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Microwaves enable activated plasma figuring for ultra-precision fabrication of optics

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Abstract
Activated plasma figuring using microwaves aims at providing highly efficient activated energy beams for rapid fabrication of optics. The chemical nature of this type of energy beam leads to targeting silicon-based materials. Furthermore this technology is proposed to address the needs of ultra-precision optical components. In this paper, we present a novel ADTEC microwave-generated plasma torch design which is operated at atmospheric pressure. In this study, the plasma torch is fed with either argon or helium carrier gas. However this novel design for Plasma Figuring is targeted at local surface correction of crystal quartz which is a material of great interest for optical systems, such as acousto-optic devices. Also this novel design is targeted at reducing mid-spatial frequency errors such as waviness, ripple errors and residual sub-aperture tool footprints. These are responsible for the scattering of light at small angles, resulting in optical hazing effects, photonic energy loss and pixel cross-talk. Also the results of a preliminary investigation using Optical Emission Spectroscopy (OES) are reported and discussed. These results show the operating range when the main processing parameters are changed: microwave forward power values, gas flow rates and the types of gasses.

Microwave plasma, surface figuring, crystal quartz, optical fabrication.

1. Introduction

New technologies in Aerospace and Defence applications increase the demands on the engineering specifications of optical surfaces. Optics are required to be manufactured to 1nm RMS form accuracy and 0.1nm RMS surface finish. The fabrication of these optical systems requires novel ultra-precision methods.

This paper focuses on a bespoke Energy Beam (EB) based fabrication process. This EB process is created to achieve the technical specifications that are required for the next generation of ultra-precision photonic surfaces.

The proposed EB is generated by electromagnetic waves. Electromagnetic energy transfers into a plasma jet at atmospheric pressure. One of the key features of this novel EB will be its capability to process crystal quartz and other silicon based materials.

Different aspects of microwave plasma torch designs are discussed in this paper. A Microwave Induced Plasma (MIP) torch was tested under a rigorous Design Of Experiment (DOE) procedure and the main torch parameters were measured and analysed.

2. Microwave Generated Micro Plasmas

EBs with plasma jet diameters in the range between micrometre and millimetre are called Micro Plasmas [1]. Often these plasmas can exist at atmospheric pressure and have electron densities in the range of $10^{14}cm^{-3}$ to $10^{16}cm^{-3}$ [2]. Unlike other types of plasma requiring higher powers that create larger jets, micro plasmas are inherently suitable for micromachining tools and photonic surface fabrication [3].

Microwave-generated macro scale plasmas at atmospheric pressure tend to rapidly become unstable because of the high numbers of particle collisions. This characteristic increases the plasma temperature and gas particle ionisation events. Micro scale plasmas minimise this issue due to their lower numbers of particles and lower temperatures [4].

Paschen's law states that the gas pressure increases when the length of the plasma discharge decreases, consequentially the breakdown voltage remains the lowest value. Thus to scale down the length of the plasma discharge to micrometre dimensions, the value of the pressure increases to be within the range of tens of kilopascals up to megapascals [5].

$$V_B = \frac{B_{pd}}{\ln(A_{pd}) - \ln\left(\ln(1+\frac{1}{\gamma})\right)}, \qquad \text{Paschen's law}$$

In the equation, V is the breakdown voltage, B is the excitation to ionization ratio, A is the saturation ionization ratio in the gas, p is the pressure, d is the gap distance, and γ is the secondary electron emission coefficient.

After conducting an exhaustive and comprehensive literature review, MIP torch designs were investigated from a mechanical design and processing capability viewpoint. A torch capable of discharging a reactive species micro plasma for the surface modification of optical materials was identified in Amorim's paper [6].

In the framework of this research paper the focus was on a MIP torch, which is detailed and analysed in the next section.

3. Experimental Setup

Plasma emission experiments were carried out on an ADTEC MIP torch. The main torch parameters - microwave power, gas flow rate and type of gas - were systematically altered. Their respective effects on the emission spectra were measured and analysed.

The MIP torch was set to a fixed position within the processing chamber of a CNC machine. The optical fibre and the collimating lens were mounted onto the precision motion stage. The end of the diagnostic tool was moved in two dimensions: horizontal and vertical. The diagnostic tool was an Ocean Optics HR4000 Spectrometer. The resolution of the spectrometer was 240pm.

The MIP torch was connected to a solid state microwave signal generator, via a coaxial cable. The torch consisted of a three stub tuner, antenna connector, discharge tube and a nozzle (Figure 1).

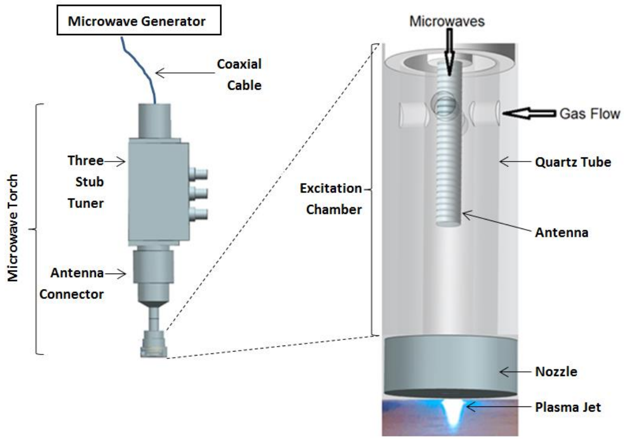


Figure 1. Experimental Setup (ADTEC Equipment).

For each experiment, the OES lens was moved precisely to discrete positions using the motion stage and the plasma plume was scanned across. The scan was carried out over a 4mm x 10mm area and the increment value was 100µm. Each experimental result contains a total of 4000 spectra which were processed with Matlab. Authors developed a bespoke routine to process the logged files.

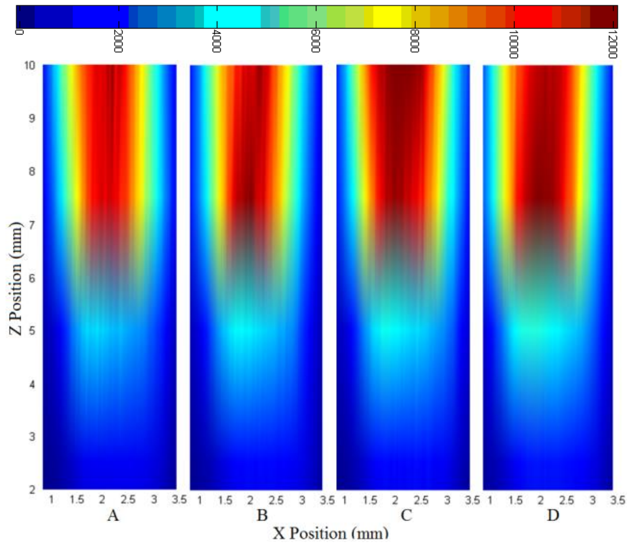
4. Results

Intensity maps of the argon and helium plasma discharges are shown in figures 2 and 3 respectfully. Both power and gas flow rate changes are displayed for the four different configurations.

The experimental results show a direct correlation between the microwave power and the intensity of the emission spectra within the plasma discharge (Figure 2 & Figure 3). The results are in accordance with the conservation of energy.

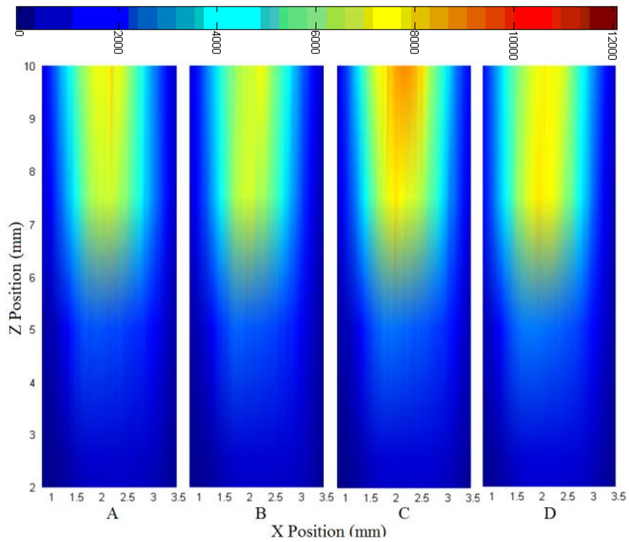
The intensity of the emission in the spectra of the helium plasma discharge is lower compared to that of the argon plasma spectra (Figure 2 & Figure 3). This observation is supported by lower particle count in the helium gas for a given gas flow rate.

Stable plasma discharge is maintained in a region where the power coupling to the gas flow rate is optimised [7]. The power coupling to the gas flow is visible when the helium power is maintained and the gas flow rate is decreased (Figure 3: C & D).



A) 13W 1L/min; B) 13W 2L/min; C) 15W 1L/min; D) 15W 2L/min

Figure 2. Argon Plasma Characterisation.



A) 13W 1L/min; B) 13W 2L/min; C) 15W 1L/min; D) 15W 2L/min

Figure 3. Helium Plasma Characterisation.

5. Conclusion

A Microwave Induced Plasma (MIP) torch discharge was characterised by using an OES technique. The main variables were systematically altered and their respective effects on the emission spectra of the plasma discharge were assessed. The intensity of the emission spectra from the helium discharges were lower compared to that of argon discharges.

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