Improvements in miniaturized Hall Thrusters by use of high-temperature SmCo magnets and additive manufacturing techniques

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Abstract. This work presents the difficulties associated with the miniaturization of Hall Thruster engines and how state of the art materials and new manufacture techniques can potentially solve these problems. Hall Thrusters are electric propulsion systems that require specific magnetic field topography and uniform propellant distribution for optimal operation which is difficult to achieve with typical materials and by conventional manufacturing methods in miniaturized engines. To keep the optimal magnetic field distribution at small thruster sizes, it is shown that new alloys of SmCo permanent magnets can generate the desired magnetic field distribution and that their high-temperature resistance properties assure its operation temperature will be under the maximum operational temperature. In addition, whereas for the small dimensions required for the anode traditional manufacture methods only allow for simple designs, it is explained how the implementation of 3D-printing techniques can improve the uniformity in the azimuthal distribution of the propellant by allowing complex geometries in the design of the anode that are unattainable with traditional manufacturing.

1. Introduction

There is a recent trend in using micro and minisatellites (10-500 kg) for low Earth orbit (LEO) missions such as Earth Observation platforms, large constellations of satellites to provide worldwide internet coverage, drag-compensation, debris removal and de-orbiting at the end of the mission [1]. Hall Thrusters have been a very successful propulsion system for spacecraft [2] and are considered as potential candidates for the increasing market in smallsat missions [3]. The application limits derive from the scarce available power (<500 W) for the system as for smallsats the size of the solar arrays is limited and for LEO missions they can spend around 30% of the operational time in eclipse. In order to adapt the Hall Thruster to lower nominal powers, a process of miniaturization of the thruster has to
be made with the technical difficulties associated with the accurate manufacturing of the small components and the increased temperatures due to the reduced radiating surfaces.

This work will be focused in presenting how the advances in magnetic materials and manufacture techniques allow the Hall thruster to be adapted to low powers, in particular to 100 Watts. The paper is divided as follows: In section 2 Hall thruster systems are introduced and it is explained the importance of the magnetic field and anode flow distribution in the performance of the thruster together with the complexities associated with miniaturization. In section 3 the permanent magnets are presented as option to generate the magnetic field and the singularities of their manufacture to the required dimensions. In section 4 it is shown the benefits of using additive manufacturing techniques for the anode which allows complex geometries to achieve a uniform propellant distribution.

2. Hall thruster dimensional constrains

Hall Thruster engines are propulsion systems where the thrust is achieved by electrostatically accelerating ions out of the thruster [4]. An axial electric field is created between an anode and a cathode, which for Hall Thruster is usually a hollow cathode and is the source of the electrons. In order to avoid the electrons streaming directly to the anode, a radial magnetic field is established perpendicular to the electric field creating an ExB drift motion in the electrons (Hall current) perpendicular to the electric and magnetic fields. The propellant, usually Xenon, is injected through the anode into the discharge chamber where collisions are produced between the neutrals and the confined electrons, ionizing the propellant. On one hand the electrons, through collisions, diffuse towards the anode and this allows a sustained discharge of the thruster. On the other hand, the ions are accelerated by an electrostatic force equal to the Lorentz force acting on the Hall current which its corresponding reaction on the magnetic structure of the thruster transmits the thrusting force to the body. The assembly uses an annular geometry to prevent the Hall current of reaching the walls of the thruster which otherwise would compromise the electron confinement.

The magnetic field is usually created using electromagnets as the magnetic field can be easily modified by tuning the current through the coils. A schematic of a conventional Hall thruster where the magnetic field is generated by magnetic windings is shown in Figure 1.

With the requirement of low power propulsion systems for smallsats the resultant thruster has to be a low-mass compact device with a relatively high efficiency. These characteristics cannot be accomplished by operating a large thruster at low power level and hence scaling down of the dimensions has to be done. The parameters of the 100-W thruster are described in Table 1.

Figure 1. Schematic of a Hall Thruster.
Table 1. 100-W HT parameters.

| 100-W HT                  |
|---------------------------|
| Thruster Diameter (mm)    | 15.7  |
| Channel Width (mm)        | 4.9   |
| Channel Length (mm)       | 4     |
| Discharge Power (W)       | 100   |
| Discharge Voltage (V)     | 300   |
| Discharge Current (A)     | 0.33  |
| Magnetic Field Strength (G)| 223   |
| Propellant Flow Rate (mg/s)| 0.37  |
| Thrust (mN)               | <6.44 |
| Specific Impulse          | 1786  |
| Efficiency                | <0.56 |

For a correct performance of the thruster, two aspects are of great relevance:
- Topography of the magnetic field
- Uniform distribution of the propellant

The work of Hofer [5] provides a detailed description of the desired settings of the topography of the magnetic lines. The summarised guidelines for a proper magnetic distribution design are:
- Symmetry of the magnetic field along the centre of the discharge channel.
- Notable gradient of the magnetic field from the anode to the location of the maximum
- Concavity of the magnetic field lines.
- Higher value of the magnetic field close to the walls.

While this requirements can be easily satisfied in traditional medium size Hall thrusters (1-2 kW), it becomes increasingly difficult to cope with all of them when scaling down the thruster. In particular the lack of space to place the magnetic coils together with the increased temperature in the windings and the increasing magnetic coil required power to thruster power ratio, make the coils a less attractive option in contrast with the permanent magnets [6].

Permanent magnets, although they allow a compact design and power savings during operation compared to coils, deprive flexibility to the magnetic configuration. To alleviate this situation, several permanent magnet configurations have been designed to take into account different magnetic field intensities and topographies. As explained below, the development of new magnetic materials allow the required sizes of permanent magnets to be manufactured and ensure that maximum operating temperatures are not reached during the discharge of the thruster. An illustration of the 100-W Hall Thruster with permanent magnets is shown in Figure 2.

Figure 2. 100-W Hall Thruster.
For Hall Thrusters it has been shown that azimuthal non-uniformity distribution of the flow affects negatively to the thruster performance [7]. Compared to an azimuthally uniform propellant flow distribution, the non-uniformity enhances the electron diffusion incrementing the discharge current. In miniaturized designs, to tackle this problem becomes increasingly tricky as traditional manufacture techniques where welding is required introduce accuracy problems or are unable to reproduce complex features. This is one of the problems considered in the reduced performance of the MHT-9 [8]. To solve this contingency, additive manufacture will be used for the anode.

3. Modified SmCo alloy for the permanent magnets

The requirements shown in section 2 for the magnetic topography can be substantially satisfied by the use of permanent magnets as shown in the nominal design in Figure 3. The design uses one permanent magnet ring of 24.2 mm inner diameter and 2mm width with a thickness of 2mm and another ring of 34.6mm inner diameter and 2 mm width with a thickness of 4 mm.

The material used in the manufacture is a new recently developed high-temperature SmCo series 2:17 (Sm$_2$Co$_{17}$) permanent magnet [9]. This permanent magnet was chosen because its superior performance at high temperatures compared to previously reported SmCo magnets. They were manufactured in the traditional powder metallurgy process; Figure 4 depicts all the steps of the process and the time expended in each of them. Alloys with nominal composition Sm(Co,Fe,Cu,Zr)$_z$ were prepared by arc-melting under Argon atmosphere at 0.6 bar. The alloy powders were obtained by ball milling with a particle size of 3-5 µm that were aligned and pressed in a magnetic field up to 20 kOe and further compacted by cold isostatic pressing. The green compacts were sintered in a vacuum tube furnace and solution heat treated at 1200-1220°C for 1-4 hours and after they were quenched to room temperature. The magnets were further aged at 780-850°C for 24 hours and slowly cooled down to 500°C at a rate of 0.7°C/min, then aged at 400°C for 10 hours, followed by water quenching. After machining the final shape, the permanent magnet is magnetized. As the magnet will operate in vacuum, coating was not required. The final manufacture of the magnets can be seen in Figure 5.

The basic properties of the high-temperature resistant SmCo permanent magnets can be seen in Table 2. Thermal simulations estimate a value of around 300°C for the two permanent magnet rings in the nominal design and a value of 500°C for the highest temperature operating point in the off-nominal design of 300W. Both values are inside the maximum operating temperature of the modified SmCo permanent magnet.

![Figure 3. Magnetic field topography (left), magnetic field at halfway of the discharge channel along the radial coordinate (center) and magnetic field for different radial coordinates along the axis coordinate(right).](image-url)
Figure 4. SmCo manufacture process.

Figure 5. High-temperature resistant SmCo permanent magnets. A coin has been used for reference. The two magnets above the coin are used in the nominal design. The bigger magnet in the upper part of the photograph is used for another magnetic configuration with higher magnetic field.

Table 2. Modified SmCo permanent magnet properties.

| Material Properties                        | Properties       |
|--------------------------------------------|------------------|
| Br (room temperature)                      | 0.9~0.95 T       |
| Hcj (room temperature)                     | 30~40 kOe        |
| (BH)max (room temperature)                 | 20~22 MGOe       |
| Br (550°C)                                 | 0.65~0.7 T       |
| Hcj (550°C)                                | 6.5~7.5 kOe      |
| (BH)max (550°C)                            | 9~10 MGOe        |
| Thermal coefficient of Br                  | 0.04~0.06%/°C    |
| Thermal coefficient of Hcj                 | -0.1~0.2%/°C     |
| Density                                    | 8.3~8.5g/cm³     |
| Hardness                                   | 550~750 HV       |
| Maximum Operating Temperature              | 550°C            |
| Curie Point                                | 825°C            |
4. Additive manufacturing for the anode

Additive manufacture, usually known as 3D printing, has been used during two decades but it was recently when it has been successfully implemented in the aerospace industry. Before, this manufacturing technique was limited to prototypes and for testing purposes but with the refinement of the processes 3D printed materials begin to be used in operational products [10]. Among the different methods of additive manufacturing, when low production quantities are required, selective laser melting (SLM) is the most convenient method to manufacture complex geometries as it has the highest resolution [11,12].

For electric propulsion, additive manufacturing has been recently used for manufacturing the channel and parts of the distributor of the Hall Thruster with PEI and ABS polymers respectively [13]. While this work showed the potential benefits of using 3D printing in Hall Thrusters, the temperature of the discharge was beyond the temperature limits of the materials used, not allowing a steady state operation of the thruster. Thus, our research finds particularly interesting the applications of additive manufacture with metal materials, which could overcome the thermal limitations. The recent research of M. Sangregorio et al. [14] shows the advantages of manufacturing the metal grids of ion thrusters with SLM instead of traditional techniques. They show how with accuracies of 20 µm and good mechanical properties they reduce the manufacturing time from 400 hours to less than one day and how the price of the product decreases from several thousands of dollars to a few hundred. Although the geometry complexities of the ion grids and the Hall thruster anode are different, it seems there is no reason the benefits from the SLM techniques could not be achieved in the Hall thruster anode manufacture, where the minimum feature size is limited to 0.5 mm.

By using SLM for the anode, we can just not reduce the cost and time span for the manufacturing but we can design a more complex geometry that provide better azimuthal uniformity in the propellant flow at the exit of the anode. In Hall thrusters, the anode is not only the positive bias for the electrostatic field but it has the additional function of distributing the propellant flow all around the discharge chamber. A manifold with orifices which communicates the flow from the inlet of the anode to the discharge channel is usually used for this purpose. The restrictions in the dimensions enforce the use of a single feed entrance to inject the propellant into the manifold bringing along accentuated azimuthal distribution heterogeneity. With traditional manufacture techniques this problem can be partially solved but the limitations associated to the miniaturized assembly impede the optimal design. The limitation in our design include the minimum diameter of the orifices could not be smaller than 0.5 mm and welding process was restricted to assembly the feeder and anode distributor to the anode cup or body. The cross-sections of the different components of the anode are shown in Figure 6.

![Figure 6. Anode cross section (for conventional manufacturing).](image)

Using SLM for the manufacture of the anode, we can introduce modifications in the geometry with the aim of slowing down the flow and allowing for homogeneous flow diffusion along the channel. Two different geometries have been chosen to illustrate the benefits of using SLM. In design A, it was included just a simple set of baffles that redirect the flow after the propellant is injected through the orifices. In design B, a more complex geometry is used to redirect the flow with similar purposes.

Table 3 shows the three different designs (traditional manufacture, 3D-printing A and 3D-printing B) with the isometric view of the anode, the cross-section of the distributor and the propellant
distribution at the exit of the anode. The isometric view has been sectioned in order to illustrate the inner geometry in the distributor. It can be seen how the propellant distribution in the traditional manufacture design has a high concentration region corresponding to the location where the feeder is assembled and another concentration peak at the diametrically opposite region. Both 3D-printed designs offer a more uniform azimuthal distribution, specially design B. This can be numerically quantified by taking the densities distribution along the anode’s exit midradius of each design. Making statistical analysis of the distributions, it can be observed in Figure 7 the improvements in the density distribution of each 3D-printed design compared to the traditional manufacture design.

### Table 3. Anode designs.

|                      | Traditional manufacturing | 3D printing – A | 3D printing – B |
|----------------------|---------------------------|-----------------|-----------------|
| **Isometric view**   | ![Image](isometric_view.png) | ![Image](isometric_view_A.png) | ![Image](isometric_view_B.png) |
| **Cross-section**    | ![Image](cross-section.png) | ![Image](cross-section_A.png) | ![Image](cross-section_B.png) |
| **Propellant**       | ![Image](propellant_distribution.png) | ![Image](propellant_distribution_A.png) | ![Image](propellant_distribution_B.png) |

![Figure 7](normal_distribution.png)

**Figure 7.** Probability density functions of the flow density at the anode’s exit midradius for the three designs. Assuming normal distributions, the probability density function for the anode with traditional manufacturing has been standardized and the 3D-print respective distributions have been accordingly referenced.

After running thermal simulations, stainless steel 316 was chosen for the anode as there is extensive experience in printing this material, its relative permeability is close to one and its melting
point (1400ºC) is far above of the operational temperature (680º C). It has been reported that for a deposition layer thickness of 20 µm the properties of SLM stainless steel 316 are similar to the materials obtained by traditional metallurgical methods [15] although significant porosity can be found in the surface. The porosity can be reduced by post-processing methods as finish machining or it may induce fatigue failures of the material [16]. In any case, as the anode is not a structural component of the thruster, it is not a major concern the surface quality of the anode after 3D printing.

5. Conclusions
This work was focused on introducing the associated complexities of miniaturizing a Hall Thruster engine to adapt its nominal power to 100 Watts and how high-temperature resistance permanent magnets and new techniques of manufacturing can potentially solve these problems. As electromagnetic coils have to been ruled out when scaling down the thruster due to increments in the temperature and increments in the magnetic coil required power to thruster power ratio, it was shown how a design with permanent magnets can provide the required magnetic field according to the guidelines for a proper magnetic field distribution. In addition, thermal simulations confirm that the maximum operating temperature of the new alloy of SmCo magnets will be within the nominal operation temperature of the thruster.

Finally, it was explained how additive manufacture, together with the benefits of reducing cost and time of manufacture, allows for geometries that are unattainable with traditional manufacturing techniques resulting in better azimuthal distributions that are expected to improve the performance of the thruster.

6. References
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