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

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Background Information

Background: Trends in Optics Manufacturing

Manufacturing Method	Application Range	Surface Roughness
Glass molding from carbide moulds	High-end consumer optics	1.0~2.0 nm Ra
Plastic molding from nickel alloy moulds	Low-end consumer optics or complex shapes with high texture requirement	0.5~3.0 nm Ra (depending on application)
Direct glass grinding and polishing	Small-volume or aperture size > 50mm	0.5~2.0nm Ra (depending on application)

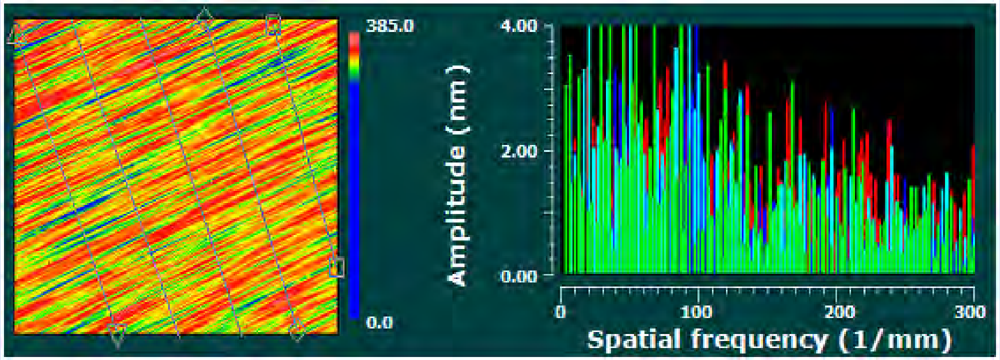
Background: Limitations of Generating Methods

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).

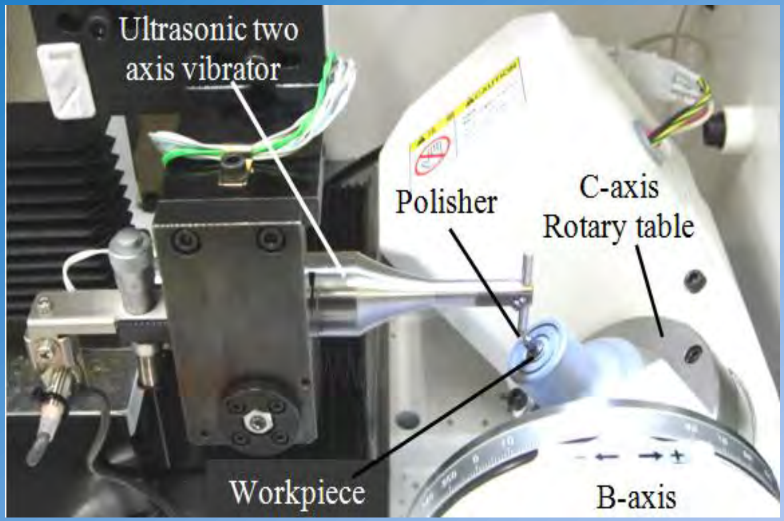
Gradually improving, but fails to meet stringent ultra-precision requirements

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

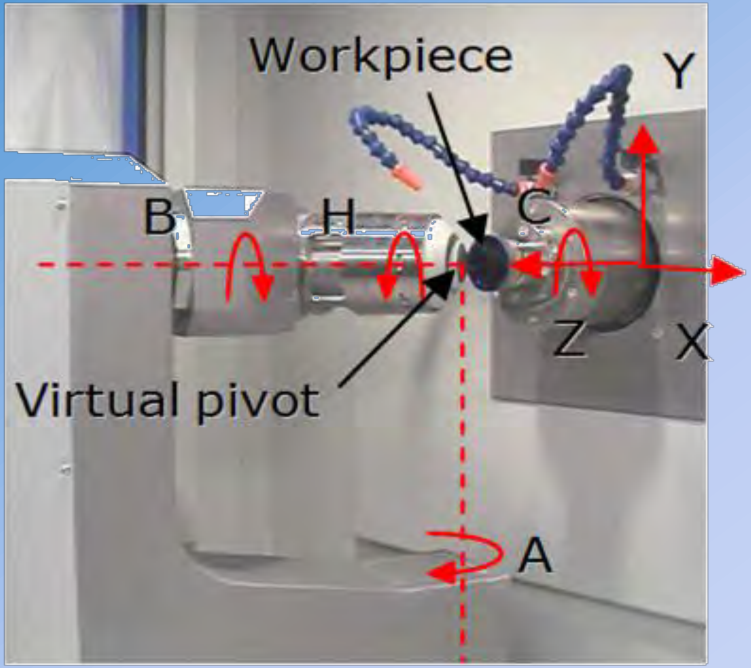
For rotationally symmetric shape, but suffers from figure distortion on aspheric shapes

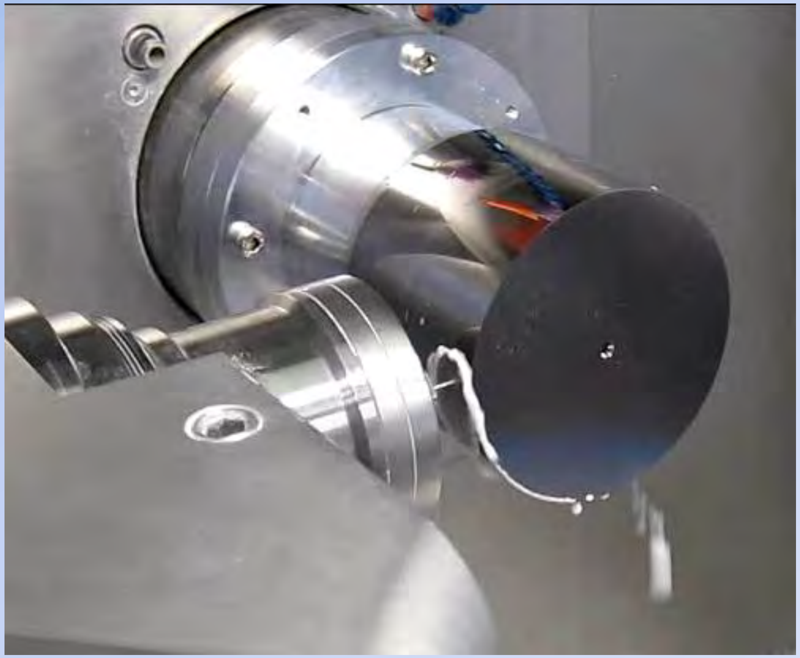
Fluid Jet Finishing Method

Fluid Jet Method: Overview of 7-axis CNC machine

Polishing fluid is compressed and delivered through a nozzle, allowing the spot area to become continuously replenished with abrasives and coolant.

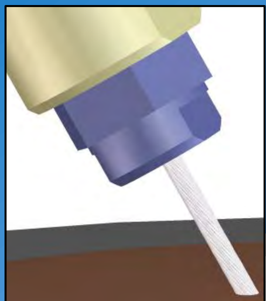
Process parameters include: Abrasive type and concentration, Inlet pressure, Nozzle diameter, Impingement angle, Surface feed of spot.

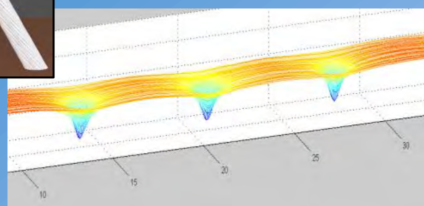




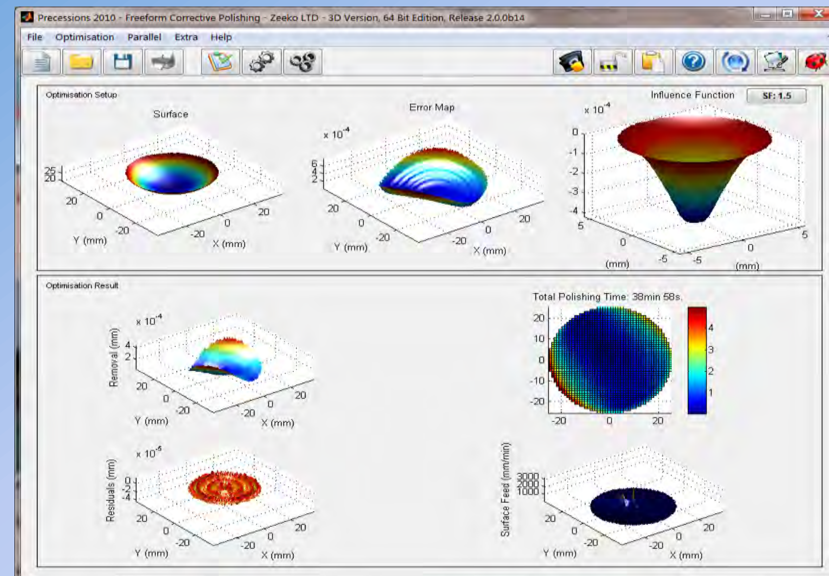
Fluid Jet Method: Tool-Path Generation Software

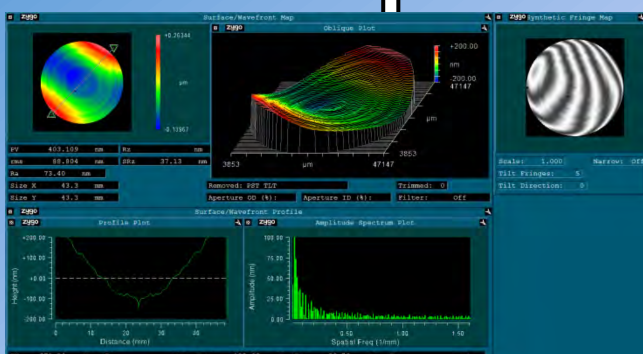
Influence Function (single or family)



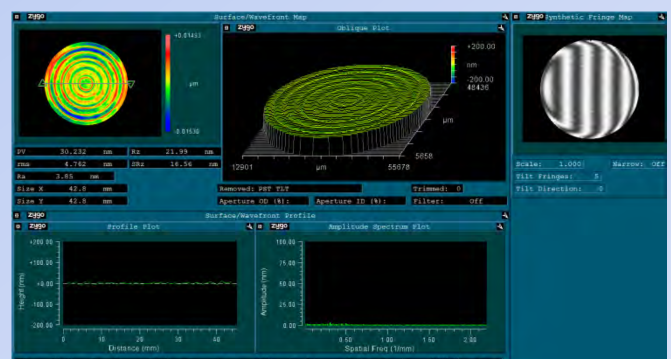


Numerical Optimisation





Metrology: Initial Form Error



Metrology: Final Form Error

Modeling and Optimization

Modeling: Numerical Method

The simulation uses COMSOL's turbulent 2-phase flow model, with the incompressible Navier-Stokes equations:

$$\rho\left(\frac{\partial v}{\partial t} + v.\nabla v\right) = -\nabla p + \mu\nabla^2 v + f$$

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: $V_{slurry} = (1+\phi)/2$

After initialisation, the evolution of Φ is governed by Cahn-Hilliard equation:

$$\frac{\partial \phi}{\partial t} + (v.\nabla)\phi = \nabla.\gamma\nabla G$$

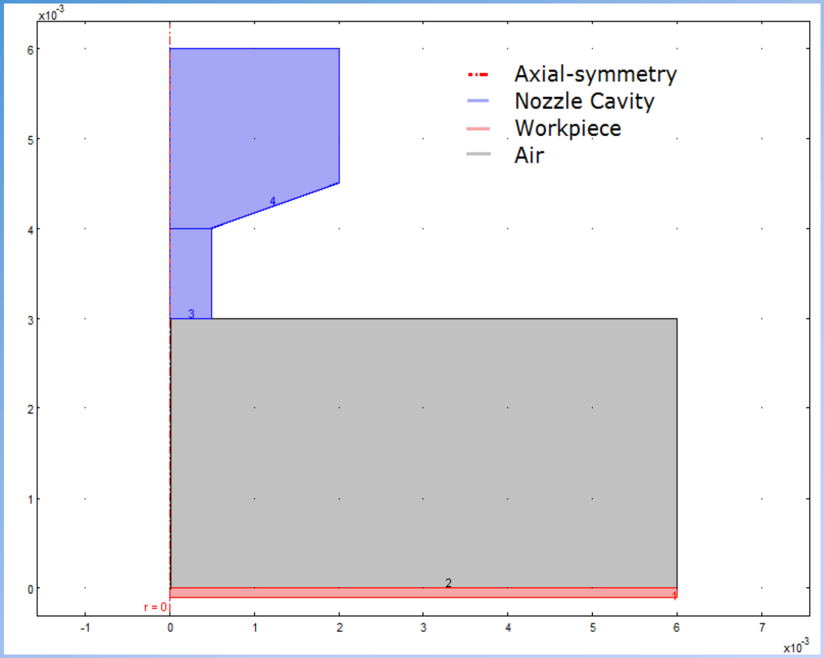
In the case of Level-set, the dynamic density and viscosity are defined as functions of Φ: $\rho = \rho_{air} + (\rho_{slurry} - \rho_{air})\phi$ $\mu = \mu_{air} + (\mu_{slurry} - \mu_{air})\phi$

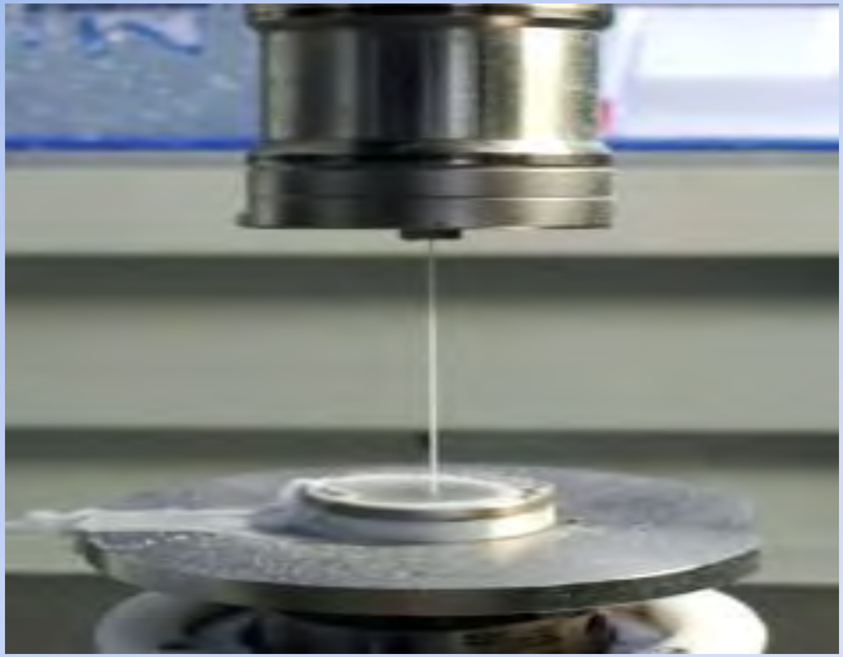
After initialisation, the evolution of Φ is governed by the convection equation:

$$\frac{\partial \phi}{\partial t} + v.\nabla\phi = \gamma\nabla.(\varepsilon\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|})$$

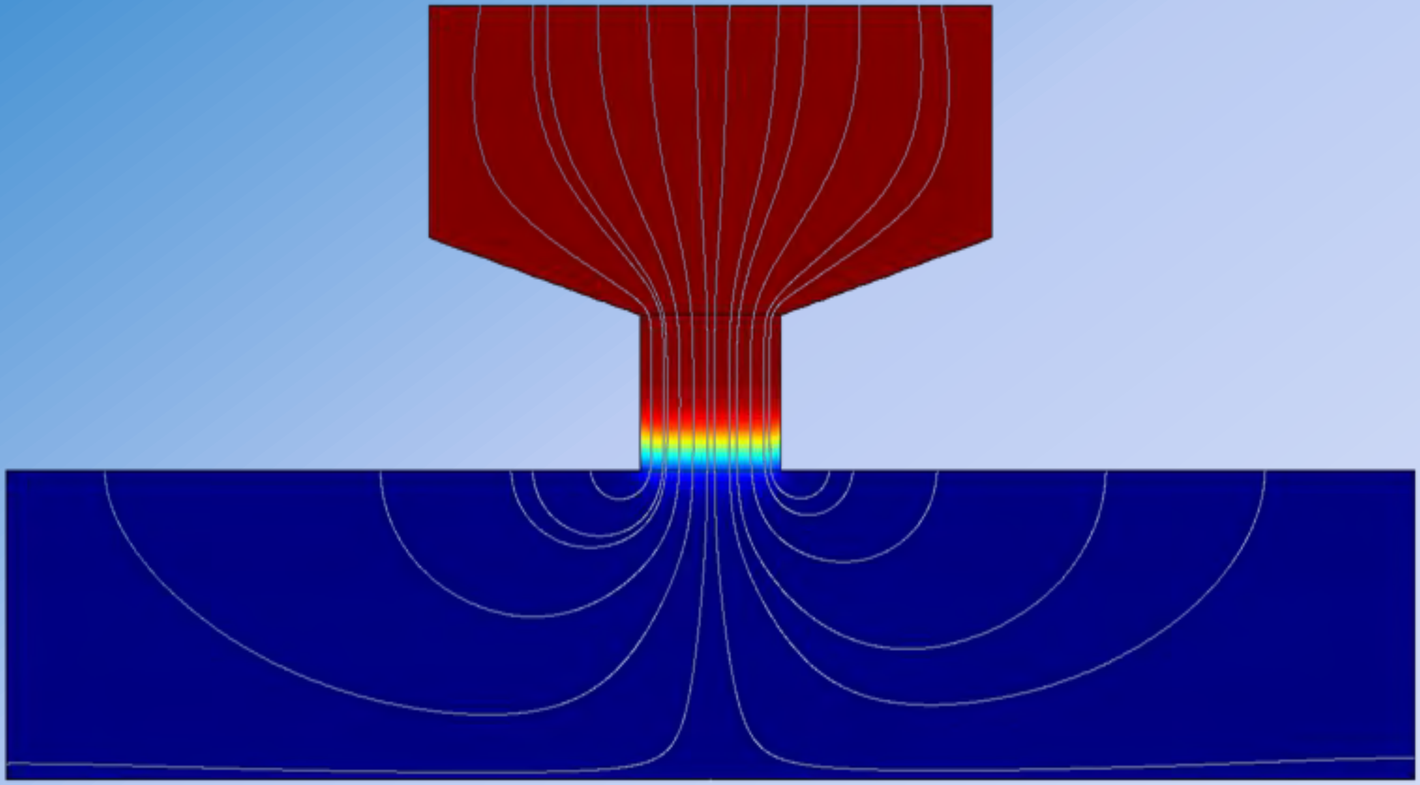
Modelling: Simulation

- 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





Modelling: Simulation



Modeling: Particle Tracing

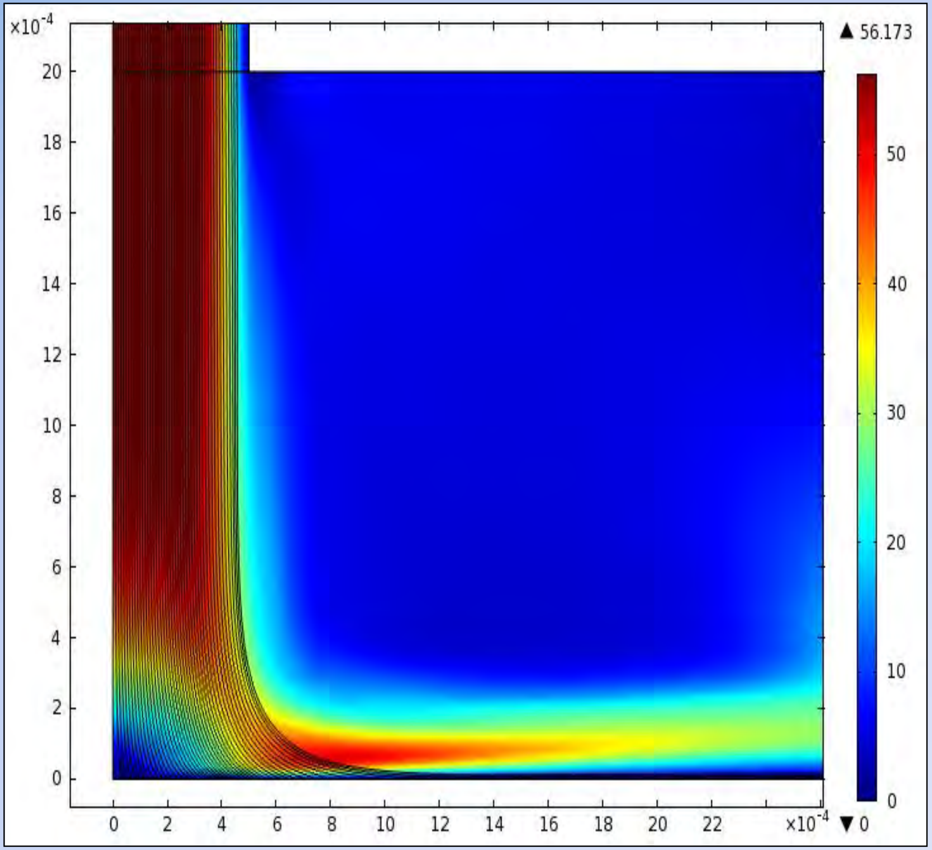
To determine polishing conditions, it is necessary to study how abrasive particles interact with the surface.

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

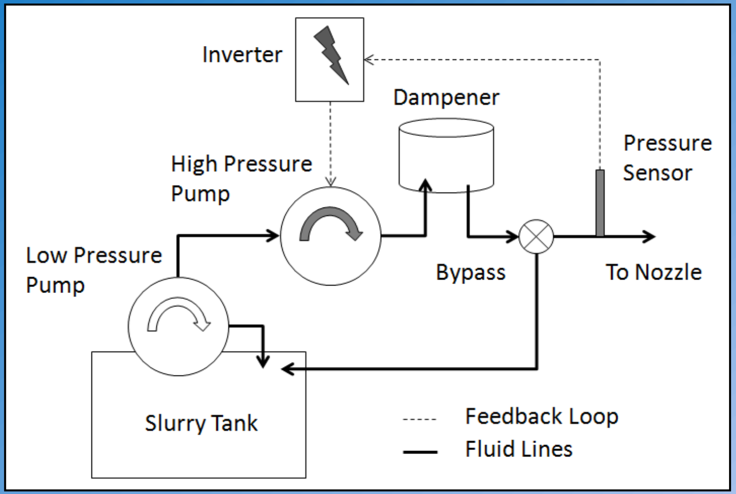
$$m\frac{\partial^2 p}{\partial^2 t} = F$$

- 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:

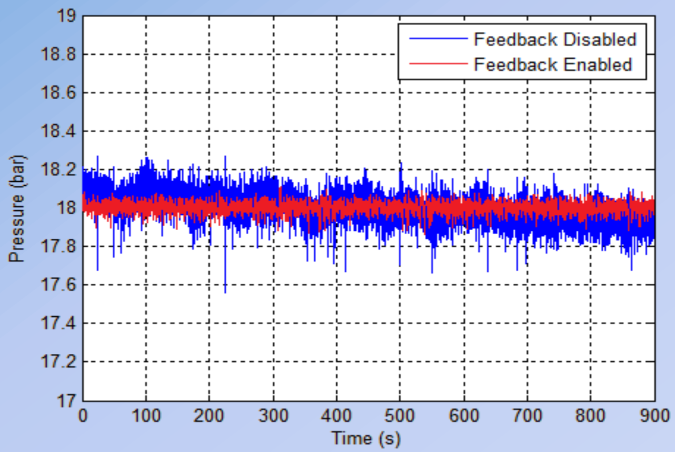
$$F = \rho C_D v^2 \frac{A}{2}$$



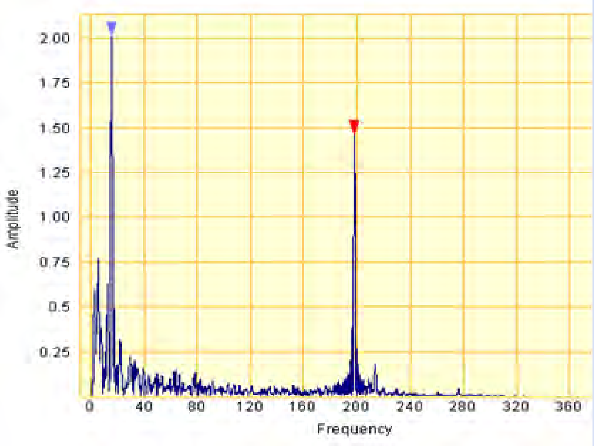
Optimization of Process Conditions



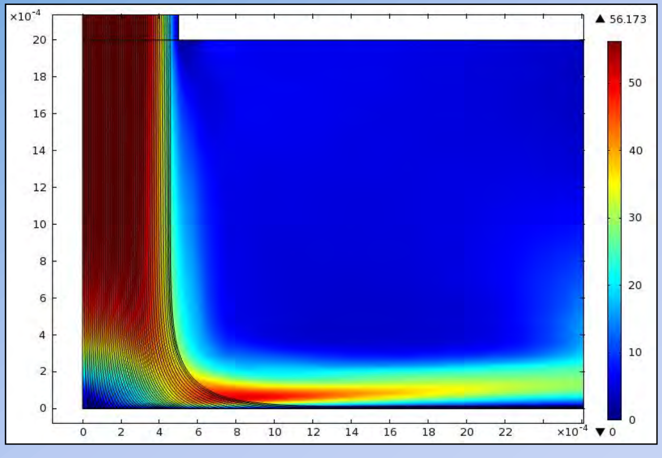
Live Pressure Logging



Fourier Analysis

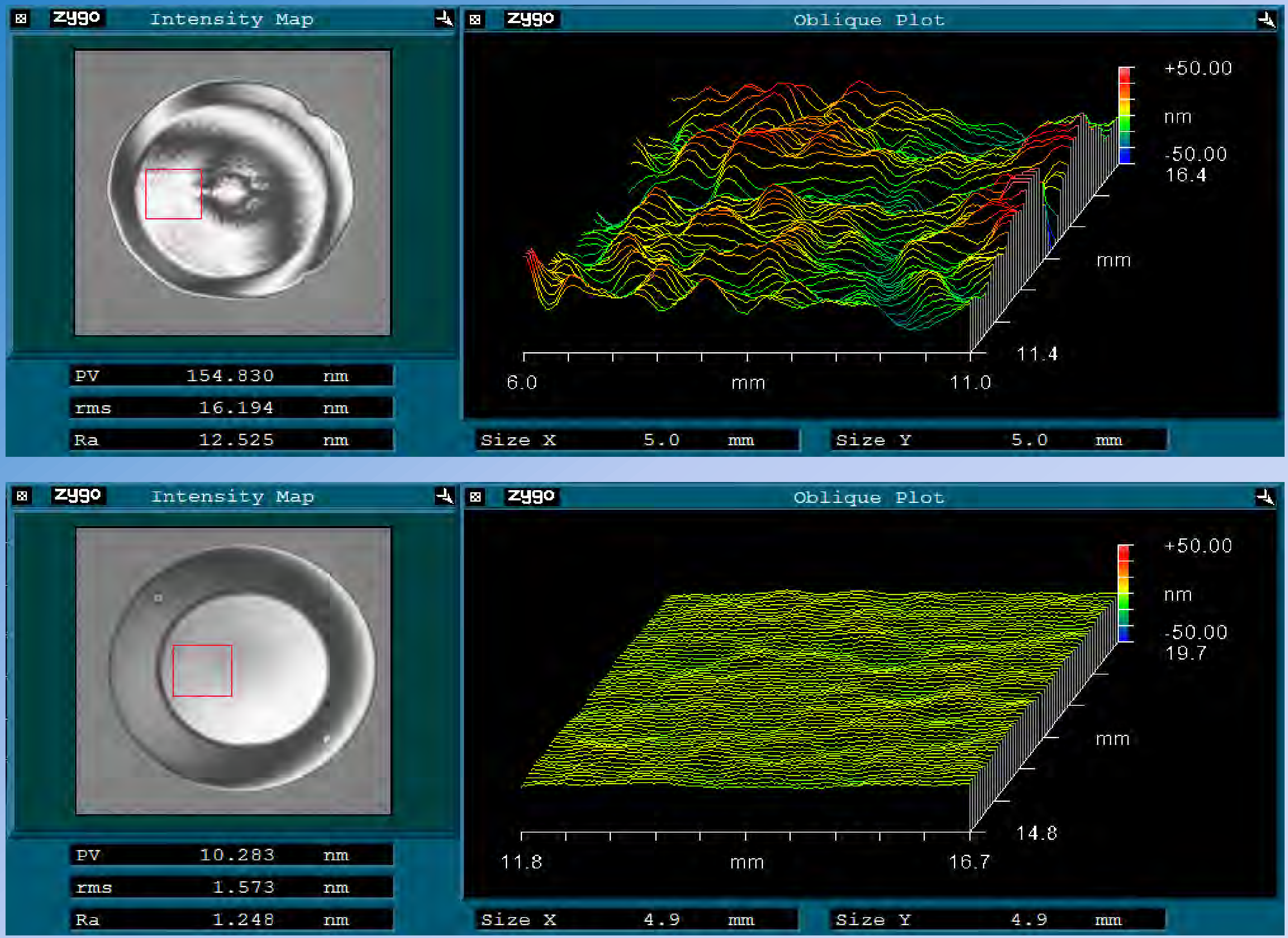


Simulation of Time Series



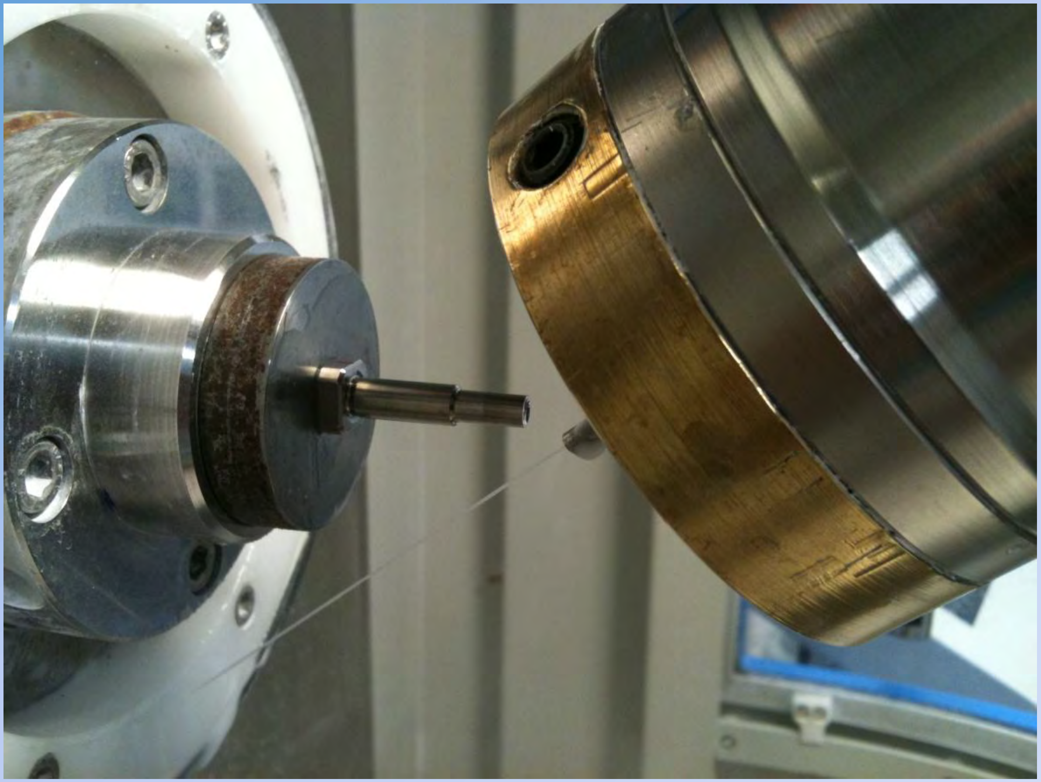
Adjust Process Conditions

Surface Waviness before and after Optimization

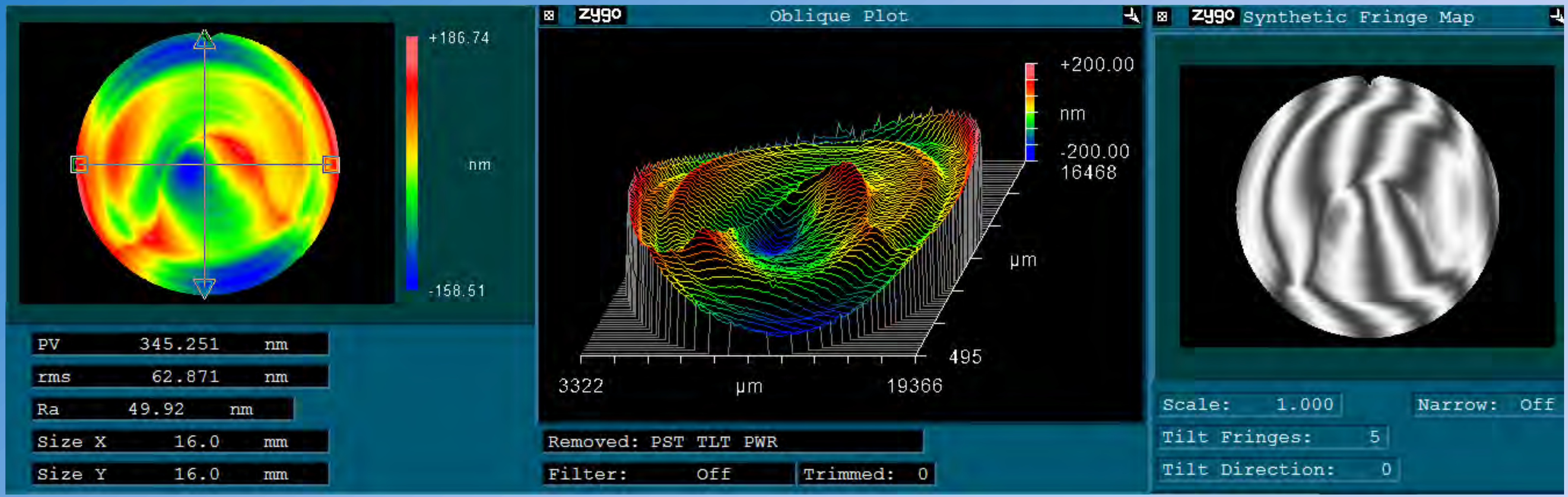


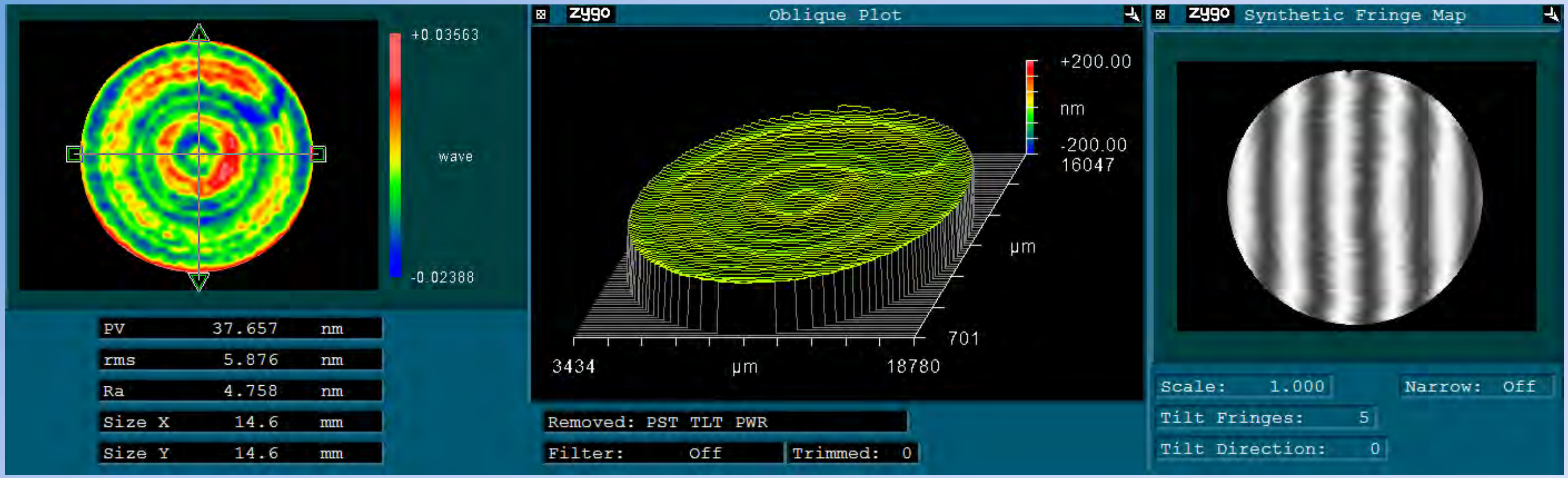
Waviness across 5x5mm area (Ra 12.5nm >> 1.2nm)

Application to Optical Moulds



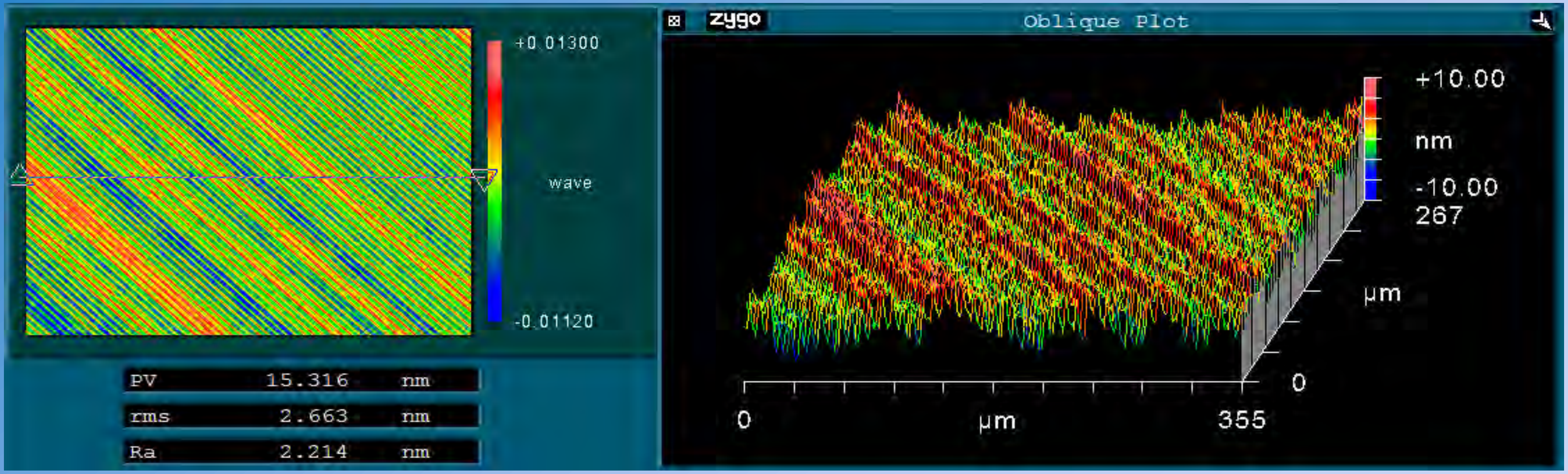
16mm Concave Mould: Form error

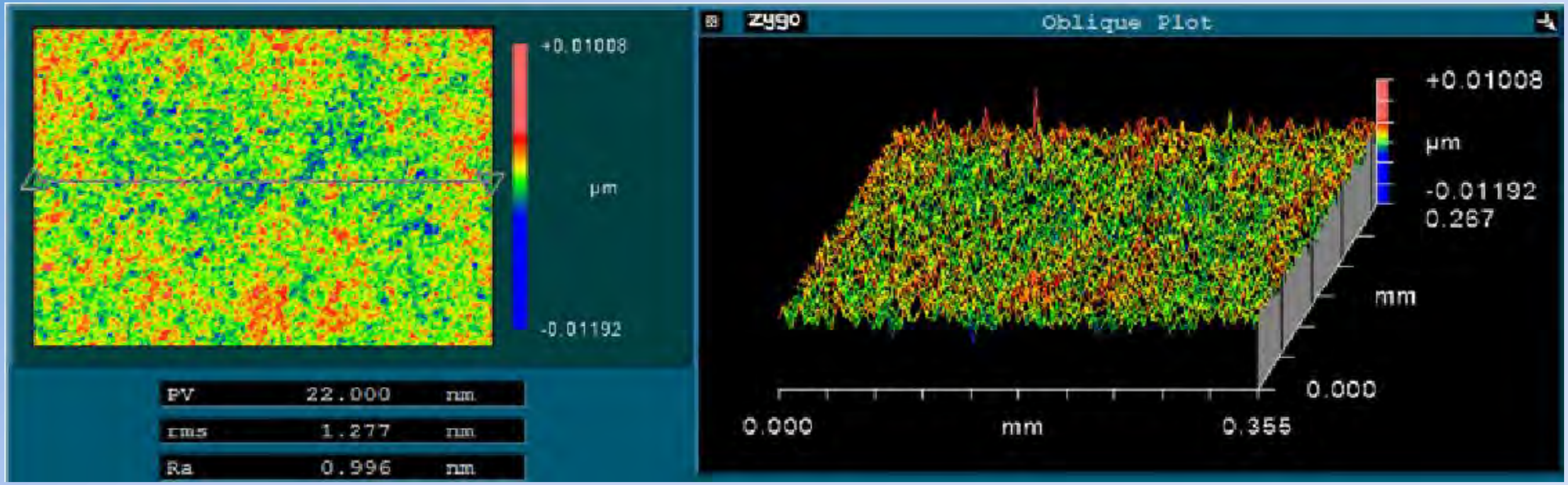




Form Correction of Optical Mould (P-V 345nm >> 37nm)

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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