INVESTIGATION OF ARCJET CATHODE MATERIAL PROPERTIES

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ABSTRACT

Current limitations on arcjet thruster performance and lifetime are primarily a factor of cathode erosion. Investigation of several refractory Tungsten-based cathode materials, W-ThO₂ (2%, 4%), W-La₂O₃ (1.5%, 2%), and pure W (99.95%), to evaluate their resistance to cathode erosion revealed several important material properties which contribute towards increased erosion resistance. These properties are work function, density, porosity, and grain structure. After a series of measurements, 4% Th-W is the best choice for arcjet thruster cathodes as the small grain size, low density/porosity, high oxide concentration and low work function will drastically reduce erosion and increase cathode working life.

INTRODUCTION

Arcjet Thrusters are a form of electrical rocket propulsion which ionize an inert gas and expand the hot plasma by means of a converging-diverging nozzle to supersonic speeds. Cold gas flows in the chamber around a high voltage cathode where it is ionized at the throat entrance and exhausts through the diverging outlet section to provide a low thrust high specific impulse gas plasma plume. Arcjet thrusters are a promising space based propulsion systems, and their limited use is a direct function of lifetime issues, typically constrained by the lifetime of the cathode.

Figure 1: Simplified system diagram of arcjet thruster.

HYPOTHESIS

Given samples of different cathode materials under typical plasmadyfamic loading (arc attachment); a correlation can be made between the severity of erosion of different cathodes and their material properties.

BACKGROUND

Work Function

Work function is the amount of energy required to remove an electron from an atom, specifically the amount of energy required to remove an electron from the first two-three layers of atoms of a substance. It is measured in electron volts (eV), and is a significant determinant of material performance in arcing scenarios. Electrodes with a lower work function require less voltage to pull electrons from the cathode to start and maintain an arc. As voltage increases with current, higher voltages therefore result in higher temperatures. By minimizing the work function of a material the working temperature of the cathode can be decreased, thereby reducing erosion (Fig. 2). Oxide additives in the material matrix will lower the net work function of the cathode, and thus allow for easier arc-starting. Unfortunately, work function additives also decrease the melting point of the material (tungsten), and so there is a trade-off between arc-starting and erosion.

Work function can be measured using Kelvin Probe Force Microscopy. Kelvin Probes use a vibrating tip 0.2 - 2.0mm above the sample which forms a virtual parallel-plate capacitor. When there is a direct-current (DC) potential difference between the tip and the surface, the AC+DC voltage offset will cause the head to vibrate. The resulting vibration is detected using scanned-probe microscopy and transduced back to a voltage...
difference. This difference is used to determine the work function of the material.

![Figure 3: Kelvin Probe apparatus measuring the work function of representative cathode samples.]

**Density and Porosity**

Density of the cathode material can be accurately determined using water volume displacement. There are two feasible methods which can be used to determine the porosity of a material; the direct method whereby the volume of the actual sample and the volume of the sample without pores is determined and the difference is taken, and the optical method which uses a scanning electron microscope to take a detailed image of the microstructure of the material. Once an image has been produced, binarization of the image using a shading correction and a median filter to reduce the image to black and white, allows porosity to be determined. One color will be the material and another is the encapsulating epoxy. The black to white ratio then corresponds to the porosity of the substance.

![Figure 4: SEM micrograph (A) and binarized micrograph for porosity analysis.]

Though detailed porosity analysis was planned for this study, technical issues prevented planned progress in this space so at best a visual assessment can be made on the matter of porosity.

**Grain Structure and Oxide Advantage**

Prior research and materials science theory indicates that tungsten with electropositive oxides embedded within the crystal matrix improves arc starting and stability of the cathodes. The oxides migrate throughout the matrix, moving between the grain boundaries to the point of the cathode, where they lose the oxide element to the arc and leave a metal film on the tip. This film has a different temperature which is based on the element work function, and this temperature also assists with easier arc starting than pure tungsten. If oxides are homogenously distributed throughout the base metal and the grains of the material are fine enough, the oxides can easily diffuse through the metal, along the grain boundaries, to the surface where they replenish the lost oxide elements. If the grains are too large from the manufacturing process, or the temperature of the cathode is too high, a process called “grain growth” occurs and individual grains fuse together. This reduces the available boundaries and channels which the oxides can use to migrate to the tip. As oxide migration both serves to improve arc starting and stability, the reduced oxides at the surface will necessitate a higher current to maintain the arc, which will increase the working temperature of the arc and cathode, resulting in faster grain growth and faster erosion. Additionally, as oxide migration serves to prevent grain growth, the reduced oxide migration will again increase grain growth, resulting in greater erosion.

**Microstructure Imaging**

The ability to image in detail the surface of the cathodes before and after arc attachment, using the SEM, allows classification of the type of erosion (pitting, ablation, recrystallization, sputtering or liquid droplet removal), the magnitude and severity of this erosion (form the size of the erosion and the changes to the surrounding microstructure), the compositional changes of the material as a function of the erosion, and the grain structure of the material, which is key in the ability of the additive oxide to improve the performance characteristics of the cathode and extend the cathode life.

### REQUIRED MATERIALS

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Required Size</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5% Lanthanated Tungsten</td>
<td>1/8”</td>
<td>14.02</td>
</tr>
<tr>
<td>2.0% Lanthanated Tungsten</td>
<td>1/16”</td>
<td>15.40</td>
</tr>
<tr>
<td>2.0% Thoriated Tungsten</td>
<td>1/16”</td>
<td>15.00</td>
</tr>
<tr>
<td>ICE-T 4.0% Thoriated Tungsten</td>
<td>1/16”</td>
<td>21.76</td>
</tr>
<tr>
<td>Pure Tungsten</td>
<td>1/8”</td>
<td>13.36</td>
</tr>
</tbody>
</table>

### RESULTS

**Work Function**

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured Work Function (eV)</th>
<th>Theoretical Oxide Work Function (eV)</th>
<th>Theoretical Metal Work Function (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2% W-Th</td>
<td>4.711</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>4% W-Th</td>
<td>4.552</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>1.5% W-La</td>
<td>4.5031</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>2% W-La</td>
<td>4.5101</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Pure W</td>
<td>4.9414</td>
<td>NA</td>
<td>4.5</td>
</tr>
</tbody>
</table>
It was expected that the measured values for the cathode work function would be higher than the theoretical values as the interaction of oxygen and moisture in the atmosphere will raise these values significantly. If samples of 2.6 eV (theoretical) were to exist in air then they would photoemit electrons when exposed to visible light. With polished aluminum (reference sample) 3.8 eV is one of the lowest work functions possible. As this study aims to compare the performance characteristics of a set of cathodes, relative work function data was more important than absolute measurements, so the effect of air is acceptable.

From the table of results, it can be observed that indeed oxides do lower the work function significantly relative to pure metal and that both Lanthanated cathodes and the 4% Thoriated cathode have the lowest work functions.

**SEM AND OPTICAL IMAGING OF CATHODE SAMPLES**

The following series of images were taken with both a scanning electron microscope of the surface of the cathodes before arc attachment, and with an optical microscope after attachment, to observe any pitting or erosion.

**Pure Tungsten Pre-Arc Attachment**

![Pure Tungsten Pre-Arc Attachment Image](image1)

**Pure Tungsten Post Arc-Attachment**

![Pure Tungsten Post Arc-Attachment Image](image2)

The black spots in the SEM images are regions of air, and these images give an indication for the porosity of the material; in the case of pure Tungsten it is the most porous of the cathode materials selected. The original SEM images also highlight the non-obvious grain structure of pure tungsten, though in the later images the arc-attachment points reveal some grain structure, and are large, characteristic of high erosion (liquid) in the arc-region.

**1.5% Lanthanated Tungsten Pre-Arc**

![1.5% Lanthanated Tungsten Pre-Arc Image](image3)

![1.5% Lanthanated Tungsten Pre-Arc Image](image4)
The Lanthanum additive has decreased porosity and improved homogenous grain structure as evidenced by the SEM images, and the arc-attachment points indicate moderate erosion and grain growth, as exhibited by larger grain sizes inside the arc-produced “crater” on the material surface.

As the material increases in oxide concentration there is a clearer grain structure, with moderate sized grains that are homogenously distributed. There is less erosion relative to pure tungsten, and there is some grain growth inside the arc crater. The material is still relatively low in density and porosity.
4% Cryogenically Treated Thoriated Tungsten Post-Arc

It can be observed that this cathode material is a higher density and lower porosity selection than other options, and displays a very clear grain structure. The grain sizes are small and there are distinct oxide migration boundaries which is excellent for the work function. Though there is observable grain growth inside the crater it is quite low. This cathode material has excellent erosion characteristics.

CONCLUSIONS

The work function measurements and microstructure imaging of the different cathode materials in this study point to a clear correlation between cathode erosion characteristics and several key material properties. As the additive concentration increases the porosity of the material decreases. Measuring the experimental work function confirmed the theoretical trend between the different cathode materials. 1.5%-2% La-W and 4% Th-W have significantly lower work functions than 2% Th-W or Pure W. Work function provides an indication of the relative ease with which a material can start an arc, but examination of the material melting point informs the relative lifetime of the cathode under high temperature conditions. Of the low work function materials, 1.5% La-W has a higher melting point than 2% La-W and is therefore indicated for use over 2% La-W. 4% Th-W has the highest melting point however, and also the lowest work function. Examination of the grain structure is the final step in the cathode selection process. 4% Th-W has the clearest grain structure, and smallest grain size, indicating good oxide migration properties and thus good arc sustaining characteristics. 4% Th-W is therefore the best choice for arcjet thruster cathodes as the small grain size, low density/porosity, high oxide concentration and low work function will drastically reduce erosion and increase cathode working life.