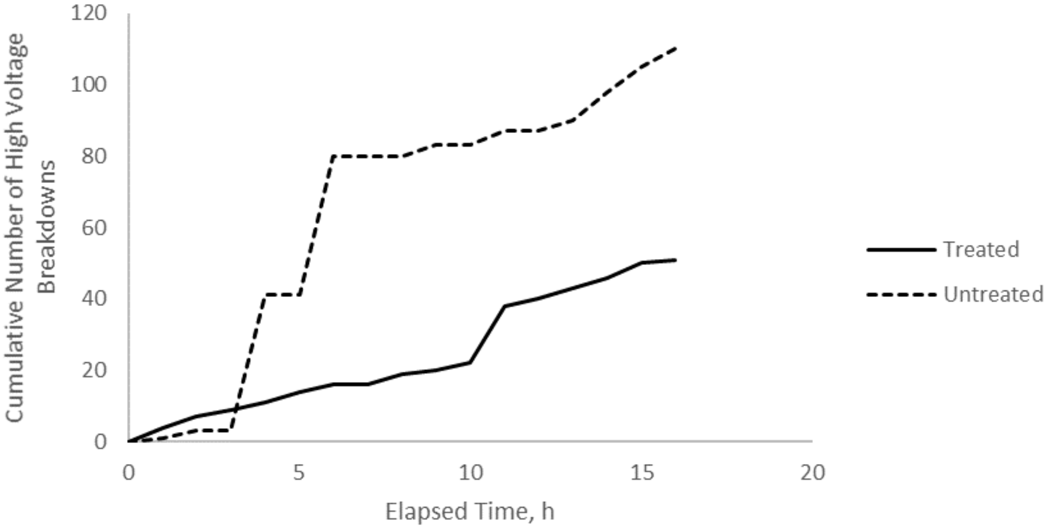


Figure 13. Cumulative number of high voltage breakdowns

IV. Discussion

Sandblasting was effective to dull the sharp ridges on the perimeter of the holes; however, it seemed to reduce the thickness of the test coupons beyond necessity. There remain many parameters, such as the distance between the nozzle and work, unchanged in this study and adjusting the parameters would bring a better result.

In this study, head and tail of a grid with respect to the drill incident had not been well cared. Sharpe ridges were found more on the drill incident faces; therefore, we may lower the frequency only by turning over both grids. It may be more effective for lowering the frequency to find out how much head and tail of the grids influences it than to run thruster even longer.

V. Conclusion

Only sandblasting among the three methods conducted in this study dulled the sharp ridges on the perimeter of the holes significantly. Changing the parameters in sandblasting may result better. The best method to treat the grid surface was a combination of sandblasting and ion etching. Though especially frequent period did not appear in the 16-hours thruster running, the run time was too short to judge the effectiveness of this method in lowering the frequency. How much head and tail of the grids with respect to the drill incident influence the frequency must be found out before judging the effectiveness of this method.

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