Material Selection Process for a Low-Power Magnetically Shielded Hall Thruster

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I. Nomenclature

R = magnetic reluctance
μ_0 = permeability of free space
μ_r = relative permeability
dl = differential path length of a magnetic flux tube axis
A = magnetic flux tube area
V_B = breakdown voltage
P = cathode pressure
l = distance between cathode cup and orifice
γ = secondary electron emission ratio

II. Introduction

Hall thrusters are a type of electric propulsion device that ionizes and accelerates a plasma to provide low thrust at high efficiencies. ORB-1-D1 is a low-power magnetically-shielded Hall thruster (≤ 1.35 kW) developed by the OUROBOROS project in the University of Alabama in Huntsville Electric Propulsion Club that is designed to run on krypton and features a center-mounted glow discharge cathode. ORB-1-D1 is estimated to undergo its first test by May 1, 2025 on argon propellant to determine design feasibility by successful thruster ignition. A large portion of the development of the system was dedicated to the materials selection of integral components of the thruster, including the discharge channel, magnetic circuit, and the glow discharge hollow cathode.

III. Discharge Channel Material Considerations

All Hall thrusters require a discharge channel to primarily protect the magnetic circuit and other components from the plasma and high energy ions and electrons. When considering the materials that are appropriate for a discharge channel, four primary considerations are made: dielectric properties, thermal characteristics, sputtering and secondary ion emission, and manufacturability. Given the specificity of these properties, the list of viable materials is relatively short. Despite the short list additional cost and manufacturability become more important when dealing with extremely specialized materials.

A. Dielectric Properties

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There are two prevailing types of Hall thrusters, a thruster with anode layer (TAL) where the wall of the discharge channel is a metallic material, and a stationary plasma thruster (SPT) where the discharge channel is a material with high dielectric strength [6]. ORB-1-D1 was designed to be an SPT due to the abundance of literature on this variant of a Hall thruster and the design's prevalence in spaceflight applications. The dielectric material prevents the electric fields generated by the plasma from penetrating the discharge channel while still allowing magnetic fields to permeate through the discharge channel walls.

B. Thermal Characteristics

The walls of the discharge channel will be in direct contact with, or extremely close to plasma which is maintained at a relatively high temperature. With the walls of the discharge channel around the ionization region reaching an estimated 600 degrees C, a material that does not warp or melt at relatively high temperatures is ideal [5]. This criteria immediately eliminates any materials with low melting points, or materials with unfavorable thermal expansion properties because changes in the geometry of the discharge channel will adversely affect the Hall thruster's performance.

C. Sputtering and Secondary Ion Emission

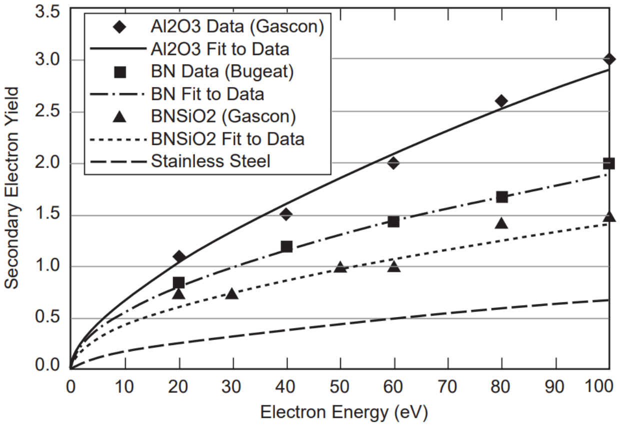

Fig. 1 Comparison of Candidate Material Secondary Ion Emission Characteristics Adapted from Ref.[4]

Sputtering is the process of plasma removing material from the discharge channel wall, which usually occurs at the ionization region of the thruster and by its exit plane, where the plasma is typically the densest [6].

D. Manufacturability

The discharge channel material has to be easily manufactured by accessible means of machining. Additive manufacturing techniques like 3D printing tend to have fast manufacturing times but are limited by the capabilities of commercial fused deposition modeling 3D printers. Silicon carbide and zirconium silicate PLA filaments are two candidates, as silicon carbide is a commonly used material in Hall thruster discharge channels [7]. The manufacturing process requires that any printed material would have to be processed in a sintering furnace in order to remove the PLA from the structure [16]. However, due to the porosity of the final structure, this material was passed over pending future research into methods of decreasing porosity [8]. Manufacturing a discharge channel through machining a suitable material, such as a ceramic, is a suitable method provided the appropriate tooling is available.

IV. Magnetic Circuit Material Considerations

A. Magnetic Properties

The magnetic circuit of a Hall thruster is composed of coils that generate the field and flux guides that make up the general exterior structure of the thruster. Designing the magnetic circuit necessitates that the overall magnetic field generated by the coils does not exceed the saturation point of the material making up the poles and flux guides. This has caused multiple teams to seek out exotic iron-cobalt alloys such as Hiperco-50 [1]. Low carbon steel has also been used in this way, given that it is much cheaper and more readily available while maintaining to a slightly lesser extent the desirable magnetic properties of more exotic alloys [2]. Of chief importance for theoretically determining magnetic field strength anywhere in the circuit is knowing the magnetic reluctance (similar to resistance in electrical circuits) at any point in the circuit, so equation (1) used by the team at SITAEL in their paper is used to evaluate the circuit [3].

$$R = \int_0^s \frac{dl}{\mu_0 \mu_r \cdot A(l)} \tag{1}$$

B. Thermal Properties

The highest priority when it comes to the thermal properties of the Hall thruster is the temperature of the coils. In a Hall thruster, one of the more difficult aspects of magnetic field design is the balance of field strength, coil current, and thruster weight. All of these factors are interdependent, and thruster weight and coil temperature are also related in that as the number of windings and current increase, the resistivity of the wire causes heat to be generated in the coil. Some teams have gotten around the thermal constraints of some wire types by employing fiberglass coated copper wire, which can handle higher temperatures [4]. The main drawback to these fiberglass coated wires is the increased wire diameter, which allows for fewer windings in the space as well as more mass for the same number of turns.

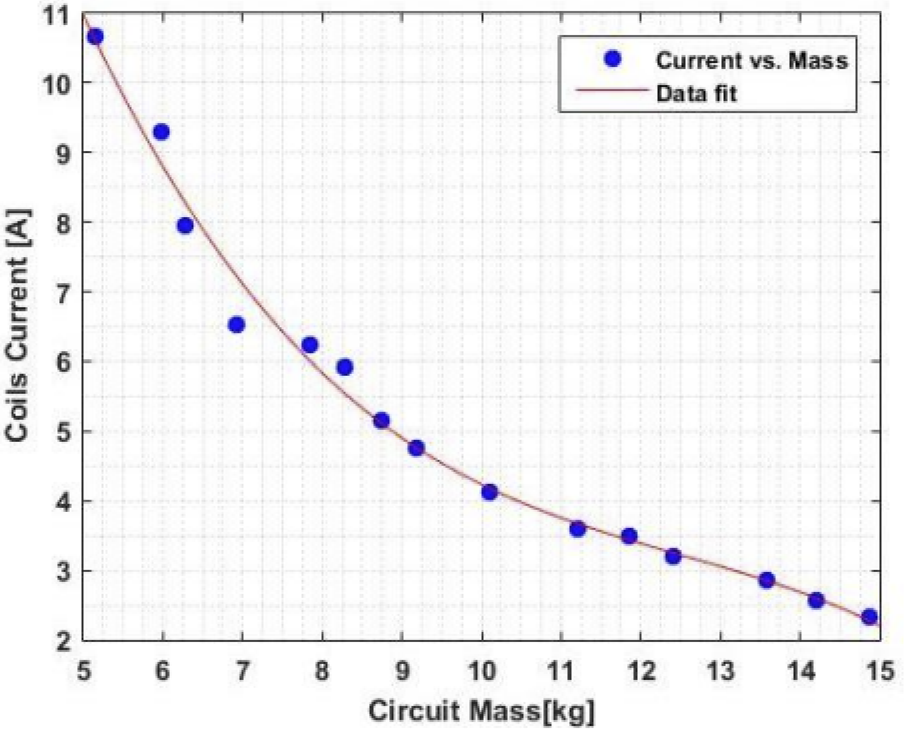

Fig. 2 Coil current as a function of circuit mass Adapted from Ref.[3]

C. Cost, Ease of Manufacture and Procurement

The material we select for the thruster housing as well as the magnetic circuit in general will likely be a low carbon steel such as 1010 steel. It is easy to source and can be manufactured with traditional machining methods. It has a relatively high permeability and it is machinable by traditional methods [2]. Moreover, it can be sourced from places such as McMaster-Carr, with very little lead time compared to other materials that may have long lead times or ship from overseas.

V. Hollow Cathode Material Considerations

The hollow cathode is an important component of the Hall thruster, providing an electron source for ionization of the propellant gas and effective neutralization of the thruster plume. Three architectures were considered: traditional and heaterless cathodes with thermionic emitters, and a glow discharge hollow cathode. The main drivers of technical decisions regarding the hollow cathode were cost and relative technical complexity, directly related to the materials used in the system.

In a traditional hollow cathode, thermionic emitters such as lanthanum hexaboride (LaB_6) or barium oxide (BaO), or low-work function inserts like C12A7, are heated to release large amounts of electrons [14]. A low-voltage discharge between the keeper electrode and the cathode initiates and sustains plasma generation. Once operational, the cathode is self-sustaining, meaning the electron discharge and plasma heating maintain its temperature without the need for the heater. An alternative to the traditional hollow cathode is the heaterless hollow cathode, which omits the cathode heater that is typically used to initiate the thermionic emission process. The physics behind these systems are largely well understood, and traditional hollow cathodes with thermionic emitters have flown in space on previous Hall thruster missions [13]. However, thermionic emitter material cost and manufacturability was a major concern, as most thermionic emitters cost hundreds or thousands of dollars and require care when machining.

An alternative experimental option for the cathode system is the glow discharge hollow cathode. Instead of utilizing a thermionic emitter or a low-work insert, the glow discharge cathode achieves direct ionization of the gas propellant by applying high voltage between a cathode cup and neutralizer orifice, achieving the namesake glow discharge effect that creates a plasma. Breakdown occurs based on pressure differential and applied voltage based on Paschen's law [9]:

$$V_B = \frac{BPl}{ln(APl) - ln(ln(1+\frac{1}{\gamma}))} \qquad (2)$$

where V_B is the breakdown voltage, P is the cathode pressure, l is the distance between the cathode cup and orifice, and γ is the secondary electron emission ratio. A and B are experimentally determined coefficients that relate to the gas saturation ionization and excitation/ionization energies, respectively. Existing literature on the glow discharge hollow cathode for use in electric propulsion is very limited, but they have been successfully demonstrated by Applied Ion Systems, the ZAP Lab at National Cheng Kung University, and the Plasma Propulsion Laboratory at Harbin Institute of Technology [10-(11)-12]. The glow discharge cathode does not use any expensive thermionic emitter materials and is much simpler mechanically than the traditional and heaterless hollow cathode mechanisms.

VI. Downselection Methodology

The materials selected for the construction of our Hall thruster were chosen based on a variety of factors, however material cost and ease of manufacture were the main limiting factors for our thruster design. For the discharge chamber, many options were considered for the material. Boron Nitride is the industry standard due to its superior properties in secondary electron emission and ion sputtering. However, BN discharge chambers are prohibitively expensive. Literature shows that Aluminum Oxide discharge channels are similarly well suited to Hall thruster applications [7]. Aluminum oxide is much cheaper than BN, with options being available from large material suppliers for blocks that can be traditionally machined.

The material selection process for the magnetic systems follows a similar path, as there is both an ideal solution, and one that is easily bought and machined. A high permeability, high saturation point material such as iron cobalt alloys would allow for more flexibility in the design of the magnetic circuit before issues such as saturation occur. However, similar results can be achieved with the use of low carbon steel alloys, as they have relatively high permeability, and decent saturation points. Low carbon steel by comparison to alloys such as Hiperco-50, are very cheap, and easy to machine through traditional methods. Given these advantages, low carbon steel was the obvious choice.

As for the glow discharge hollow cathode, since the design does not require a thermionic emitter, the material selection is limited to what has already been demonstrated in the literature. As cost is the primary barrier to a traditional or heaterless hollow cathode, the selection criteria for a type of cathode is dependent on the total cost of the cathode compared to its effectiveness at achieving ionization and neutralization. The cathode can be manufactured out of materials common in thruster housing designs, including ceramic or steel [10-(11)-12].

VII. Conclusion

One of the most challenging aspects of Hall thruster development by students is the high cost and low availability of materials most commonly used to construct them. The materials used in commercial thrusters as well as those developed by space agencies around the world are often difficult to source, machine, and afford for projects with a limited budget. Bringing down the cost of designing and building these devices can be achieved through the conjunctive use of materials that, while not ideal, can function in their intended roles well enough if their deficiencies are accounted for in the design process. We expect that our discharge channel will not have performance identical to their BN equivalents, so considerations as to the thickness and overall geometry must be made. Additional mass may be required to achieve the same magnetic properties found in high end Hall thrusters, however, the differences are not significant enough to make effective field topology design impossible. Using glow discharge cathodes with thrusters at our intended scale is unusual, however, the design favors a more compact and less expensive alternative to the hollow cathodes commonly found in other designs. If our thruster is able to produce meaningful and measurable results, it will demonstrate the feasibility of designing a small to medium size hall thruster with a much lower barrier to entry in the materials space.

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