Performance of Porous Tungsten Needle LMIS for Use as Indium FEEP Emitters

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Abstract: A new class of Indium Needle FEEP thruster was developed using porous tungsten as material. Potentially they provide a higher thermal cycle capability, lower sensitivity to contamination and promise a relaxation of the manufacturing efforts in comparison to for the one for standard indium needle FEEPS (e.g. LISA PF type). These porous tungsten needles are infused with liquid indium in the porous matrix such that the liquid metal is internally transported to the needle tip and subsequently field emitted at voltages in the range of 4-9 kV in order to generate thrust at high efficiency.

Nomenclature

\[ \eta = \text{mass efficiency} \]

I. Introduction

TRADITIONALLY, a liquid metal ion source (LMIS) consists of a tungsten needle with a tip radius of 1-2 µm which is covered on its surface by a thin film of liquid metal such as gallium or indium. Upon application of a sufficiently strong electric field, the liquid film takes on the characteristic shape of the Taylor cone and commences emission of ions, which can then be used to micro-machine a part in a focused ion beam⁴, to neutralize a positively charged spacecraft or to generate thrust on a spacecraft through emission of high-velocity ions.

While needle emitters can be serviced easily in a terrestrial focused ion beam column, this is not the case in space applications. Since it is impractical or impossible to perform repeated maintenance on spacecraft, the liquid metal sources need to be extraordinarily reliable under any circumstances⁵. An issue, which has been found to limit the reliability of said emitters, is a discontinuity of the thin film of liquid metal between the propellant tank and the needle tip. Once this vital connection is severed, the emitter cannot function anymore. The probability of such an event occurring is greatly increased when the liquid propellant undergoes solidification and re-melting, as in a full

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thermal cycle. This may occur due to spacecraft operational or mission constraints or in case of an emergency power shut down on the spacecraft.

Due to the importance of reliable operation, great efforts have been undertaken\textsuperscript{3,4} to eliminate the risk associated with tearing of the liquid metal film during thermal cycling, and, while successful, introduce a high level of complexity to the emitter manufacturing along with long manufacturing times.

In this document, a solution to this recurring problem is presented which addresses the root of the problem by eliminating the thin film of flowing liquid metal and replacing it with a volumetric flow through the matrix of a porous needle. In doing so, the emitter is endowed with properties of a capillary, which are known to be far more tolerant to thermal cycling, but without sacrificing the sharp tip of a needle, which is necessary for efficient emission\textsuperscript{5}. A novel method of fabricating such porous tungsten needles rapidly and reproducibly has been developed based on a process called micro powder injection moulding. In the following chapters, first results obtained with this new class of porous tungsten needles are presented and compared to classical bulk needles. The emphasis lies on space propulsion, but the results are just as meaningful for other applications, as listed above.

II. Manufacturing of Porous Tungsten Needles by Powder Injection Moulding

A porous tungsten matrix is achieved by sintering tungsten powder. The pore size is predominantly a function of the grain size, the sintering temperature and duration. Sharp porous structures for use as ion emitters have been investigated previously\textsuperscript{6,7}, but without emphasis on achieving very sharp needle tips in the range of 1-2 µm. The tip sharpness is the most important parameter for the efficiency of the ion emitter. The ratio of mass ejected as ions to the total ejected mass is the mass efficiency $\eta$. Since only the charged portion of the ejected mass can be accelerated to very high velocities of 80 km/s, it ultimately determines the amount of thrust per propellant mass.

After preparation of a mixture of tungsten powder with binding components to obtain the feedstock, it is injected into a suitably formed mould, i.e. a cylindrical mould with a diameter of 0.5 mm and a length of 50 mm. After moulding and sintering of these parts, one can obtain several hundred porous tungsten rods per day. These rods are then etched electrochemically in a NaOH bath in order to obtain a sharp tip as shown in Figure 1.

A. Wetting

At this stage it is important to note that the obtained porosity is of the ‘open’ type, meaning that all pores are interconnected, so that a liquid can flow internally from the tank to the needle tip in comparison with the standard needle FEEP where flow occurs only on the needle surface.

In this wetting stage, the porous tungsten matrix is brought into contact with the liquid metal with the goal of establishing a bond between the two dissimilar materials. In the cases studied within this document, the liquid metal of choice is indium, due to its advantageous melting point of 159°, which permits it to be solid during the launch phase, which is characterized by strong vibrations, yet turns liquid at temperatures which can easily be achieved with an electric heater.

The wetting of a porous needle differs markedly from the wetting of a bulk needle, since the porous matrix promotes the flow of indium from the reservoir to the needle tip by capillary action. In the process of heating the needle to wetting temperatures (typically in the range of 1000°C), the porous needle is infused automatically with the liquid metal. The result of this process can be seen in Figure 2, in which

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure1.png}
\caption{Electrochemically sharpened porous tungsten needle.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure2.png}
\caption{Composite image of a porous tungsten needle before and after infusion with indium.}
\end{figure}
the dark gray patches on the right side of the collage are indium embedded in the pores.

The combination of having a sharp tip and liquid metal embedded in the pores is the key feature of this new class of porous tungsten emitters. In this manner the best properties of a needle (high efficiency) and of a capillary (internal flow, high reliability) can be incorporated in one design.

At this stage, the needle is ready for use as liquid metal ion source. The next section presents test results obtained with porous tungsten needle emitters using indium as propellant.

### III. Test Results

A test program including 10 needles manufactured in slightly different fashion was undertaken in order to characterize this new class of needles. Special consideration was given to fundamental performance parameters such as the current-voltage characteristic, startup voltage and response to a thermal cycle. In total, more than 1200 hours of test experience with porous tungsten needles of various compositions and manufacturing methods was accumulated and more than 20 thermal cycles were completed successfully. Four needles were manufactured by the micro powder injection process and tested. In the following, the results from these 4 porous needles shall be discussed.

All needles presented herein have been manufactured from the same batch and have a tip sharpness in the range of 1-5 µm, depending on the etching recipe used during manufacturing. Three needles have been welded to a reservoir holding 1.2 g of indium and 1 needle has been attached to a tank with a capacity of 15 g indium. The electrical setup involves the emitter itself, which is biased positively up to 12 kV and a circular extraction electrode surrounding the emitter needle at a distance of 4 mm, which is biased to -1 kV. The potential difference between these two electrodes generates a strong electric field at the needle tip and leads to field emission of positively charged indium ions from the liquid metal.

Figure 3 shows that the starting voltage of all 4 emitters is very similar, with ranges from 4.1 kV to 5.5 kV. The slopes of the curves, signifying the impedance of the emitters is also comparable within the group of inspected emitters as well as comparable to classical bulk needles (in the range of 20-40 MΩ), thus showing that there is no significant difference in actual emission between a standard bulk material needle and the porous needle.

#### B. Thermal Cycling

The porous tungsten needle emitters were specifically developed to improve the reliability and performance after repeated thermal cycling and avoid sensitivity issues against spacecraft outgassing. This increase in reliability is due to the fact that the liquid metal is no longer arranged in a thin film on the surface of the needle, but rather is distributed throughout the entire porous needle. In this manner, the liquid metal is shielded from potential outgassing problems.

<table>
<thead>
<tr>
<th>Porous needle #</th>
<th>Startup voltage, V</th>
<th>Test duration, h</th>
<th>Thermal cycles completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>4100</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>5500</td>
<td>390</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>4500</td>
<td>627</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 3. Current-voltage characteristics of 4 porous tungsten needle emitters. The solid line represents the I/V characteristic of a 15 g emitter (LISA PF standard, whereas the other 3 emitters were mounted in a tank of 1.2 g indium.

Table 1. Summary of test program. Every needle was operational at the end of testing, which demonstrates the robustness of the concept to thermal cycling.
contamination from the outside and the failure mode of tearing the surface film is mitigated. A comparable
disconnection of the liquid metal film across the entire volume of the needle is highly unlikely, due to the large
surface across which the liquid metal flows and due to capillary action striving to keep the pores filled at all times.

Indeed, when subjected to repeated thermal cycles, the needles always resumed operation upon reheating and
the operational characteristic of the needle did not change in any significant fashion. The summary of
test duration and the number of completed thermal cycles is shown in

Table 1. The longest test (627 hours) was performed with needle #4, which was mounted into the largest tank,
holding up to 15 g of indium (identical with the tank volume designed for LISA PF). As with classical bulk needles,
the emission is relative stable between 4.5 kV and 5 kV for a constant emission current of 50 µA, as shown in Figure
4 (200 point average line fit). Furthermore, Figure 4 shows that the thermal cycle which was performed after 70
hours, did not affect the operating voltage. The mean voltages and their standard deviation for a representative
thermal cycle are listed in Table 2.

In addition to standard testing and thermal cycle assessments, long term storage test was performed
with one of the porous tungsten needles to study potential deterioration during prolonged exposure to
air. For this purpose, the emitter was stored 6 months in nitrogen atmosphere and then re-tested,
yielding an unchanged characteristic. Following this, the emitter was placed for another 6 months in air
and subsequently tested - again showing no change in performance.

Table 2. Average voltages before and after a thermal cycle. The change in voltage is very small and well within a single standard deviation.

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Average voltage @ 50 µA, V</th>
<th>Standard deviation over test duration, V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4750</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>4775</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 4. Emission voltage of porous tungsten needle #4 at a constant emission current of 50 µA. A thermal cycle after 70 hours of emission did not affect the operating

IV. Conclusion

A new type of porous tungsten needle emitter was developed based on a rapid prototyping manufacturing process
termed micro powder injection moulding. Using a low viscosity feedstock, structures with a diameter of 0.5 mm and
an aspect ratio of 1:100 could be fabricated in large numbers for use as liquid metal ion source in space propulsion.
Due to the open porosity of the matrix, the liquid metal can flow internally and is thus protected from surface
contaminants. Furthermore, the transition from a surface flow in classical bulk needles to a volumetric flow in
porous needles increases the reliability of operation, especially after performing a thermal cycle in which the liquid
metal solidifies. Since this is one of the most prevalent failure mode of classical needles, introduction of sharp and
porous needles can greatly increase the probability of success in long-term missions. It was shown that the
characteristics of porous needles is otherwise comparable to classical bulk needles and may replace them in
applications where the increased tolerance to thermal cycling is relevant. In conclusion, the porous needle type
eliminates many challenges which have been experienced with the standard (bulk) needle type, namely, the limited
number of allowable thermal cycles, contamination sensitivity, and most important the rather complicated and time
consuming manufacturing process.
References

1 J. Orloff, L.W. Swanson, M. Utltaut, Kluwer Academic/Plenum Publishers 2003, High resolution focused ion beams