Alternative manufacture technologies for the manufacture of HET larger ceramic chamber

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Abstract:

The feasibility of Discharge Chamber up-scaling is a key factor for developing a large Hall Effect Thruster, since the conventional manufacturing technique Hot Pressing has limitations related to the maximum dimension to be processed. Current state of art largest HETs on the market are 20kW class with a DC diameter of 330mm. HP technology is able to manufacture such dimensions with pure BN material. DC of BN/SiO_2 can also be produced, but it does not exist any commercial model yet. Alternative manufacturing solutions were envisaged for near-mid future up-scaling stage, for the manufacturing of Large Ceramic Discharge Chamber, particularly for the "European approach", more reluctant to use pure BN (easier to process). Two of them, multi-element chamber, and ceramic plasma coating chamber have been selected for further experimentation to appropriately assess its applicability.

Nomenclature

Al_2O_3	=	Alumina
BN	=	Boron Nitride
$BN\text{-}SiO_2$	=	Borosil
CTE	=	Coefficient of thermal expansion
DC	=	Discharge Chamber
EP	=	Electric Propulsion
HET	=	Hall Effect Thruster
HP	=	Hot Press
LCDC	=	Large Ceramic Discharge Chamber
SEY	=	Secondary Electron Emission Yield
SHS	=	Self-Propagating High-Temperature Synthesis
SiO_2	=	Silica
Xe	=	Xenon

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I. Introduction

High power electric propulsion seems to be one of the future key factors for further space missions. It would allow a significant reduction of overall cost of satellites and increases net payload for exploration missions.

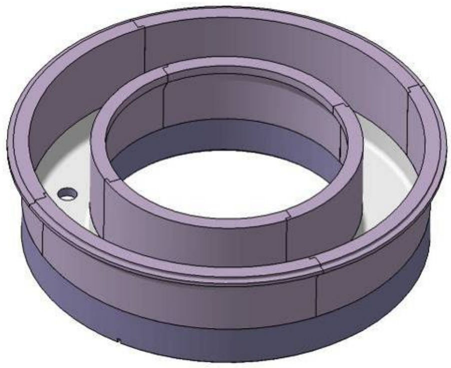
Future thrusters should be able to assume both orbit transfer and station keeping maneuvers. So, high thrust and high I_{sp} will be the parameters to achieve.

Present activities on the up-scaling of Hall Effect Thrusters (HET), is particularly focusing on the impact on the ceramic discharge chamber. Indeed, the feasibility of DC up-scaling is a key factor for developing a large HET, since the conventional manufacturing technique (Hot Pressing) has limitations related to the maximum dimension to be processed.

Current state of art largest HETs on the market are 20kW class with a DC diameter of 330mm and 345mm (external diameter) for the HIPER 20kW HET[1]. HP technology is able to manufacture such dimensions with pure BN material. DC of BN/SiO_2 can also be produced, but it does not exist any commercial model yet. Near/mid future announces the possibility of up-scaling thrusters up to 50÷70kW with estimated maximum DC sizes ranging somewhere around 450 to 550mm of diameter. Hot Press technology can still be applicable, but now it is right on its very limit. Particular difficulties when pressing BN/SiO_2 material can probably lead to reduce this maximum size below 400÷450mm (depending on the particular formulation).

Two technologies, multi-element chamber and ceramic plasma coating chamber, have been previously identified and investigated[2], to enable the manufacturing of discharge chamber which overcome current HP limitations in terms of maximum block size.

Previous results reveal an idea which might be clearly interesting to further analyse: the possibility of combining a ceramic coated support (upstream part of the chamber), with external ceramic rings made out of bulk ceramic multi-elements (downstream regions, plasma acceleration zone and exit plane where the plasma erosion is maximum). A hybrid chamber integrating both technologies may take profit of the advantages coming from both techniques avoiding any potential drawback, and may allow achieving larger freedom on the design of up-scaled discharge chambers.



FigureI-1: Discharge chamber assembly

II. TECHNOLOGICAL DEVELOPMENT

A. Up-stream part

Results obtained after the preliminary selection of concept and experimental developments, indicate that the coating alternative (which consists in manufacturing a metallic discharge chamber covered with a ceramic coating) has extremely attractive potentiality in terms of manufacturing simplicity, design flexibility, unlimited size and cost-effectiveness. However, it has been clearly assessed that, due to the limited attainable thickness on the coating layer, it would only be applicable if the ion density impacting the wall chamber is drastically decreased from the current standard level, which is not really envisaged to occur. But the previous is only true when considering the sputtering erosion effect that would require an important thickness level to assure the targeted lifetime, and the region where this erosion mechanism occurs is really limited (surrounding of the channel exit plane). Consequently this technology can still be envisaged for regions free of relevant ionic erosion effects, i.e. the upstream regions of the discharge chamber, near the anode, precisely where dimensional constrains and complexity are usually higher and may take profit of applying a simple manufacturing technique like coating of a metallic part.

An example of the up-stream part of the DC is shown on the Figure II-1. The metallic support could be coated with a ceramic layer of Alumina, or a mixture of Alumina and Borosil.

This component could also be manufactured in a more conventional ceramic like Alumina if the plasma-wall interactions are proven to be not relevant in this upstream section of the chamber. This material does not have the manufacturing constraint of the Borosil as it can be produced by conventional pressure-less sintering process, using a traditional ceramic furnace. Size limitations of such furnaces are considerably lower than the Hot Press required for Borosil, and largely overcomes the dimensions of the long term future up-scaling.

Based on preliminary studies of the multi-component assembly, the step shape geometry can also be recommended for the p-stream/down-stream interface.
So the outlet zone of the support was machined with a step shaping, in order to fit with the ceramic rings and maintain a certain mechanical assembly. This configuration also avoids the plasma to pass through the discharge chamber wall.

Figure II-1: up-stream part of a discharge chamber

B. Down stream part (single components in contact with Plasma)

Down stream part is composed of single elements which are manufactured by Hot Press process and assembled into the rings of the future discharge chamber. This alternative is particularly interested as it permits a large up-scalability and no size limitation.

The design of single components must be carefully studied taking into account the geometry of the interface between (1) each ceramic component and (2) the metallic support and the ceramic component. The step shape must be respected in both cases to avoid plasma leakage through the joint.

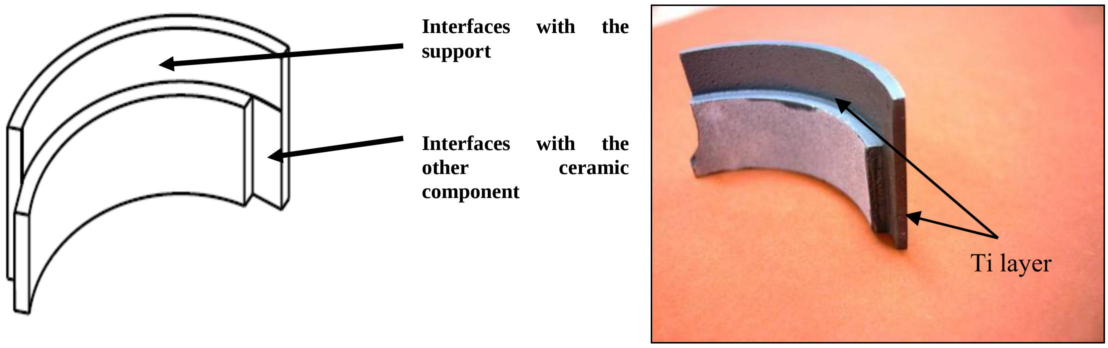


Figure II-2: Ceramic single component of the DC ring

Key factors are the joining method and corresponding filler material for the brazzing. Metal active filler TiCuSil was chosen for the joining of the interface ceramic-ceramic and ceramic-metal as a first approach because of its good properties at high temperature and its proven ability to braze ceramic materials in particularly Borosil.

Metallic support and ceramic material have a large difference of Coefficient of Thermal Expansion:

- ✓ CTE $_{\text{Borosil} \perp \text{or} /\!/}$ = 0,5→1,5.10^{-6}/ºC at Room Temperature
- ✓ CTE $_{\text{Aluminium}}$ = 23.10^{-6}/ºC at Room Temperature
- ✓ CTE $_{\text{Stainless steel}}$ = 17,3.10^{-6}/ºC at Room Temperature
- ✓ CTE $_{\text{Titanium}}$ = 8,6.10^{-6}/ºC at Room Temperature
- ✓ CTE $_{\text{Alumina}}$ ≈ 8,1.10^{-6}/ºC at Room Temperature

CTE of Borosil is one order of magnitude lower than Titanium and two orders of magnitude lower than Aluminium and Stainless steel. Such a difference will induce mechanical constraint within the joint and lead to damaging the interface as shown on the following technical demonstrator of Figure II-3.

Figure II-3: failure on the technical demonstrator

It was decided to deposit a layer of Ti on the stainless steel support and on the ceramic (see Figure II-2) to accommodate the thermal expansion mismatch and consequently the thermomechancial stresses. Titanium was selected because of its intermediate CTE between ceramic and common metal, and its compatibility with TiCuSil.

The Figure II-4 shows the brazing interface of a Borosil and a metal piece without the Ti accommodation layer. One can remark that the crack generated during the brazing and thermal process do not cross the interface, but is entirely located in the ceramic material which is more fragile. The Titanium (in dark grey) of the TiCuSil migrates to the interface. This element creates a thin layer of a few microns on the ceramic surface.

Figure II-4 on the right shows the interface of the brazing filler material and the ceramic coated with a 6-10µm thickness Ti layer.

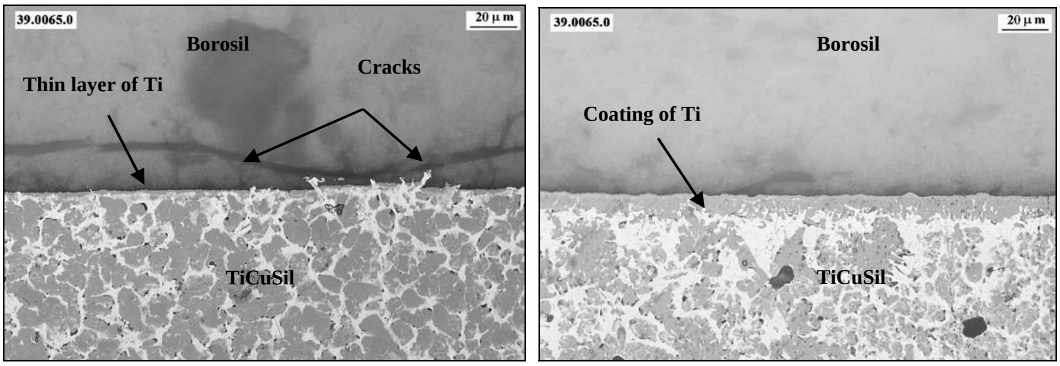


Figure II-4: Ceramic joining without and with accommodation layer of Ti

The deposition of a Ti layer, between the ceramic and TiCuSil, shows an improvement of the wetability of the metallic filler and allows accommodating thermal stresses during cooling after the joining process. Less microscopic defects and cracks were observed along the interface. The element Titanium of the TiCuSil which previously migrates directly to the contact of the Borosil, is now completely dissolved in the Ti layer.

Simple technical samples do not exactly reproduce real thermal conditions that could occur in a space application, that's why these results have to be confirmed on a breadboard. These experiments are under progress.

C. Sputtering erosion:

The hybrid chamber configuration should theoretically be designed having the metal-ceramic joint far from the regions where important sputtering effects are present. However, it is considered relevant to analyze the behaviour of such a joint under ion bombardment just in case unexpected hazardous mechanisms appear, since full avoidance of a certain level ion bombardment would probably be impossible.

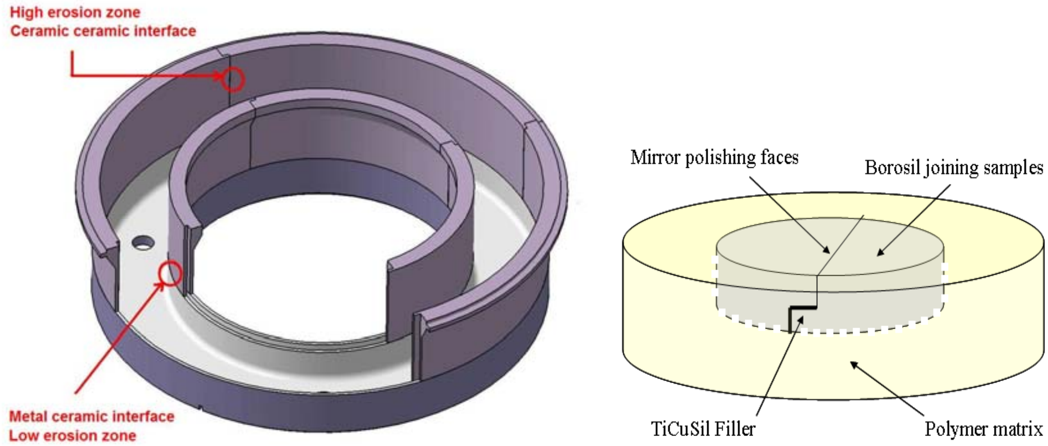


Figure II-5: erosion zones and test sample

This erosion mechanism can be easily analyzed on technical test sample with the TECNALIA' sputtering facility developed under ESA contract nº 19554/05/NL/PA.

The joining zone has been exposed to Xe ions bombardment on a 3mm's diameter unmasked region.

An ion beam of energy 5000V and a current of 10mA bombarded each samples with an incident angle α of 0º. These conditions are quite aggressive in order to provide suitable erosion in a small testing time. Specific evaluation of the sputtering behavior has been performed through picture analysis and profilometry. It was given the priority to study the presence of an eventual preferential erosion of the edge of the joint.

Firstly, the hybrid interface metal-ceramic was submitted to ion erosion. The following Figure II-6 permits to see the difference of sputtering behaviour between the insulated half part and the metallic half part.

Xe^+ ions charged cannot be evacuated rapidly and tends to form a blue plasma on the dielectric surface. At the contrary, the metallic zone allows evacuating charges from the surface and appears totally dark.

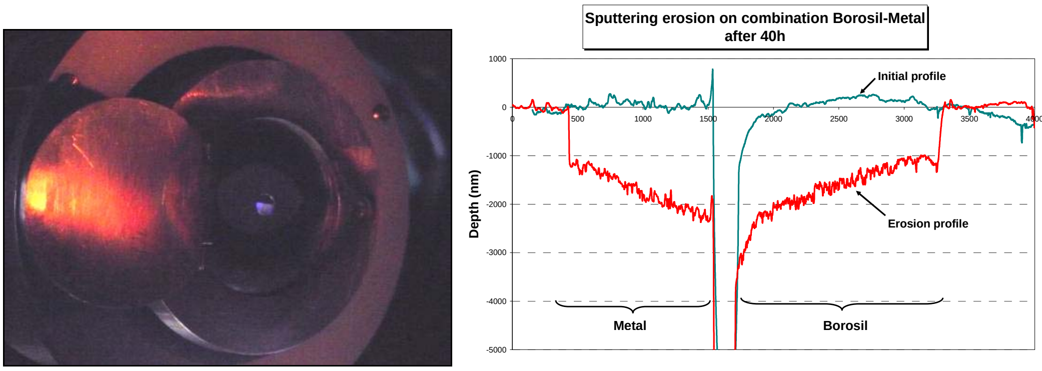


Figure II-6: Erosion profile of metal-ceramic interface

The erosion profile shows that the ceramic presents a smoother shape of the eroded edge zone as compared to the sharper angle of the metal side.

In fact, the smoother shape of the ceramic edge is the result of the initial profile. During the ion bombardment, the metal edge also keeps its sharp shape.

Sputtering yield of each part of the sample (metal and Borosil) cannot be calculated separately because of the intrinsic Gaussian like distribution of the ion beam.

The selected metal active filler does not show any interaction with the plasma during the experiments. Ions do not seem to reach TiCuSil in the bottom of the joint, and no electrical short cut was detected.

Then, the ceramic-ceramic interface was submitted to ion erosion to evaluate the effect of a discontinuity of the ceramic ring with the plasma.

The following pictures show the concentration of plasma in the unmask area. High blue colour due to Xe

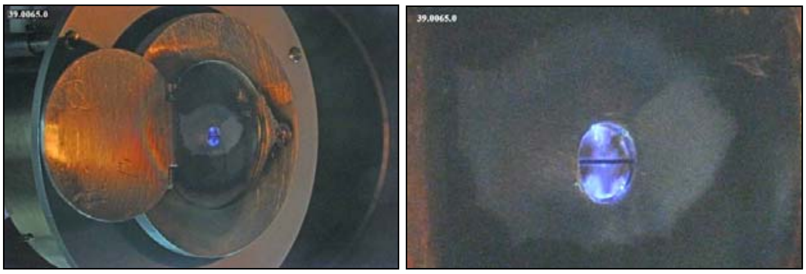


Figure II-7: sputtering test sample / ceramic-ceramic interface

ionisation and the surface electrical charging is mostly distributed on the boundary wedge of the mask, and more lightly on the joint wedge. The inside of the joint appears totally dark and free from plasma.

No abnormal electric behaviour, i.e. no short cuts nor increase of sample current were detected during experiments. The average ionic current of a typical sputtering experiment on Borosil sample is about 3.3±0.60µA. It is barely equal to the ionic current measured for a sample joint with TiCuSil, of about 3.8±0.65µA.

The same sample was submitted to two more erosion experiments of 40h each one. The evolution of the erosion profile after 40h, 80h and 120h of ion bombardment is also presented on.

The plateau shape of the 40h profile traduces uniform erosion along the horizontal axis, except in the right and left side, where erosion was harder. This is confirmed by the presence of a visual plasma on Figure II-7.

Average depth of the plateau is about 1400µm with a maximum of 2080µm and a minimum of 780µm.

Ions perpendicularly bombarded the joint. Walls of the joint do not present any preferential erosion as it could have been expected.

It can be noted that the erosion rate decrease between the two first experiments (erosion of 1400µm for the first 40h, and 900µm for the second). It can be explained by the effect of the mask which is used to ground the sample,

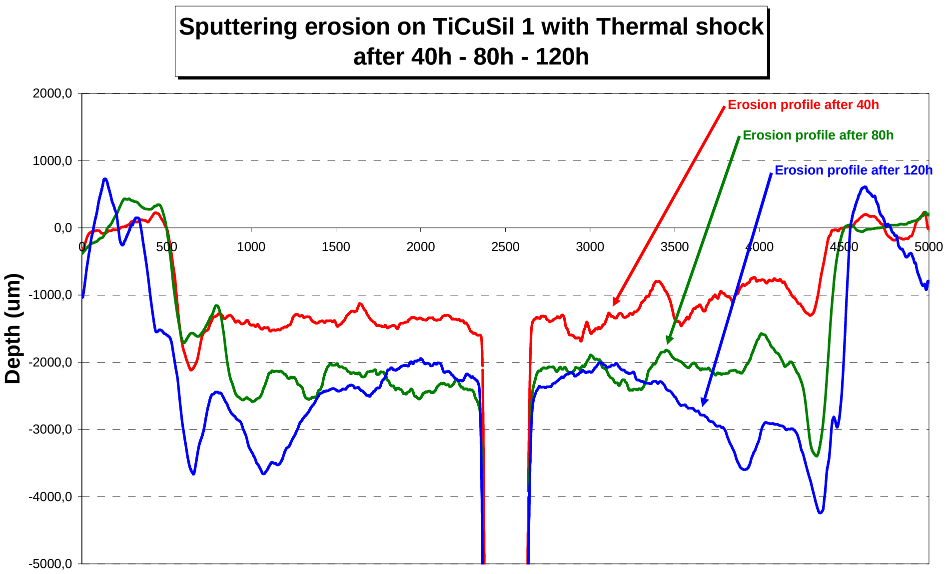


Figure II-8: Erosion profile of ceramic-ceramic interface

and define the unmasked area. Meanwhile the zone is deeper; the ions must cover a larger distance to strike the ceramic surface. So, they can be caught more often by the sides of the aluminium mask which is grounded. A lower part of the ion beam is then bombarding the ceramic.

This tendency is confirmed by the third profile, which shows a preferential erosion of the edge of the unmasked area but not of the joint interface.

Moreover, a redeposition phenomenon was observed on the centre on the sample. The mask is sputtered and the ceramic is coated with an aluminium layer

III. CONCLUSION AND FUTURE WORK

The possibility of combining a ceramic coated support (upstream part of the chamber), with external ceramic rings made out of bulk ceramic multi-elements (downstream regions, plasma acceleration zone and exit plane where the plasma erosion is maximum) was experimentally studied.

The overall design of a potential hybrid chamber must be very carefully designed, to keep thermal constraints as low as possible, avoiding the risk of ceramic cracking.

Particularly, the design must:

- Reduce the thermal mismatch to the lower possible limits by selecting a metallic material with reduced CTE. Titanium can be envisaged a candidate because of its adequate light weight properties, compatibility with the brazing filler (TiCuSil) and relatively low thermal expansion coefficient.
- Assure the presence of accommodation layers such us the one studied (Ti)
- Assure that the stresses induced by this thermal mismatch during cooling after the brazing process generates compression stresses on the ceramic part rather than tensile ones, since the compressive strength is largely more important that the tensile one for the Borosil. Brazing based joining technique has been studied to join Borosil ceramic with metallic supports. Due to the extremely low CTE (Coefficient of Thermal Expansion) of the Borosil, thermal expansion mismatch is a mayor issue to take into account on such a brazed joint.

Thermo-mechanical results must be considered and confirmed on breadbroads reproducing the combined DC shape, and be submitted to space like conditions.

Sputtering experiments do not show any concentration of ionic erosion in the critical zone of ceramic-ceramic and metal-ceramic interface. The metal active filler selected does not present any interaction with the plasma. Ions do not seem to reach TiCuSil in the bottom of the joint, and no electrical short cut was detected.

These first experiments suppose that the plasma of a HET shall not be disturbed by the discontinuity on the internal wall of the discharge chamber, and should not provoke any preferential erosion in these zones.

Another alternative way to produce Borosil was described as a new reaction of combustion synthesis[3]. Powder of basic components of Boron Nitride BN, or Boron Oxide B_2O_3 and Silica SiO_2 was submitted to high pressure of N_2, and electrical ignition. The products of the combustion synthesis are hex-BN with SiO_2.

Combustion synthesis facilities have a large capacity so Borosil blocks may overcome current size limitation of hot presses, and then permit to manufacture larger discharge chambers. Tecnalia will try to reproduce this material in its SHS facility and determine physical properties of the material (density, composition…) to verify if it can fit with space propulsion application

Acknowledgments

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