Dynamic Multi-Phase Modelling and Optimisation of Fluid Jet Polishing Process

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Background Information
## Background: Trends in Optics Manufacturing

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<td>Glass molding from carbide moulds</td>
<td>High-end consumer optics</td>
<td>1.0~2.0 nm Ra</td>
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<td>Plastic molding from nickel alloy moulds</td>
<td>Low-end consumer optics or complex shapes with high texture requirement</td>
<td>0.5~3.0 nm Ra (depending on application)</td>
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<td>Direct glass grinding and polishing</td>
<td>Small-volume or aperture size &gt; 50mm</td>
<td>0.5~2.0 nm Ra (depending on application)</td>
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Aspheric/Freeform shape generation performed by micro-grinding or diamond turning:

- Form error control on small moulds is usually around 100nm P-V.
- Surface texture is generally dominated by high-frequency cyclic marks.
- Overall roughness usually in the range:
  - 4~8nm Ra (grinding).
  - 1~3nm Ra (turning).

Gradually improving, but fails to meet stringent ultra-precision requirements.

Typical Micro-Grinding Signature (6nm Ra)
Background: Some existing finishing methods

**Ultrasonic vibration assisted polishing**
- Aspheric capability, but only for very small moulds (low removal rate)

**Hand polishing**
- Any mould size or shape, but human resource intensive

**Semi-automated “conventional” oscillating head polishing**
- For rotationally symmetric shape, but suffers from figure distortion on aspheric shapes
Fluid Jet Finishing Method
Polishing fluid is compressed and delivered through a nozzle, allowing the spot area to become continuously replenished with abrasives and coolant.

Process parameters include: Abrasive type and concentration, Inlet pressure, Nozzle diameter, Impingement angle, Surface feed of spot.
Fluid Jet Method: Tool-Path Generation Software

Influence Function (single or family)

Numerical Optimisation

Metrology: Initial Form Error

Metrology: Final Form Error
Modeling and Optimization
The simulation uses COMSOL’s turbulent 2-phase flow model, with the incompressible Navier-Stokes equations:

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f} \]

Slurry/Air interface is modelled using either Phase-field or Level-set method.

In the case of Phase-field, the volume fraction of slurry is:

\[ V_{\text{slurry}} = \frac{(1 + \phi)}{2} \]

After initialisation, the evolution of \( \phi \) is governed by Cahn-Hilliard equation:

\[ \frac{\partial \phi}{\partial t} + (\mathbf{v} \cdot \nabla) \phi = \nabla \cdot (\gamma \nabla G) \]

In the case of Level-set, the dynamic density and viscosity are defined as functions of \( \phi \):

\[ \rho = \rho_{\text{air}} + (\rho_{\text{slurry}} - \rho_{\text{air}}) \phi \quad \mu = \mu_{\text{air}} + (\mu_{\text{slurry}} - \mu_{\text{air}}) \phi \]

After initialisation, the evolution of \( \phi \) is governed by the convection equation:

\[ \frac{\partial \phi}{\partial t} + \mathbf{v} \cdot \nabla \phi = \gamma \nabla \cdot (\epsilon \nabla \phi - \phi(1-\phi) \frac{\nabla \phi}{|\nabla \phi|}) \]
Modelling: Simulation

- Simulation consists of jet impinging a flat surface along the local normal.
- This simulation is axi-symmetry, allowing simplification of problem to 2D.
- The experiment can be easily reproduced on-machine in the laboratory.
Modeling: Particle Tracing

To determine polishing conditions, it is necessary to study how abrasive particles interact with the surface.

The trajectories of individual particles can be derived from Newton’s second law of motion:

\[ m \frac{\partial^2 \mathbf{p}}{\partial t^2} = \mathbf{F} \]

- Particle collisions are assumed to cancel each other out (necessary simplification, but concentration may probably varies).
- Because of the high fluid velocity, it is assumed that gravitation, buoyancy, and collisions are all small compared with the drag force.
- So the drag force can be simply calculated from Rayleigh’s equation:

\[ F = \rho C_D v^2 A / 2 \]
Optimization of Process Conditions

Adjust Process Conditions

Live Pressure Logging

Fourier Analysis

Simulation of Time Series
Surface Waviness before and after Optimization

Waviness across 5x5mm area (Ra 12.5nm >> 1.2nm)
Application to Optical Moulds
16mm Concave Mould: Form error

Form Correction of Optical Mould (P-V 345nm >> 37nm)
16mm Concave Mould: Surface Roughness

Surface Roughness of Optical Mould (Ra 2.2nm >> 0.99nm)
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Thank you for your attention!

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