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Creation of electrospray emitters from a flat polytetrafluoroethylene sheet through the use of laser micro-manufacturing

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Abstract. Electrospray propulsion is a form of electrostatic propulsion that shows potential for use as a thruster on small satellites. Electrospray emitters traditionally use arrays of capillaries, however, this paper investigates the suitability of manufacturing an emitter by laser drilling holes in sheets of polytetrafluoroethylene (PTFE), also known as Teflon. This is done by examining factors such as the machining time, hole shape and degree of taper in holes drilled through different methods. Experimental work was done to determine the shape of holes drilled in a flat sheet, and a computational model was used to simulate the performance of these drilled holes. These results were used to judge if this would be a valid method to manufacture electrospray thrusters, and how these thrusters would compare to more traditional emitters. Based on these results, it was concluded that a PTFE sheet with a width of 0.81 mm would be sufficient to achieve electrospray at voltages lower than those needed for traditional emitters.

1. Introduction

A nanosatellite, or "nano-sat", is a type of small satellite that weighs between 1 and 10 kg. In recent years, satellites such as these have seen a surge in popularity, due in part to their relatively low cost and ease of construction. However, one major aspect which these devices are lacking is an easily available method of on-board propulsion, which would significantly improve the variety of missions that these devices can be used for. Traditional rocket propulsion methods are typically too large for these satellites, which can have a minimum total surface area as low as $600\,\text{cm}^2$ [1]. One possible solution to this is electrospray (ES) propulsion. Electrospray propulsion is a form of electrostatic propulsion, whereby a potential difference is applied between an electrode and a conductive liquid. This, in turn, generates an electric field, which pulls the liquid towards the electrode, causing it deform into a cone shape known as a Taylor cone [2]. When this electric field reaches a certain magnitude, the tip of the cone begins to emit charged particles, which propels the system in the opposite direction [3].

Traditionally, an ES thruster, (also referred to as a colloid thruster) would consist of an array of capillary shaped emitters. These capillaries would feed the propellant to the Taylor cone, while also ensuring that the electric field was focused on the tip of the emitter. However, one alternate method for ES propulsion would be to drill holes in a flat plate for use as an emitter. Maximising the performance of these holes relies on a variety of factors, such as maximising the aspect ratio (AR), minimising the degree of taper and choosing a material with minimal wetting. Additionally, it was found that by using a plate with a suitably low relative permitivity, ES propulsion could be achieved using potential differences comparable to, or potentially even lower than, traditional capillary emitters [4]. For the purpose of this project, three suitable materials were identified: polyether ether ketone (PEEK); polymide; and polytetrafluoroethylene (PTFE), also known as Teflon. However, this paper will focus solely on PTFE, and its suitability as a material. These findings present the opportunity to manufacture ES emitters solely using laser ablation, by ablating holes in low permitivity material for use as ES emitters.

2. Overview of Laser Ablation

Laser drilling is a subtractive process that uses a focused laser beam to ablate features in the surface of a material. Laser machining relies on a concept known as photoablation, wherein part of the thermal energy of the laser is transferred to the targeted material, resulting in some of it being ablated. The actual manner in which the material is ejected from the target varies, with melting, vaporisation, plasma formation, and phase explosion all being processes through which the material can be removed from the target [5]. Regardless of the actual process that is undergone, the amount of ablation that occurs is dependent on the amount of energy that is absorbed by the target. If more energy is reflected, then less energy can be converted to heat in order to ablate the target [6].

Laser ablation has a history of use in manufacturing microthrusters, with work done by NASA and MIT demonstrating the viability of this method [7, 8]. Referring specifically to ES emission, the Environmental Molecular Sciences Laboratory used laser drilling to manufacture an array of ES emitters, for use in mass spectrometry [9].

Laser ablation has the potential to be significantly faster than methods such as deep reactive-ion etching (DRIE), which is one of the more commonly used methods for manufacturing ES emitters [7, 10, 11]. According to literature, DRIE can etch a trench in silicone that is 130 µm deep and 10 µm wide at a rate of 2.5 µm per minute [12]. With this estimation in mind, the rate at which materials are ablated will be examined to determine how they compare to other manufacturing methods. This will allow for the speed of DRIE and laser ablation to be compared, and will also provide a metric by which various materials can be compared.

3. Ablation Rate

All of the materials previously listed have a history of being laser ablated, and thus the ablation rate for each can be judged from literature.

Figure 1 depicts the depth of material that is ablated with each pulse, across a range of fluences. This contains data taken from multiple sources [13–15] for PTFE, PEEK, and polymide. This data comes from different experiments, and thus a variety of laser systems. In order to ensure a fair comparison, the etch rate is measured according to the laser fluence. The fluence of a laser is an indication of the amount of energy that can be absorbed, which is determined by the energy delivered per unit area. It has the SI unit $\mathrm{J\,m^{-2}}$, and can be calculated from equation 1. Here,

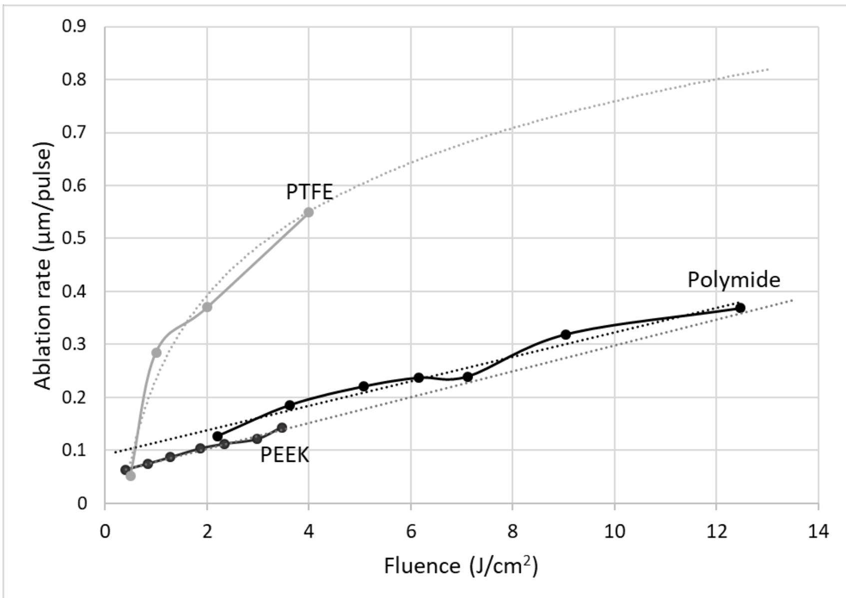

Figure 1: A comparison of ablation rates of PTFE, PEEK and Polymide. Data taken from [13–15]

H is the fluence , P is the maximum average power, A_l is the effective focal spot area and f is the repetition rate of the laser.

$$H = \frac{P}{A_l f} \tag{1}$$

For the purposes of this investigation, experimental testing will be done across these three materials using a single laser setup. This will be done using an an Edgewave PX-series Laser, which has a maximum average power of 90 W, and emits a beam with a wavelength of 355 nm and a spot size of 100 µm [16]. When operating at a minimum repetition rate of 404.7 kHz, the system has a fluence of $2.83\,\mathrm{J\,cm^{-1}}$. Referring to figure 1, it can be seen that this should correspond to an ablation rate of 0.47 µm per pulse, which corresponds to $190.89\,\mathrm{mm\,s^{-1}}$.

This was verified by running an ablation rate test on PTFE for a fixed fluence. This involved 10 holes being drilled, for times ranging from 1 s to 10 s. This test resulted in a calculated ablation rate of $0.135\,\mathrm{mm\,s^{-1}}$, or 3.33×10^{-4} µm per pulse at 404.7 kHz.

This is significantly slower that the ablation rate taken from Figure 1 [14], and further work will be done to determine the reason behind this. This is most likely due to the laser setup not being correctly optimised, or being otherwise different from the setup seen in literature. Regardless of this, it can be seen that the speed of laser ablation is still notably faster than that of DRIE. Referring back to speed of DRIE in the previous section, it can be seen that the measured etch rate of $0.135\,\mathrm{mm\,s^{-1}}$ (or 8100 µm per minute), exceeds DRIE's measured speed of 2.5 µm per minute by four orders of magnitude. The main benefit that DRIE has over laser ablation is that it can machine multiple emitters at once, whereas most laser systems can only drill one hole at a time. However, these figures show that this only gives DRIE an advantage if more than 3240 emitters are needed, with figure 2 showing a comparison of the time taken to machine a given number of emitters for each method.

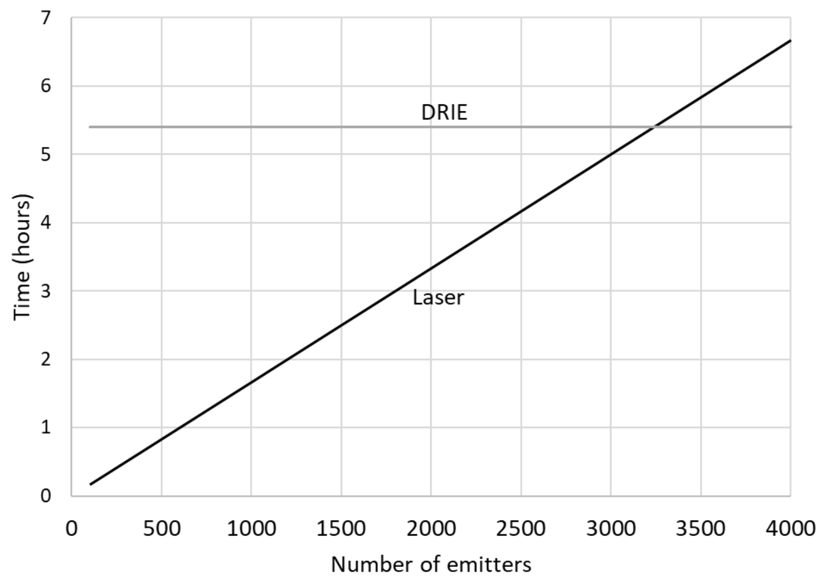

Figure 2: Time taken to machine a number of 0.81 mm hole emitters for both laser ablation and DRIE

ES thrusters are usually arrays of multiple emitters, in order to maximise thrust. However sources examined [7, 8], often have less than 1000 emitters per thruster. As such, while the speed of laser ablation approaches that of DRIE as the amount of emitters required increases, it should still be faster for most ES applications. Additionally, it should be noted that these are taking into account the experimentally observed figures for laser ablation. As more testing is done, it is hoped that the etch rate will begin to more closely match the source used for Figure 1 [14], which would make laser ablation even more suitable. However, the rate at which these emitters are created is not the only criteria for success. More important is the suitability of these emitters for achieving electrospray, and in order to judge this the hole shape must be examined.

4. Hole Shape

To assess the appropriateness of using laser ablation to manufacture PTFE emitters, multiple through holes were drilled through a 0.81 mm sheet of PTFE. These holes were drilled using the previously described Edgewave laser, with all settings as described in the previous section. The first hole was drilled using simple percussion drilling, whereby a series of successive 12 ps laser pulses were used to ablate a hole. This method was chosen as it would minimise the diameter of the hole, and thus maximise the aspect ratio. An additional examination was made into a hole drilled using a technique similar to the one known as trepanning drilling [17]. This process began similar to the previously described hole, with a series of successive pulses ablating a hole through the material. However, once this hole is completed, the laser is moved relative to the hole, allowing it to ablate more material along the side of the hole. It was thought that this would result in a larger diameter, and thus a smaller AR, but it would also result in less taper.

Once both holes were drilled, the shape of these holes were examined using a Keydence VHX-5000 microscope. A image depicting both holes can be seen in figure 3.

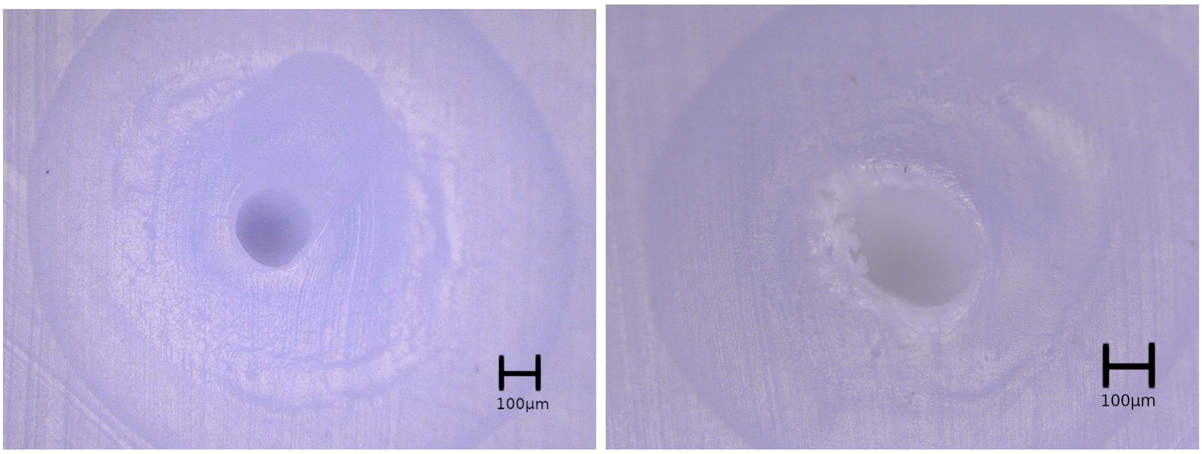

Figure 3: Comparison of hole drilled by percussion drilling (left), and hole drilled by trepanning drilling (right)

Here it can be seen that both holes are circular through holes, albeit with some differences. The trepanning hole appears to have a more elliptical shape, and has some burr formation, while the percussion hole is more uniformly circular. While the percussion hole does have what can initially appear to be a burr formation to the top right of the hole, an examination of the height of this surface reveals that this is not the case, as it does not rise above the surface of the flat plate. As such, this is most likely just a section of PTFE that was partly melted by the laser.

The most notable differences between the two holes, as was expected, are the diameters of the holes and the degree of taper present. The percussion hole has a diameter of 220 μm, while the trepanning hole has a diameter of 250 μm, confirming the expectation that the percussion hole would have a smaller diameter. Similarly, the percussion hole has a taper angle (α_t) of 6.17°, and the trepanning hole has a taper angle of 2.51°. The relationship that this angle has with the entrance and exit hole diameters can be seen in figure 4.

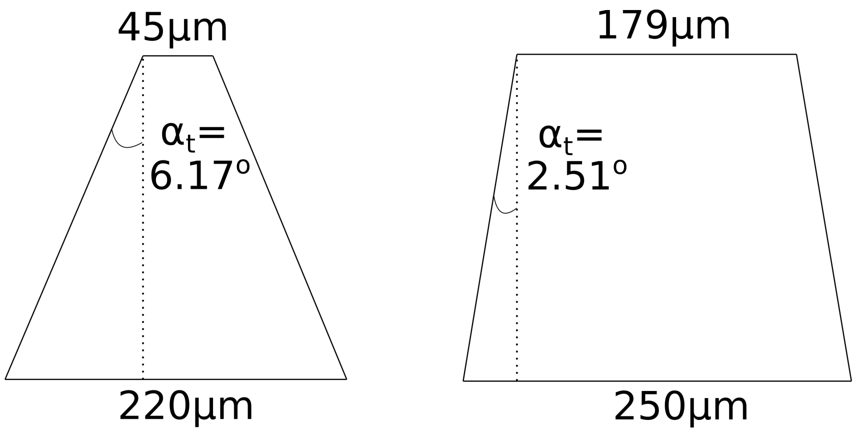

Figure 4: Taper angle for percussion (left) and trepanning (right) holes

Now that this information has been compiled, enough data is available to examine how these holes will perform as ES emitters.

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5. Computational Analysis

A computational model was constructed in order to simulate the electric fields that would form if a Taylor cone were to form at the tip of these holes. This was done using COMSOL multiphysics, which is an finite element analysis solver and multiphysics simulation tool. A model was made of a 0.83 mm flat PTFE plate, with a conductive liquid propellant flowing through it. For the purposes of this simulation, the propellant was modelled as EMI-BF_4, an ionic liquid used for ES in vacuum. There were two electrodes modelled, one inserted into the liquid, and one a set distance away from the plate. A visualisation of this geometry can be seen in figure 5. Here, d is the distance between the plate and the extractor, D is the diameter of the hole, t is the thickness of the plate, D_w is the diameter of the extractor hole, β is the half angle of the Taylor cone and r_t is the radius of the tip of the Taylor cone. The blue electrode was grounded, and the green electrode was set to a known voltage V_{tot}. The values for each of these figures can be seen in Table 1. Note that due to the symmetric nature of this geometry, only half of the model needed to be simulated.

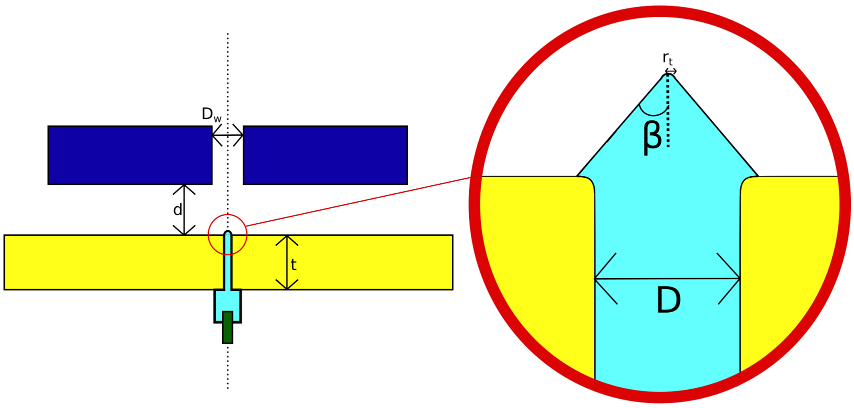

Figure 5: Geometry modelled in COMSOL

Table 1: COMSOL parameter values

Parameter	Value
t	0.81 mm
d	2 mm
D_w	2.5 mm
β	49.3°
r_t	0.2 µm
V_{tot}	6.5 kV

This model was used to simulate the plate used as a hole under three different conditions. First was the hole drilled by percussion drilling, which a diameter of 220 µm and a taper angle of 6.17°. This will be referred to as "Case 1". Second was the hole drilled by trepanning, which had a which a diameter of 250 µm and a taper angle of 2.15°. This will be referred to as "Case 2". Finally, an "ideal scenario" was modelled. This was a hole which had a diameter of 100 µm (the laser spot diameter of the system), and no taper. This will be referred to as "Case 3". This was not intended to be realistic depiction of a possible hole layout, but was simply used for comparison purposes. For all layouts, the liquid was modelled as not wetting across the surface of the plate at all. Once these layouts were modelled, the strength of the electric field at the tip of the Taylor cone was measured, and compared. As previously mentioned, the electric field is what causes the Taylor cone to emit charged particles, and is thus an indication of whether or not this system is able to achieve ES emission. The results of this simulation can be seen in Table 2.

Table 2: Results of computational Simulation

Case	Hole Type	Electric Field Strength ($\mathrm{V\,m^{-1}}$)
Case 1	Percussion	3.36×10^9
Case 2	Trepanning	1.69×10^9
Case 3	Ideal	2.25×10^9

These values were all compared to the minimum possible electric field strength required to obtain electrospray , which was obtained from equation 2 [18]. Here, E_o is the minimum required electric field strength, γ is the surface tension of the liquid and ϵ_o is the permitivity of free space.

$$E_o = (\frac{4\gamma}{\epsilon_o r_t})^{1/2} \tag{2}$$

This equation gave a value of $3.36 \times 10^8\ \mathrm{V\,m^{-1}}$. For one final point of comparison, a capillary emitter with an aspect ratio of 35:1 was modelled under similar conditions, and produced an electric field strength of $3.75 \times 10^8\ \mathrm{V\,m^{-1}}$.

6. Conclusion

Interestingly, these results show that Case 3, the so called "ideal" case, does not result in the highest electric field strength. Instead, the percussion drilling has the highest electric field strength, contrary to expectation. Although initial testing indicated that taper was detrimental to the electric field strength, a smaller hole leads to a higher electric field strength. As such, the taper in the percussion hole can actually be used to its benefit, as it results in a significantly smaller exit hole. If the plate is flipped upside down so that the Taylor cone actually forms on the smaller side of the hole, this will result in an increase in the electric field strength that more than compensates for the decrease caused by the taper. This means that percussion drilling is better that trepanning drilling in all regards: it results in a smaller hole; it results in a more circular hole; and it is quicker. As the electric field strength of Case 1 is higher that E_o, it can be concluded that this hole can achieve electrospray. Additionally, comparing it to the value obtained from equation 2 shows that these holes can produce electrospray at voltages lower than those required in traditional capillary emitters.

This validates PTFE as a material that can be used to laser ablate a ES emitter. The next step is to repeat this process for PEEK and polymide, and compare the results for all three methods. Additionally, the amount of wetting across the surface for each material will need to be examined, as this will affect the shape of the Taylor cone. This will require some experimental testing, after which the most suitable material can be identified.

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