Energy Balance Investigation of an Inductively Coupled Plasma Torch for Plasma Figuring

Nan Yu¹, Renaud Jourdain¹, Mustapha Gourma², Paul Shore¹,³

¹Precision Engineering Institute, Cranfield University
²Department of Engineering Computing, Cranfield University
³Engineering Measurement Division, National Physical Laboratory

Structure

1. Introduction
2. Methodology
3. Numerical analysis (briefly)
4. Energy dissipation calculation (in detail)
5. Conclusion and future work
1. Introduction

Research motivation

There is a large demand for metre scale ultra-precise optical surfaces

- www.eso.org  
  Ground telescope

- www.asml.com  
  EUV lithography

- lasers.llnl.gov  
  Laser fusion energy

---

1. Introduction

Plasma figuring process

This figuring process uses an Inductively Coupled Plasma (ICP) torch that provides a controllable chemical reaction for etching local regions of a surface.

State-of-the-art plasma figuring process (Courtesy Carr et al)
1. Introduction

Previous achievement

Initial figure error

Residual figure error after second figuring

(Removed)

1. Introduction

Mid Spatial Frequency (MSF)

Surface topography and Power Spatial Density (PSD) showing the MSF features

(From Castelli and Jourdain)
2. Methodology

To reduce MSF errors:

1. Use random tool-path algorithms;
2. Use smaller tool functions

*e.g.* German IOM group in Leibniz Institute reduces the tool function using RF high-frequency excitation

FWHM: 0.2-12 mm  
(Full Width at Half Maximum)

MRR: $5 \times 10^{-5}$ - $50$ mm/min  
(Material Removal Rate)
3. Numerical analysis

CFD results have been validated by
1. Comparing with benchmark modelling results;
2. Comparing with experimental footprint

(The International Journal of Advanced Manufacturing Technology, DOI: 10.1007/s00170-016-8502-y)

4. Energy dissipation calculation

Plasma delivery system

Energy dissipated items

\[ \Delta E_{\text{input}} = \text{Forward power} = \Delta E_{\text{coolant}} + \Delta E_{\text{gas}} + \Delta E_{\text{radiation}} \]
4. Energy dissipation calculation
Flow rate and temperature measurement

4. Energy dissipation calculation
Flow rate and temperature measurement
4. Energy dissipation calculation

Correlation between TD and RF power

\[ \Delta E_{\text{coolant}} = C_C \nu_C \Delta T \]

4. Energy dissipation calculation

Correlation between energy dissipated rate and RF power

\[ \Delta E_{\text{coolant}} = C_C \nu_C \Delta T \]
4. Energy dissipation calculation

**Energy absorbed rate by coolants**
\[ \Delta E_{\text{coolt}} = C_c \nu_c \Delta T = 585 \text{ watts} \]

**Energy dissipated rate by argon gas**
\[ \Delta E_{\text{argon}} = \int_{T_{\text{room}}}^{T} (C_a \nu_a) dT = 394 \text{ watts} \]

**Energy dissipated rate by radiation**
Not measured yet

5. Conclusion and future work

**Distribution of the energy dissipation rate**

<table>
<thead>
<tr>
<th>Input: RF power</th>
<th>Energy dissipation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200W provided by RF generator</td>
<td>Coil coolant 400W (33.3%)</td>
</tr>
<tr>
<td></td>
<td>Nozzle coolant 185W (15.4%)</td>
</tr>
<tr>
<td></td>
<td>Heating gas 394W (32.8%)</td>
</tr>
<tr>
<td></td>
<td>Radiation ~ 18.5%</td>
</tr>
</tbody>
</table>

**Future work**

The Rayleigh scattering laser (Picture from NPL, Spring 2006)
Thank you!

Nan Yu, Renaud Jourdain, Mustapha Gourma, Paul Shore

Contact: n.yu@cranfield.ac.uk

The authors gratefully acknowledge funding from the Engineering and Physical Sciences Research Council (EPSRC), McKeown Precision Engineering and Nanotechnology Foundation,

Special courtesy to euspen for its kindly support