euspen's 16th International Conference &
Exhibition, Nottingham, UK, May 2016
www.euspen.eu

CFD analysis of an enhanced nozzle designed for plasma figuring of large optical surfaces

Nan Yu[1], Renaud Jourdain[1], Mustapha Gourma[2], Paul Shore[1, 3, 4]

[1]*Precision Engineering Institute, Cranfield University, UK*
[2]*Oil and Gas Engineering Centre, Cranfield University, UK*
[3]*Loxham Precision Ltd, UK*
[4]*Engineering Measurement Division, National Physical Laboratory, UK*

n.yu@cranfield.ac.uk

Abstract

For addressing the correction of Mid Spatial Frequency (MSF) errors on metre scale optical surfaces induced by sub aperture figuring process, a new generation of non-contact plasma based surface figuring tools has been created at Cranfield University. In this context, this paper presents an investigation that focuses on novel enhanced nozzles that were created for a Radio Frequency (RF) Inductively Coupled Plasma (ICP) torch. The characteristics of plasma jet delivered by prototype nozzle and a selected enhanced nozzle are compared using an in-house created CFD model. The enhanced nozzle design is based on the results previously obtained throughout a numerical analysis that enabled to identify the key design aspects of these nozzles. This enhanced nozzle is predicted to provide 12.5% smaller footprint and 15.5% higher temperature.

Plasma jet, surface figuring, MSF, De-Laval nozzle, energy beam, optical fabrication, material removal footprint

1. Introduction

The final step of the optical fabrication chain - grinding, lapping, and polishing - is known to be time consuming because of its relatively small material removal rate. Fortunately other final figuring methods are available. Indeed plasma based figuring techniques have become more robust and widespread in the past decade. Today they offer an alternative to CNC polishing. One of these optical figuring techniques is called Plasma Figuring (PF). PF is highly deterministic and is capable of surface correction at nanometre level. PF is carried out at atmospheric pressure. PF is a dwell time figuring technique that fits into the core activities of Cranfield University in terms of advanced fabrication processes of metre-scale optical surfaces [1]. This novel surface figuring process uses an Inductive Coupled Plasma (ICP) torch that atomizes reactive gases such CF_4, NF_3 or SF_6 to create free radicals. Also the controllable chemical reaction for etching silicon based material is locally delivered through an advanced tool path algorithm that was created in-house. This plasma figuring technology was patented in 2002 by an American company [2], and has been further developed in Cranfield since then.

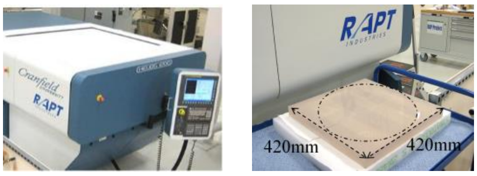

Figure 1. Helios1200 machine (left), 420mm ULE substrate (right).

The largest and most advanced PF machine -Helios 1200- was created in 2008 through collaboration between RAPT industries and Cranfield University [3]. In 2012, Castelli [4] demonstrated the fast figure correction capability on a 420mm substrate. 31nm RMS form accuracy from an initial 373nm RMS was achieved. The total process duration was less than 2.5 hours, and a material removal rate of ~1.5 mm^3/min was achieved. However Mid Spatial Frequency (MSF) errors were induced by the sub aperture process itself [5, 6] (Fig. 2).

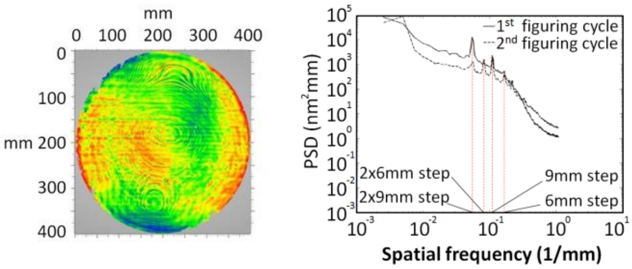

Figure 2. Topography map (left), averaged directional PSD plots across 400mm diameter ULE glass surface (Courtesy Castelli) (right).

Indeed, MSFs were highlighted through Power Spectrum Density (PSD) analysis of residual error maps (Fig. 2 left) obtained in this experimental work [6]. These MSFs were present on the entire processed surface. Peak frequencies (Fig. 2 right) are related to process parameter called birefringence and pitch. Pitch is the distance between two consecutive parallel passes. Spatial frequency is 1/3mm^{-1} and harmonics.

2. Research motivation

Enhancement of the PF capability is the research motivation for this work. This aim will be reached through the development of optimised torch nozzles. The author's approach is the creation of a model using Computational Fluid Dynamic (CFD) method.

The key results of this CFD model are used to investigate and determine the aerodynamic properties of the plasma jet [7]. First, the two investigated torch nozzles are presented.

3. Enhanced De-Laval nozzle design

The benefit of a De-Laval nozzle is to amend the energy beam characteristics. Prototype nozzle mounted at the end of ICP torch is shown in Figure 3 left. This prototype nozzle was characterised and used from 2008 up to 2013 in Cranfield.

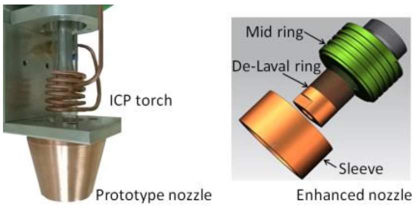

Figure 3. ICP torch and prototype nozzle (left), enhanced nozzle (right).

Since 2013, research on enhanced nozzles has been undertaken. In addition to altering the energy beam footprint, enhanced nozzles were designed to be easily fitted. The copper nozzle body was divided into two components that have different duties. The De-Laval ring was designed to transport the plasma. Mid ring and sleeve parts were designed to cool down the nozzle (Fig. 3 right).

From a process viewpoint, enhanced nozzle investigation enables to scrutinize the fundamental interactions between reactive gas and substrate surface. From an experimental viewpoint, the screw-fit feature enables authors to compare, rapidly and conveniently, different enhanced nozzles. Indeed A series of these nozzles were designed but this work focuses on the one that has the smallest throat diameter.

4. Numerical analysis of the nozzles and results

CFD modelling was utilized to investigate the aerodynamic properties of a plasma jet streamed through two De-Laval nozzles. These nozzles were the prototype and one of the author’s enhanced nozzles. A 2D axis-symmetric numerical model -based on FLUENT software- was used to perform calculations on a high temperature gas mixture. This CFD model is entirely detailed in Yu’s paper [8]. The temperature distributions in the domains are displayed in Figure 4.

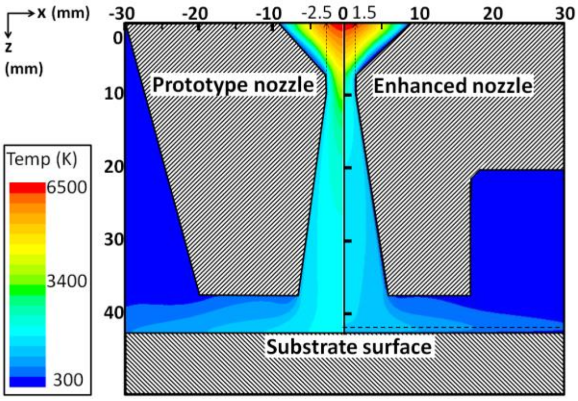

Figure 4. Temperature map of gas mixture: prototype nozzle (left), enhanced nozzle (right)

Temperature and velocity data were logged along the symmetric axis (Fig. 5) and along the impinged surface (Fig. 6).

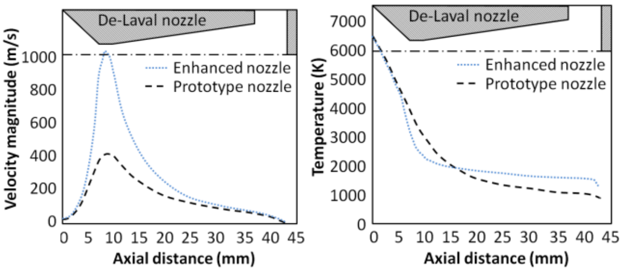

Figure 5. Axial profiles of velocity (left) and temperature (right) along the symmetric axis.

Along the axis of symmetry, gas velocity magnitude of the enhanced nozzle is faster. In the throat section -10 mm axial distance-, this velocity is 2.5 times higher (Fig. 5 left). On the other hand, temperature of the jet is 500 K higher (Fig. 5 right) at axial distance where gas impinged the processed surface -44 mm axial distance-.

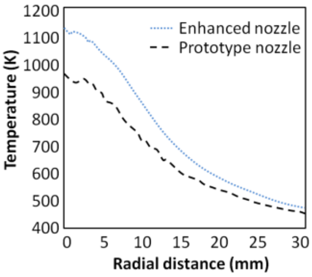

Figure 6. Radial profiles of axial velocity (left) and temperature (right) along the impinged surface.

Onto the impinged surface, results show that the radius profile of the axial velocity is smaller (Fig. 6 left) and the maximum gas temperature is increased by 150 K (Fig. 6 right).

5. Conclusion

This paper highlights the increased performance of an improved nozzle design. This nozzle is expected to enhance the processing capability of plasma figuring by reducing the MSF errors. This enhanced nozzle is predicted to deliver 12.5% smaller footprint and 15.5% higher temperature. The validation of these results will be carried out shortly in the laboratory.

Acknowledgments: This work was supported by the UK EPSRC under grant EP/I033491/1, the McKeown Foundation and the Centre for Innovative Manufacturing in Ultra-Precision.

References

[1] Shore P, Morantz P, Read R, Tonnellier X, Comley P, Jourdain R, Castelli M. ASPE, Kohala Coast, Hawaii, USA. 26th -27th June, 2014
[2] Carr, J.W., RAPT Industries Inc. 2009, US Patent, 7591957 B2
[3] Jourdain R, Castelli M, Shore P, Sommer P, Proscia D. 2013 *Prod. Eng. Res. & Dev.* **6** 665-673
[4] Castelli M, Jourdain R, Morantz P, Shore P. 2012 *Pre. Eng.* **36** 467-476
[5] Jourdain R, Castelli M, Morantz P, Shore P. SPIE, Photonics Europe, Belgium, 16th -19th April, 2012
[6] Castelli M. (PhD thesis), Cranfield University, Cranfield, UK: 2013
[7] Yu N, Jourdain R, Gourma M, Shore P. ASPE annual meeting, Boston, USA. 2014
[8] Yu N, Jourdain R, Gourma M, Shore P. International Journal of Advance Manufacturing Tech. 2015 (submitted)

2016-06-30

CFD analysis of an enhanced nozzle designed for plasma figuring of large optical surfaces

Yu, Nan

European Society for Precision Engineering and Nanotechnology

Yu N, Jourdain R, Gourma M & Shore P (2016) CFD analysis of an enhanced nozzle designed for plasma figuring of large optical surfaces. 16th International Conference of the European Society for Precision Engineering and Nanotechnology (EUSPEN), 30th May - 3rd June 2016, Nottingham, UK.

https://dspace.lib.cranfield.ac.uk/handle/1826/10598