International Academy for Production Engineering

67th General Assembly – Lugano – Switzerland - Aug. 20-26 2017

The Application of Computational Fluid Dynamics to Vibratory Finishing Processes

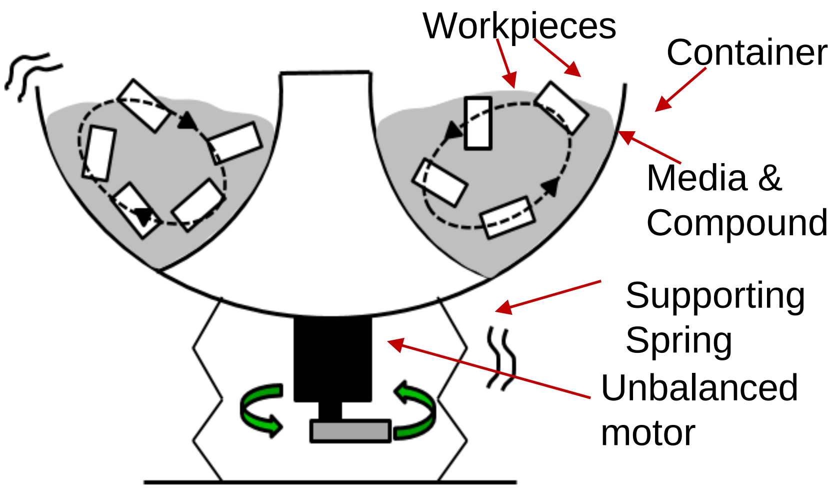
by

B. Mullany, H. Shahinian, J. Navare, F. Azimi, E. Fleischhauer, P. Tkacik, R. Keanini

Mechanical Engineering and Engineering Science
UNC Charlotte, North Carolina, USA
Email: bamullan@uncc.edu

CIRP Annals - Manufacturing Technology
Volume 66, Issue 1, 2017

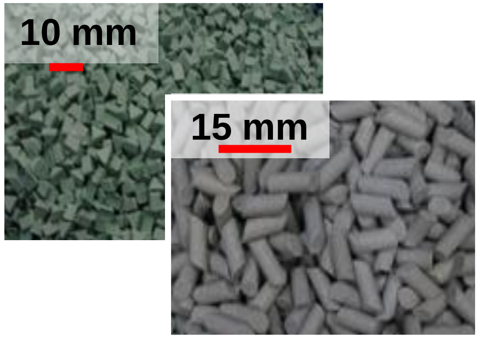
Vibratory Finishing



Applications
- Deburring
- Cleaning
- Improve surface finish

Process Dynamics:
- Vibrations ~29 Hz
- Amplitude 2 mm to 6 mm

Media:
- Plastic
- Ceramic
- Metal
- Organic

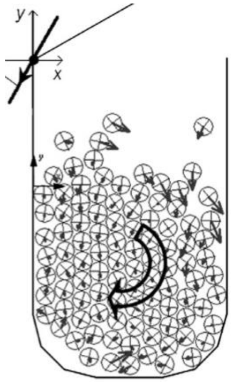


Finding application for:
- Orthopedic implants
- Blisks and turbine blades
- Tool finishing

Vibratory finishing: modeling

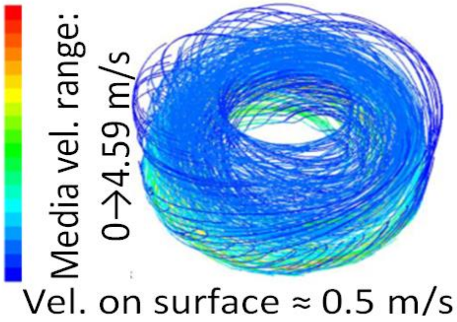
Dynamics Based approaches
- Hashimoto el al. (2015)

Discrete Element Modeling approaches
- Naeini et al. (2011)
- Uhlmann et al. (2015)
- Kang et al. (2017)

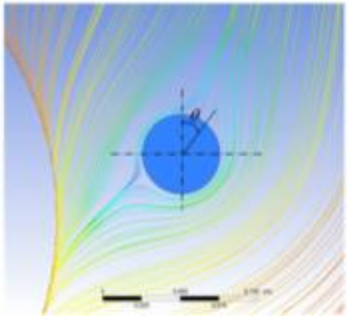


Naeini et al. (2011)

Continuum based approaches
- Cariapa et al. (2009)
- Wan et al (2012)



Cariapa et al (2009)



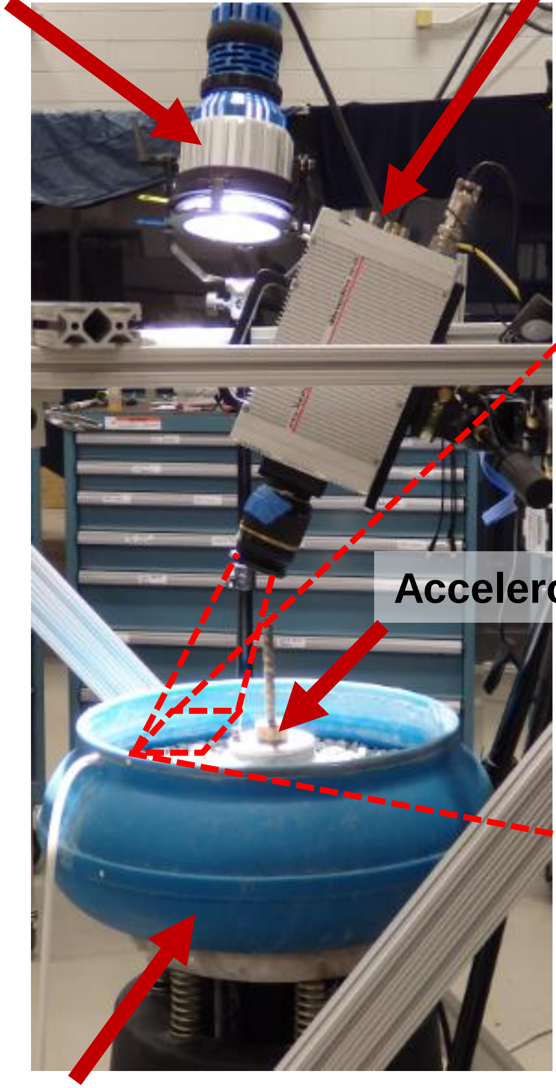
Wan et al (2012)

Particle Image Velocimetry (PIV)

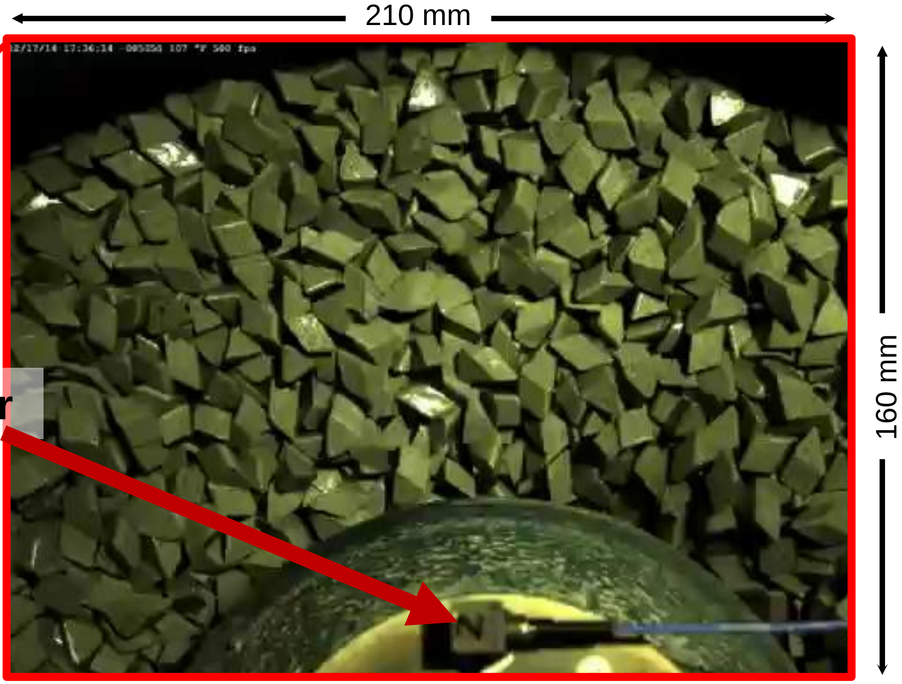
Previous Work

Halogen Light:
ARRI EB 400/575 D

High Speed Camera:
Redlake (Motionxtra HG-XR)
Capture rate: 500 fps



Accelerometer



Raytech AV-75 System (Ø 600 mm)

Operating Conditions:
Motor speed: 1740 rpm
Media: Ceramic RSG 10/10
Compound: FC FLK (3% vol.)

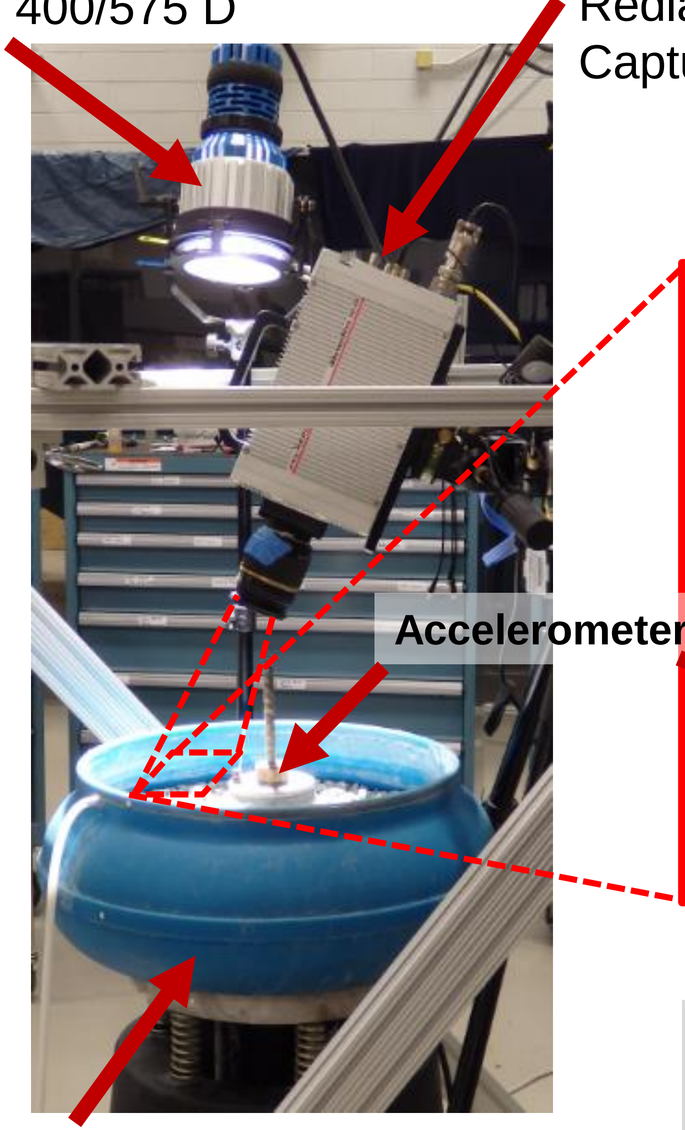
Particle Image Velocimetry (PIV)

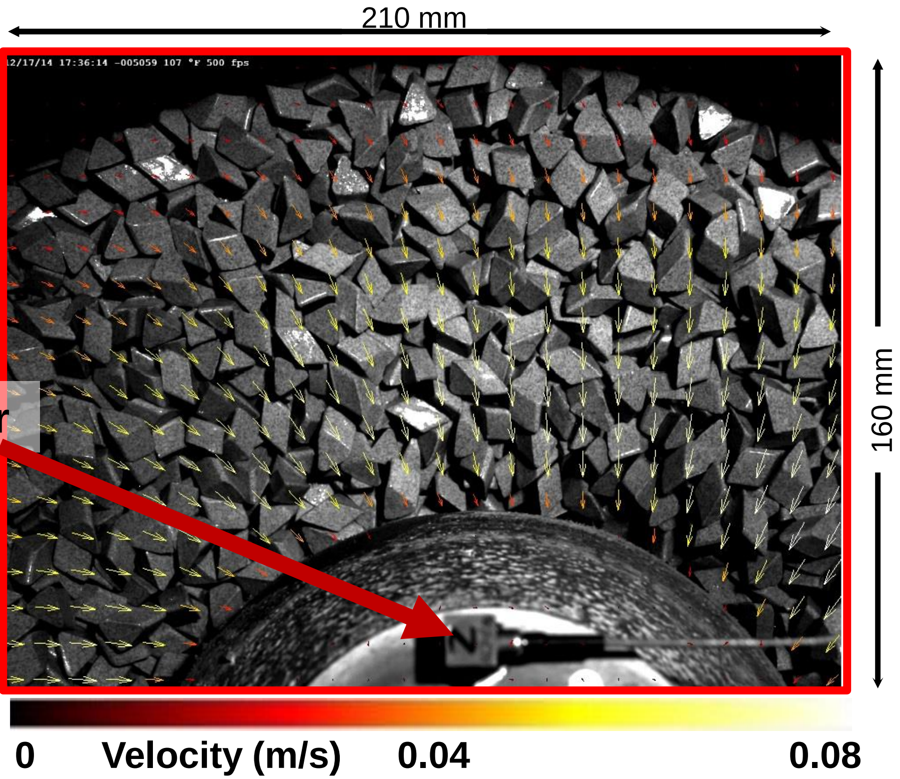
Previous Work

Halogen Light:
ARRI EB 400/575 D

High Speed Camera:
Redlake (Motionxtra HG-XR)
Capture rate: 500 fps

Each velocity vector is the time averaged velocity of 5059 vectors (10.12 s) for a 20.25 mm^2 area.





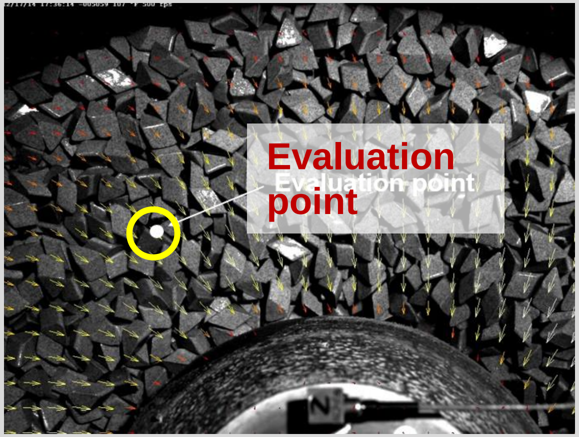
Raytech AV-75 System (Ø 600 mm)

Operating Conditions:
Motor speed: 1740 rpm
Media: Ceramic RSG 10/10
Compound: FC FLK (3% vol.)

PIV: The Discrete and Continuous

Previous Work

Continuum nature of media captured



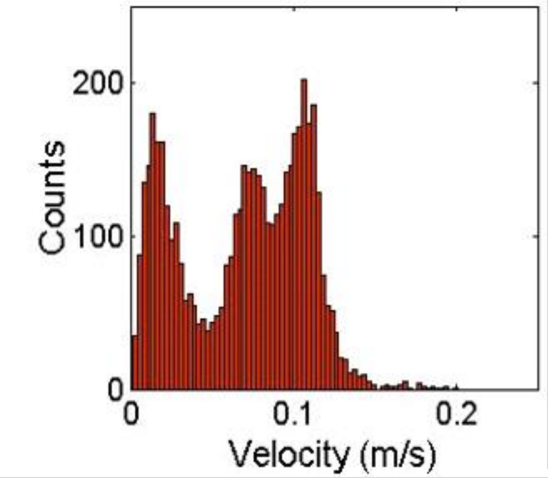
Each velocity vector = averaged velocity

Based on 5059 vectors (taken over 10.12s)

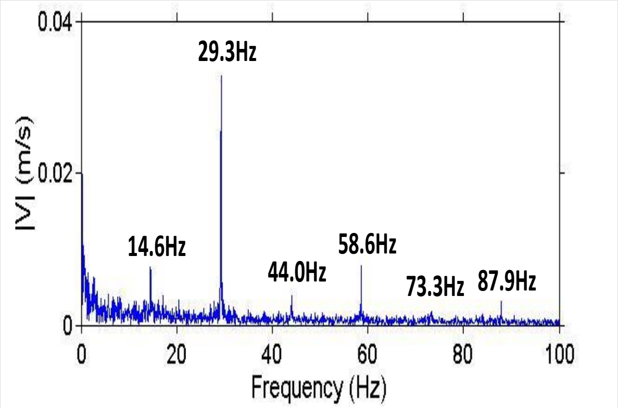
Over an 20.25 mm^2 area.

Discrete nature of media particles

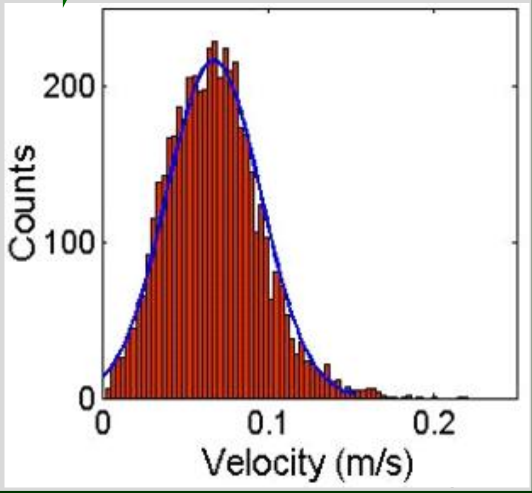
Histogram of Velocity at a single point



Fourier Filter to remove bulk media motion



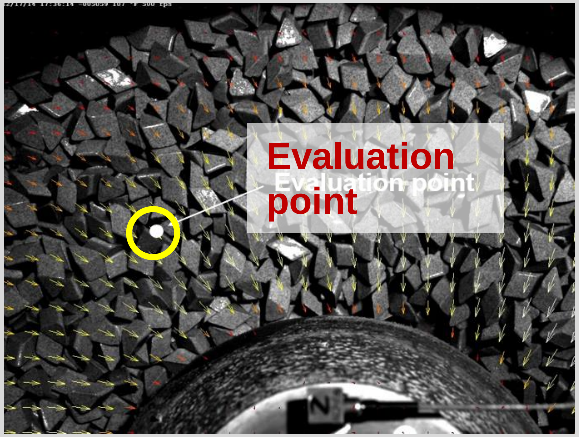
Captures media-media interactions



PIV: The Discrete and Continuous

Previous Work

Continuum nature of media captured



Each velocity vector = averaged velocity

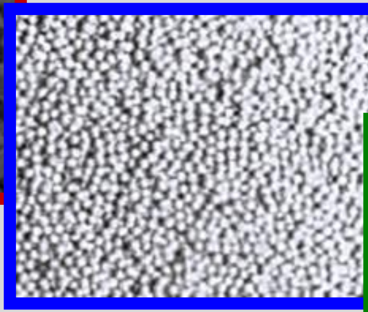
Based on 5059 vectors (taken over 10.12s)

Over an 20.25 mm^2 area.

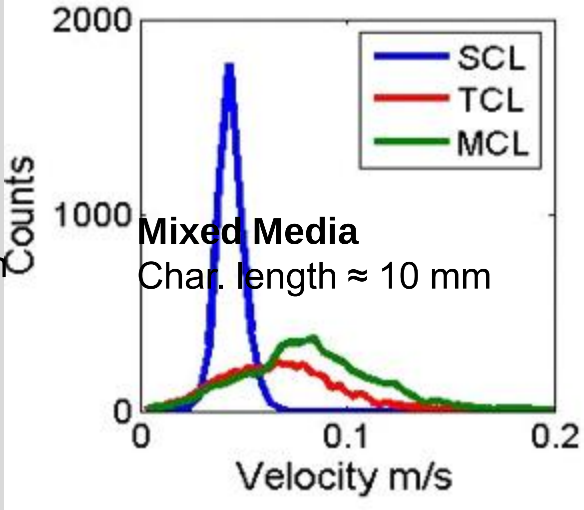
Discrete nature of media particles

RSG 10/10
Char. length ≈ 10 mm

Spheres
Char.Ø ≈ 2 mm

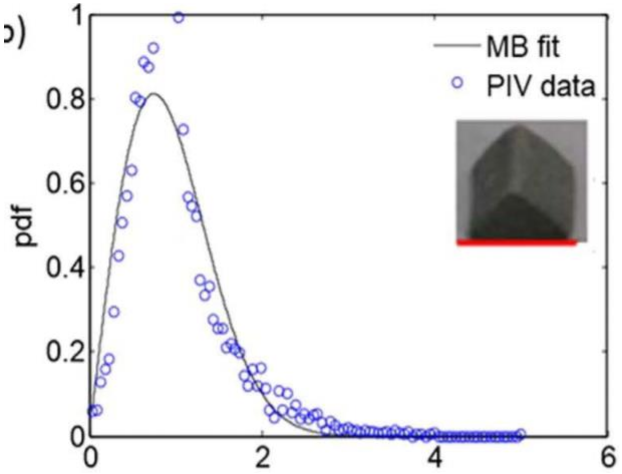


Mixed Media
Char. length ≈ 10 mm



The physics support Media ≈ Fluid

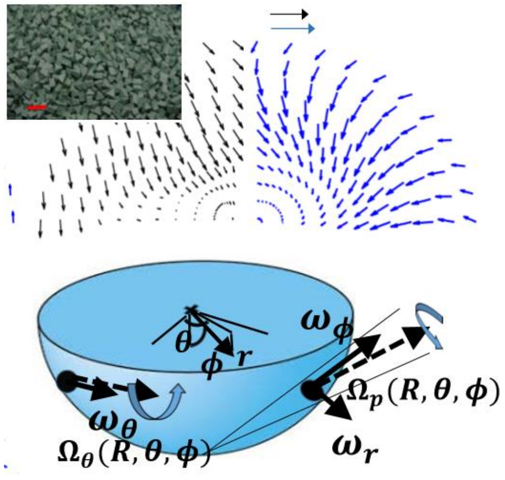
Previous Work



Maxwell-
Boltzmann
Vel. Distributions

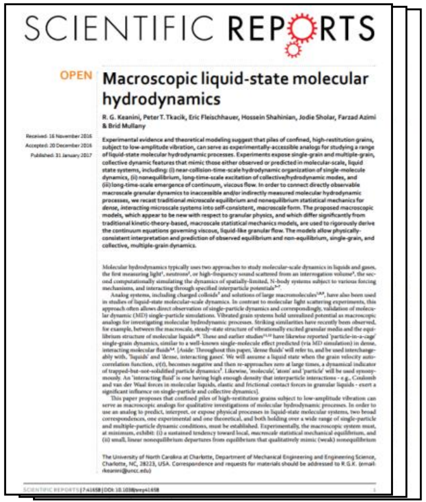
⇩

Hamiltonian



~10^{-3} s **Time scales** ~10^{0} s

Discrete ***Continuum***



SCIENTIFIC REPORTS

OPEN

Macroscopic liquid-state molecular hydrodynamics

R. G. Keanini, Peter T. Tkacik, Eric Fleischhauer, Hossein Shahinian, Jodie Sholar, Farzad Azimi & Brid Mullany

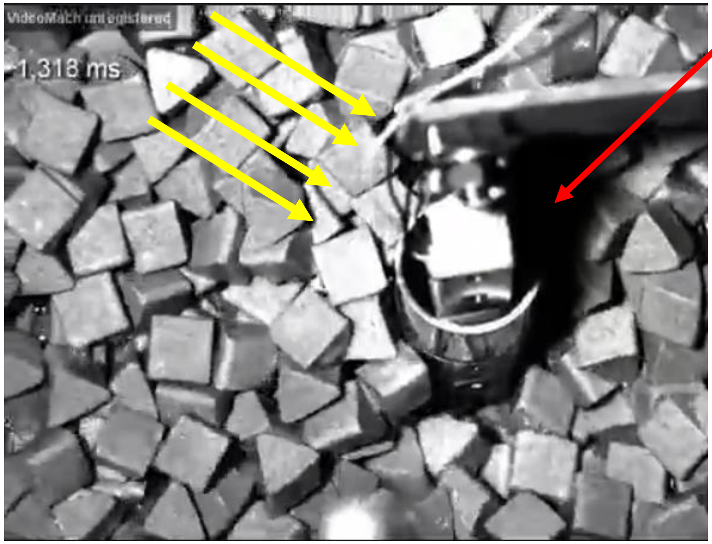
Received: 16 November 2016
Accepted: 20 December 2016
Published: 31 January 2017

Experimental evidence and theoretical modeling suggest that piles of confined, high-restitution grains, subject to low-amplitude vibration, can serve as experimentally-accessible analogs for studying a range of liquid-state molecular hydrodynamic processes. Experiments expose single-grain and multiple-grain, collective dynamic features that mimic those either observed or predicted in molecular-scale, liquid state systems, including: (i) near-collision-time-scale hydrodynamic organization of single-molecule dynamics, (ii) nonequilibrium, long-time-scale excitation of collective/hydrodynamic modes, and (iii) long-time-scale emergence of continuum, viscous flow. In order to connect directly observable macroscale granular dynamics to inaccessible and/or indirectly measured molecular hydrodynamic processes, we recast traditional *microscale* equilibrium and nonequilibrium statistical mechanics for dense, *interacting* microscale systems into self-consistent, *macroscale* form. The proposed macroscopic models, which appear to be new with respect to granular physics, and which differ significantly from traditional kinetic-theory-based, macroscale statistical mechanics models, are used to rigorously derive the continuum equations governing viscous, liquid-like granular flow. The models allow physically-consistent interpretation and prediction of observed equilibrium and non-equilibrium, single-grain, and collective, multiple-grain dynamics.

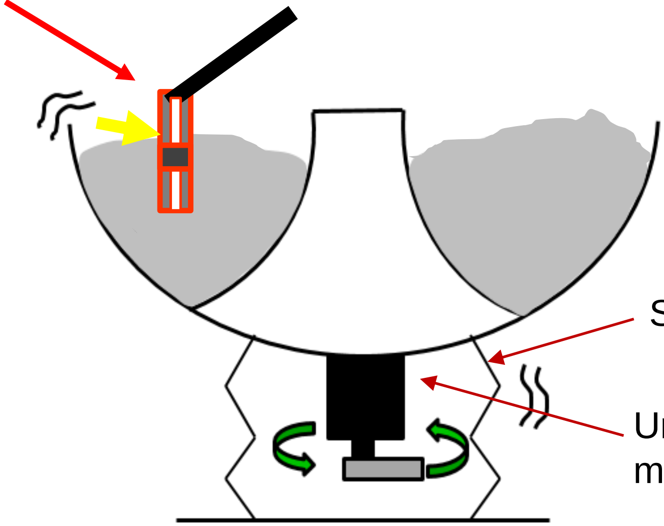
R.G. Keanini et al. Macroscopic liquid-state molecular hydrodynamics, Scientific Reports 7,
Article number: 41658, 2017.

Effective Viscosity of the Media

Top view of Cylinder in Media



Instrumented Cylinder
Ø 25 mm
Length ~150mm



Springs

Unbalanced motor

Determine Drag Coefficient, C_d

- Drag Force, F_d
- *Velocity, V*

$$C_d = F_d / (\tfrac{1}{2}\rho V^2 A)$$

⇕ Established empirical correlations (Ossen …)

$$Re = \rho V d / \mu$$

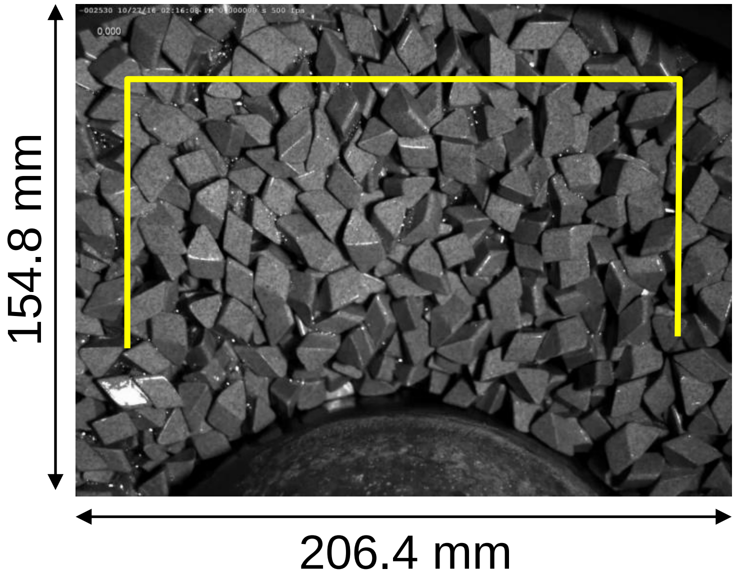
Ceramic
$\mu \approx 6$ kg/ms

Ceramic
$\mu \approx 8$ kg/ms

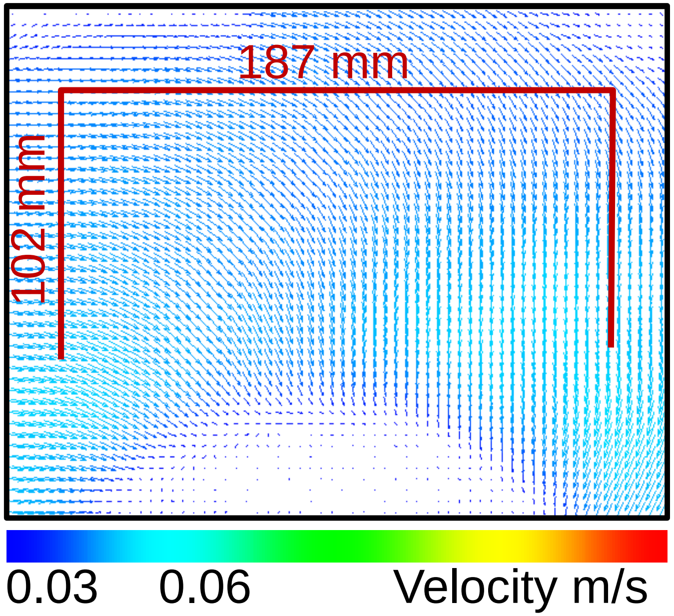
Plastic
$\mu \approx 3.5$ kg/ms

PIV data used as CFD input

High Speed Images taken of vibratory bowl, 500fps for ~10s



PIV measurement
Averaged velocity field

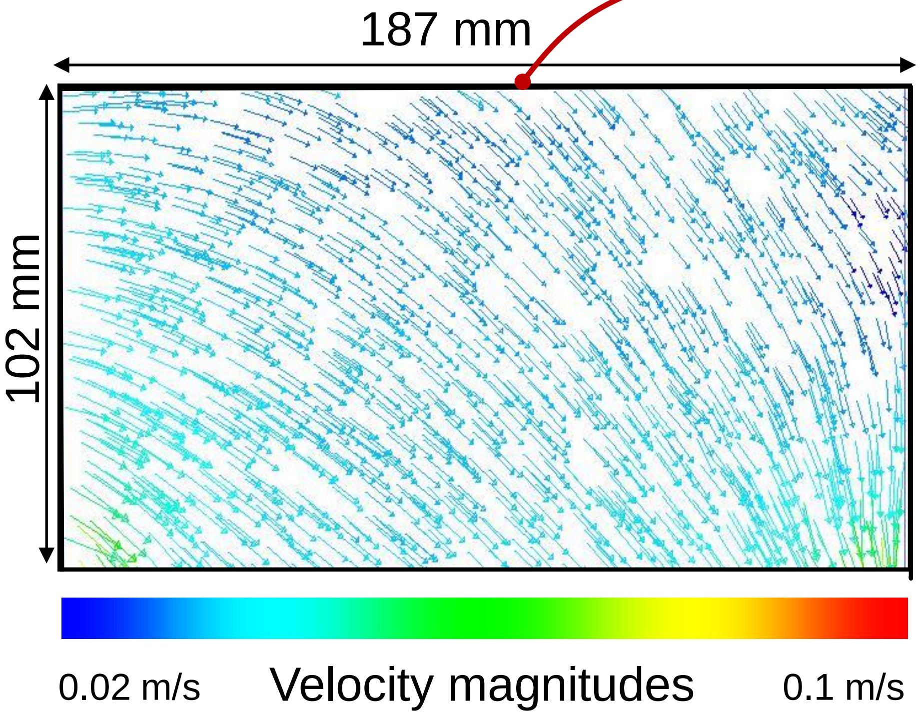


PIV Velocity Profiles imported into CFD environment

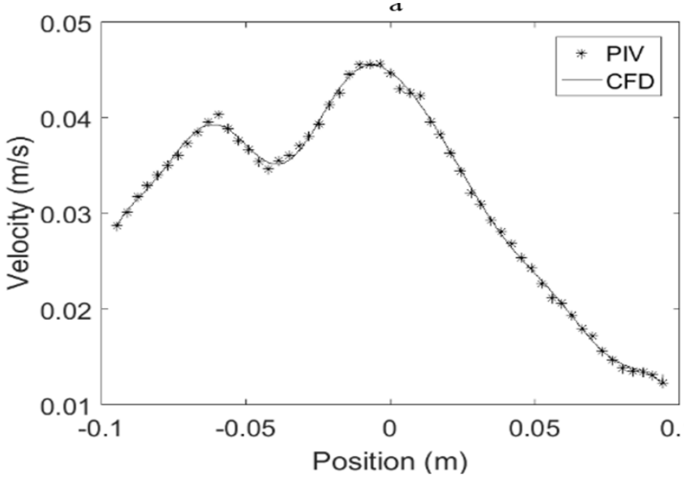
THE C PROGRAMMING LANGUAGE

ANSYS

CFD model predicted velocities



PIV and CFD velocity profiles along top inlet



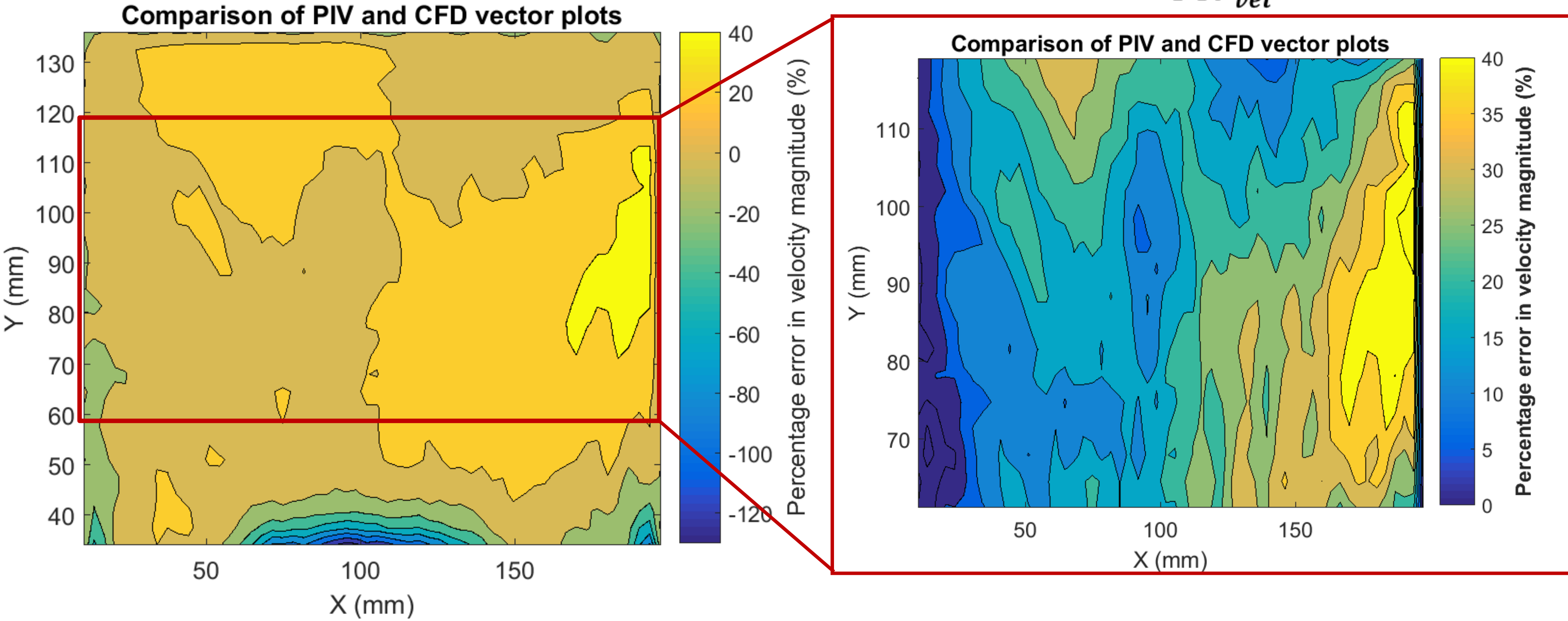
CFD Model Details:

- 1.4 million nodes (mesh sizes 0.2 to 2 mm)
- Low Reynolds flow
- No tangential stress on boundaries
- Ambient pressure at outlet
- PIV define inlet velocities
- $\rho = 1350\ kg/m^3$
- $\mu = 6.02$ Pa.s
- Solution time ~ 1 minute

UNC CHARLOTTE

Comparison between PIV and CFD

$$\% \, Error = \frac{PIV_{vel} - CFD_{vel}}{PIV_{vel}} \times 100$$



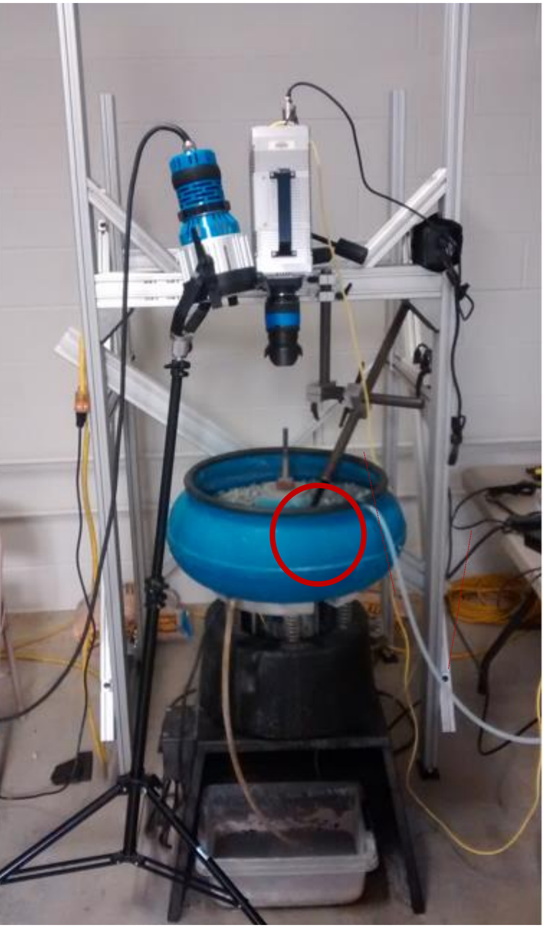
Main Source of error:

- 2D representation of a complex 3D flow

Sensitivity Analysis:

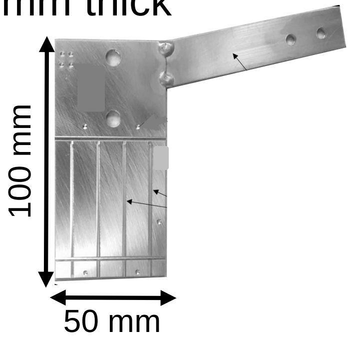
- Density: 1000 kg/m^3 → 2500 kg/m^3
- Viscosity: 0.1 → 50 Pa.s
- # elements: 900 → 1.4×10^6 elements
- Soln. Initial.: Left, Top, Right

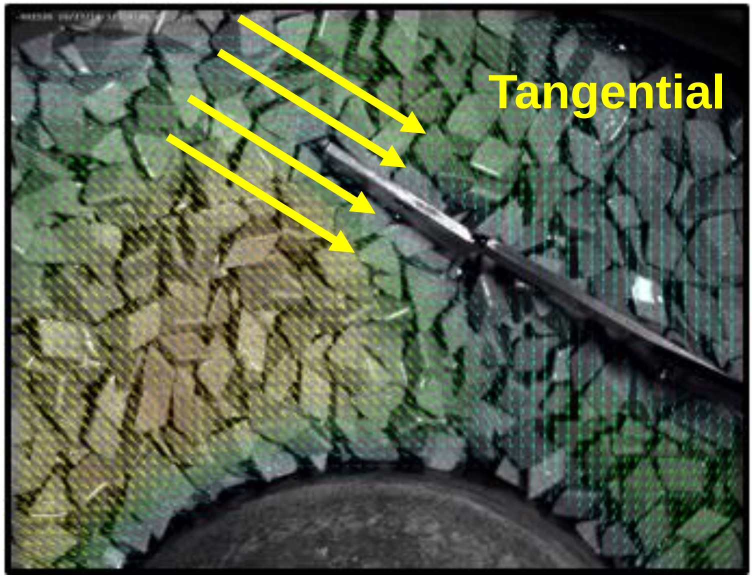
Media flow around a workpiece

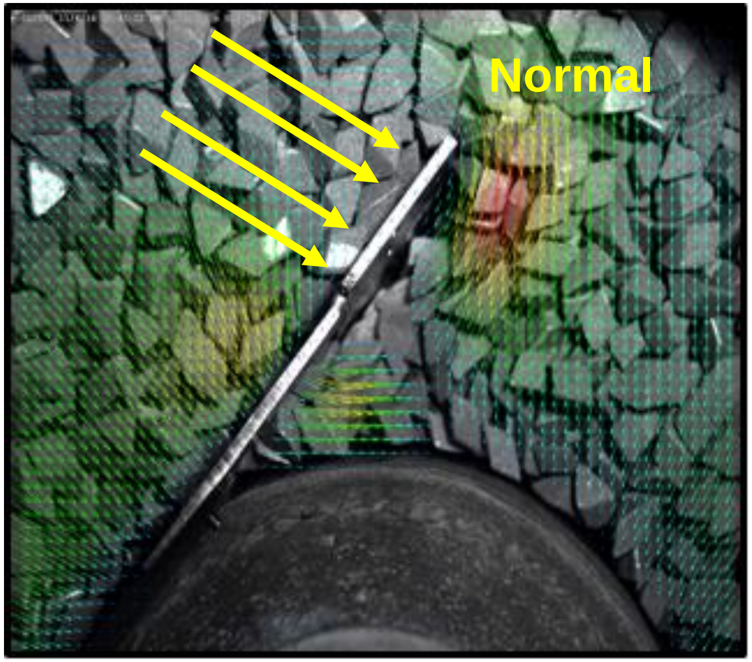


Workpiece:

- Ground Al 6061
- 3mm thick







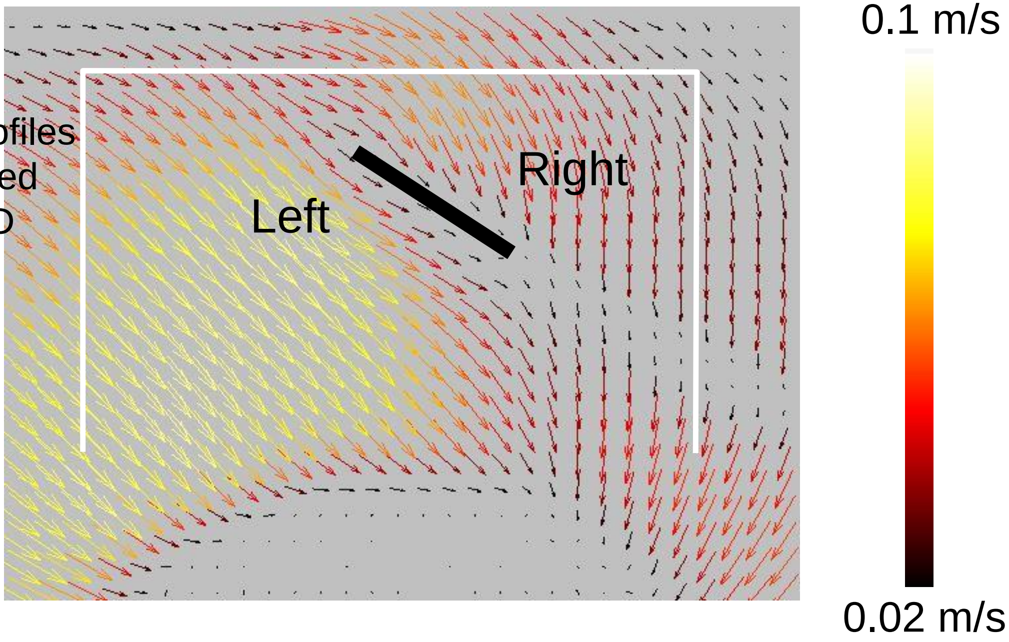
Testing conditions:

Frequency:	29.3 Hz
Vibrational amp:	~2mm
Process time:	1.5 hrs

MRRs
Surface Alteration

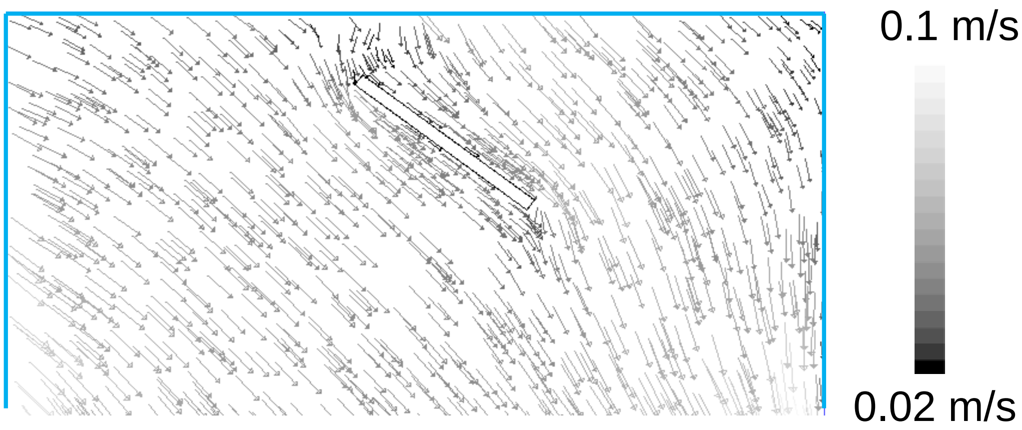
Flow tangential to workpiece

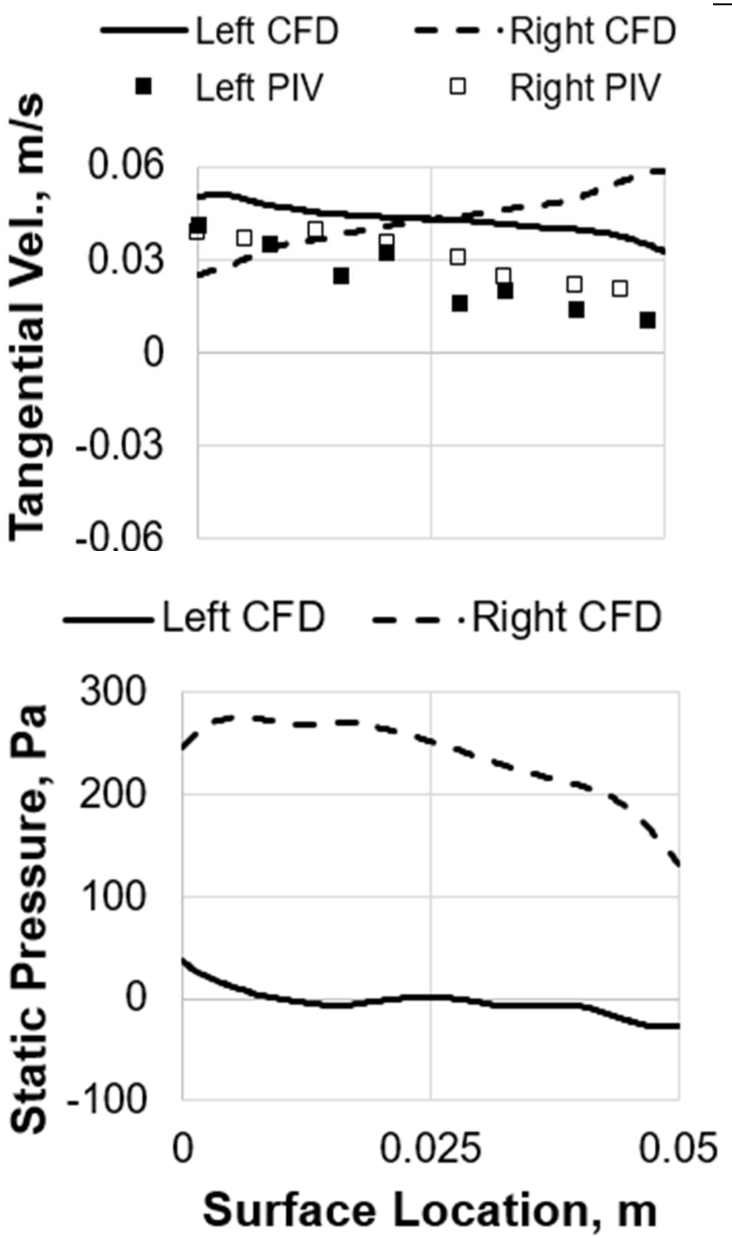
Tangential Flow –PIV measured Flow



PIV profiles extracted for CFD

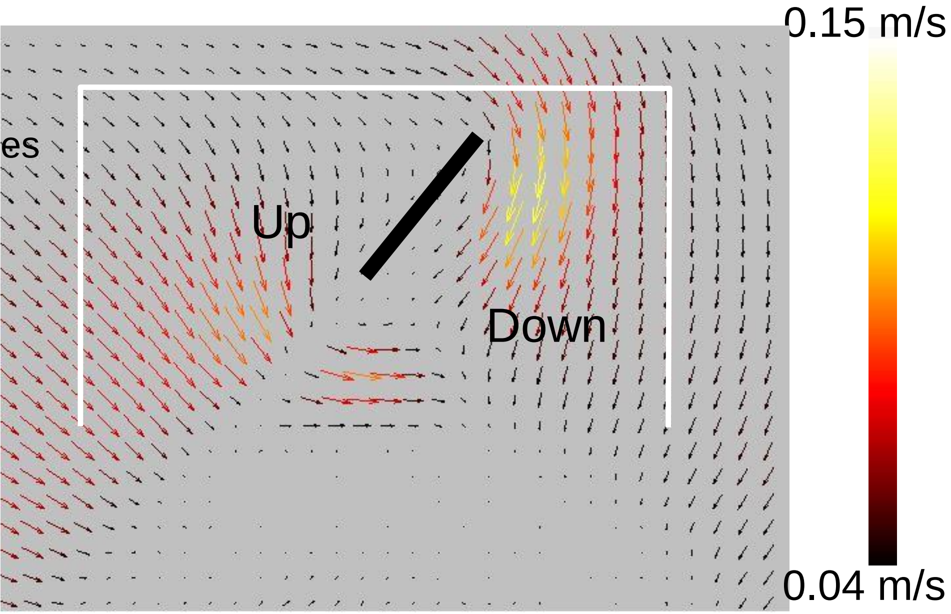
Tangential Flow –CFD predicted Flow





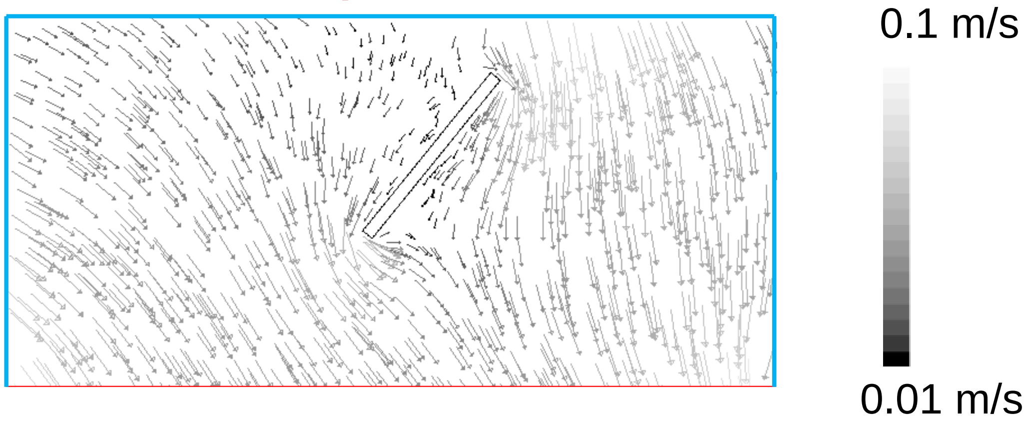
Flow normal to workpiece

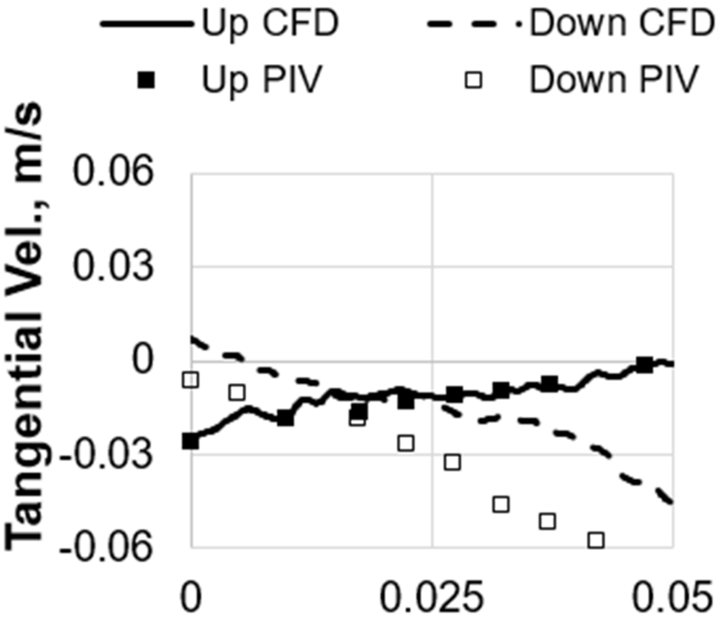
Tangential Flow –PIV measured Flow

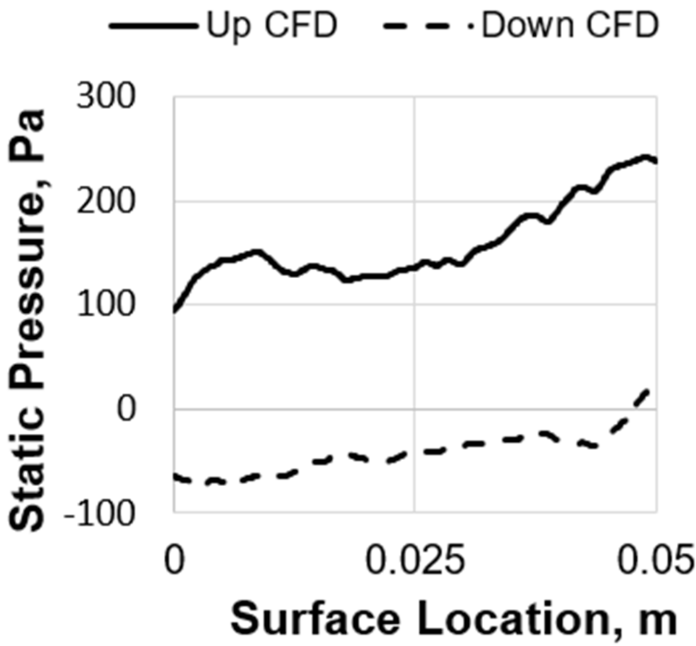


PIV profiles extracted for CFD

Tangential Flow –CFD predicted Flow

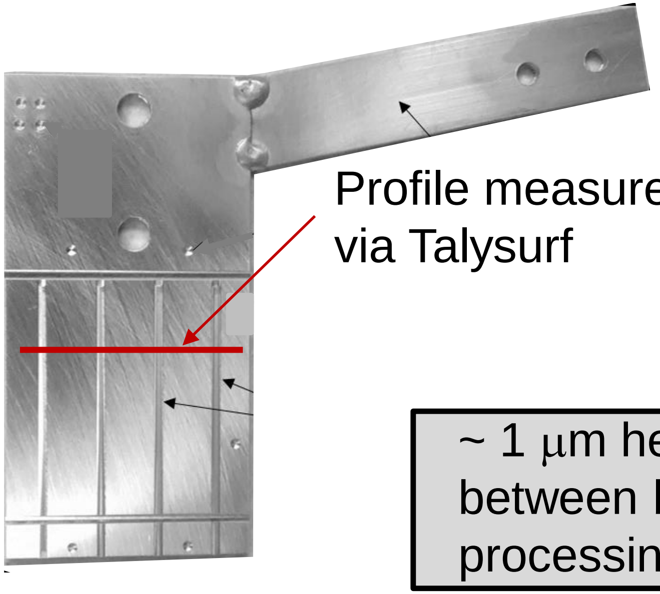






Quantification of the Workpiece

Material Removal



Profile measured via Talysurf

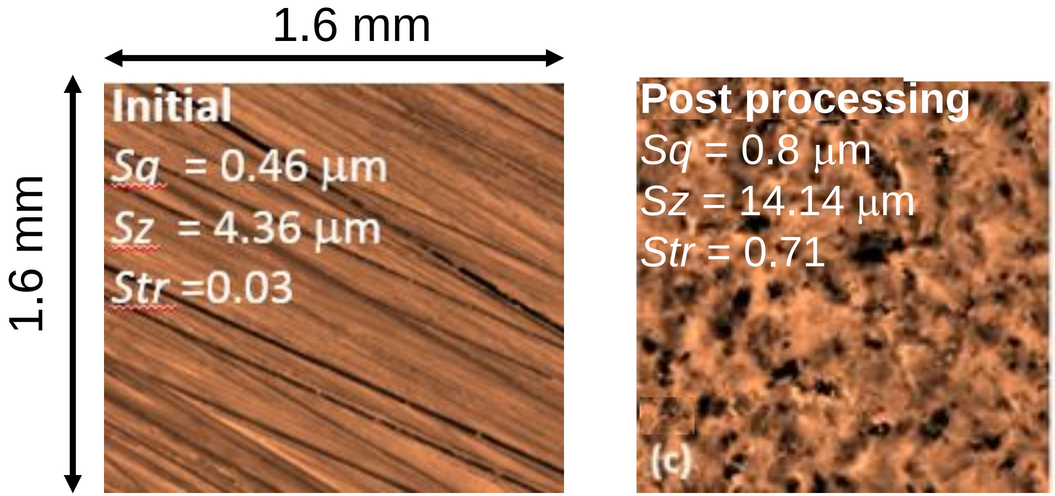
Material removal rate:

- Four slots milled
  - 2 mm wide
  - 100 µm deep
- Base of slot protected via epoxy
- Profile measured pre, and post

~ 1 µm height difference between before and after processing ⇨

- Low MR
- Surface modification via deformation

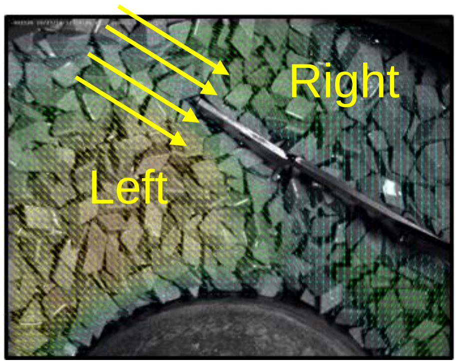
Surface Finish, SWLI 5×

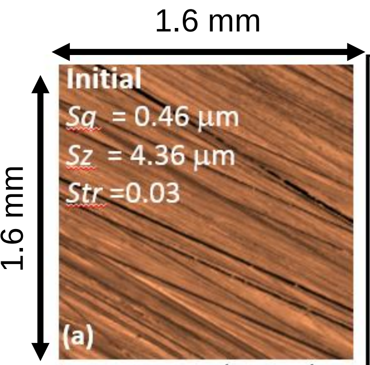


Texture aspect ratio, ***Str***

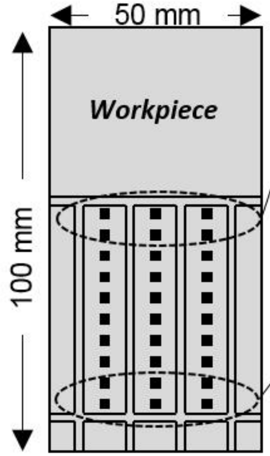
Str = 0	Anisotropic surface
Str =1	Isotropic surface

Tangential Flow – post processing





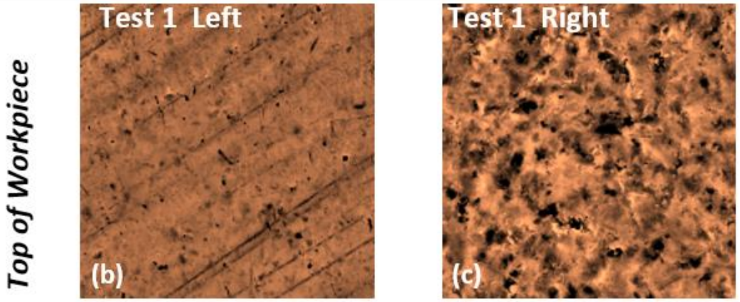
Str_{30} = 0.03 (± 0.06)



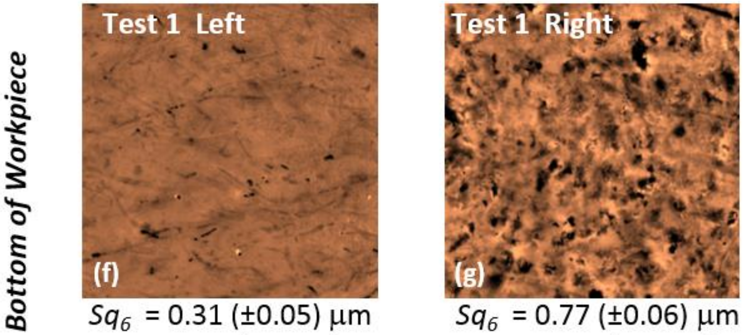
- ■ Measurement location

SWLI: 5x objective

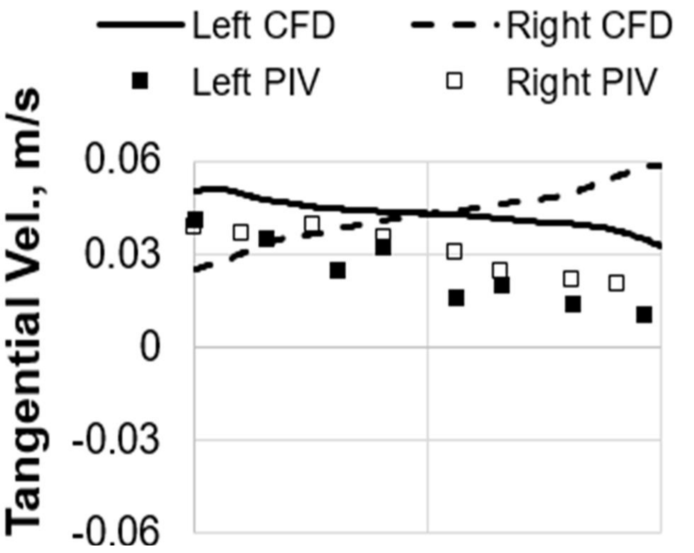
FoV: 1.66 mm × 1.66 mm

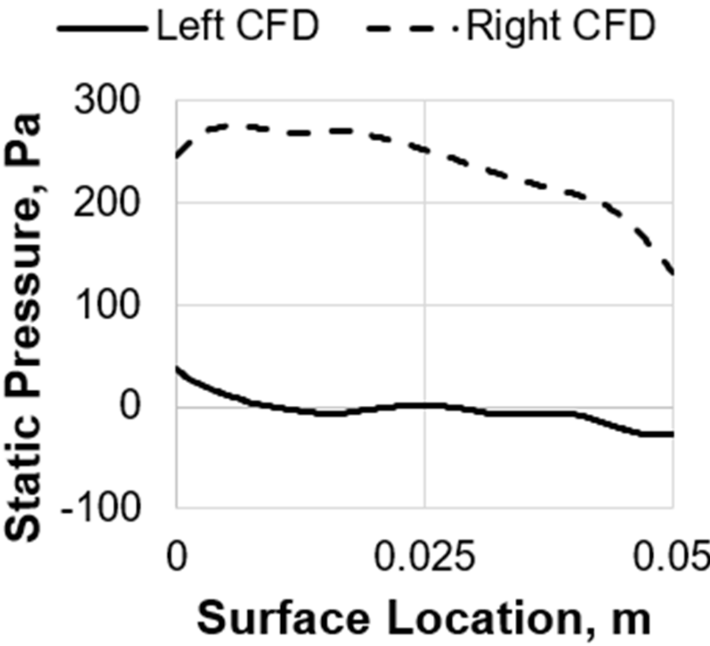


Test 1 Left	Test 1 Right
Sq_6 = 0.38 (±0.03) µm	Sq_6 = 0.8 (±0.13) µm
Sz_6 = 17.95 (±8.88) µm	Sz_6 = 14.14 (±6.49) µm
Str_6 6 = 0.24 (±0.23)	Str_6 = 0.71 (±0.33)

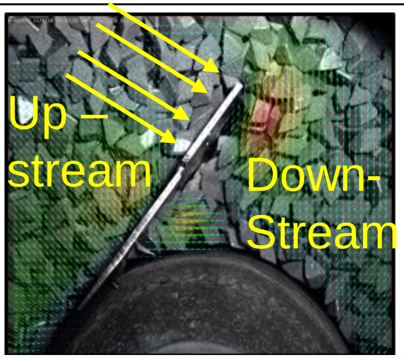


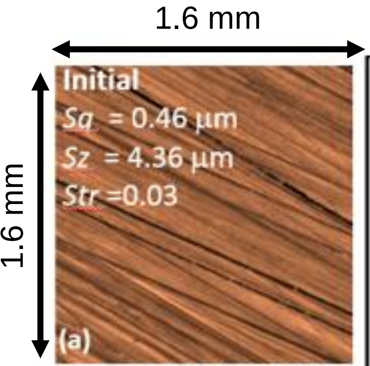
Test 1 Left	Test 1 Right
Sq_6 = 0.31 (±0.05) µm	Sq_6 = 0.77 (±0.06) µm
Sz_6 = 28.87 (±23.21) µm	Sz_6 = 20.77 (±10.67) µm
Str_6 = 0.44 (±0.2)	Str_6 = 0.83 (±0.04)





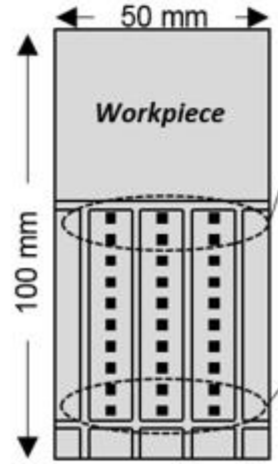
Normal flow - post processing



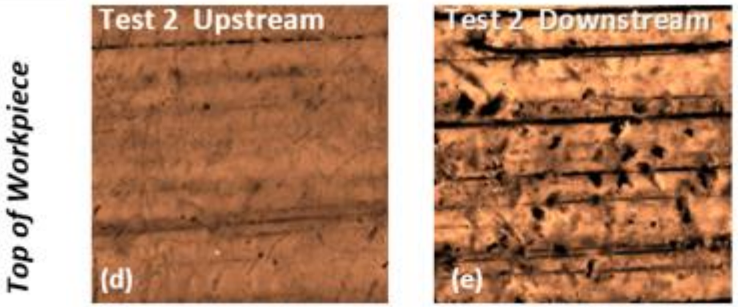


Initial
Sq = 0.46 µm
Sz = 4.36 µm
Str = 0.03

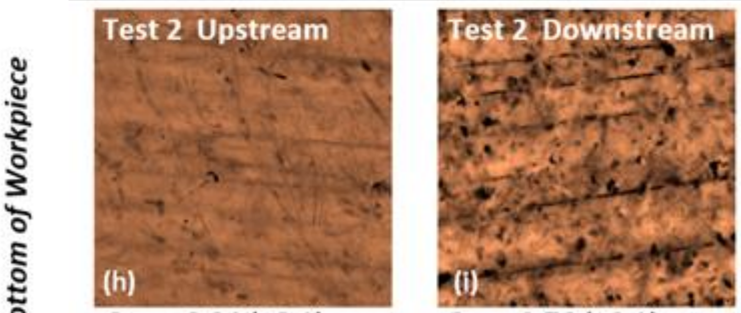
Str_{30} = 0.03 (± 0.06)



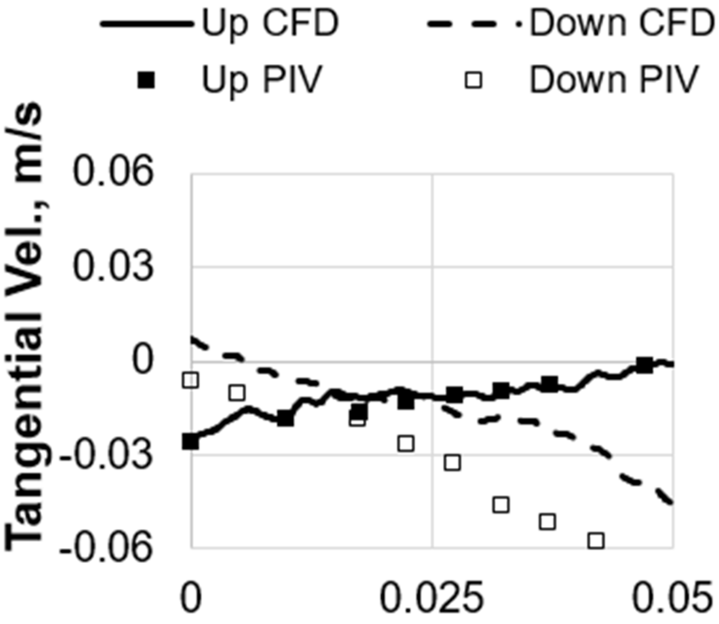
■ Measurement location
SWLI: 5x objective
FoV: 1.66 mm × 1.66 mm

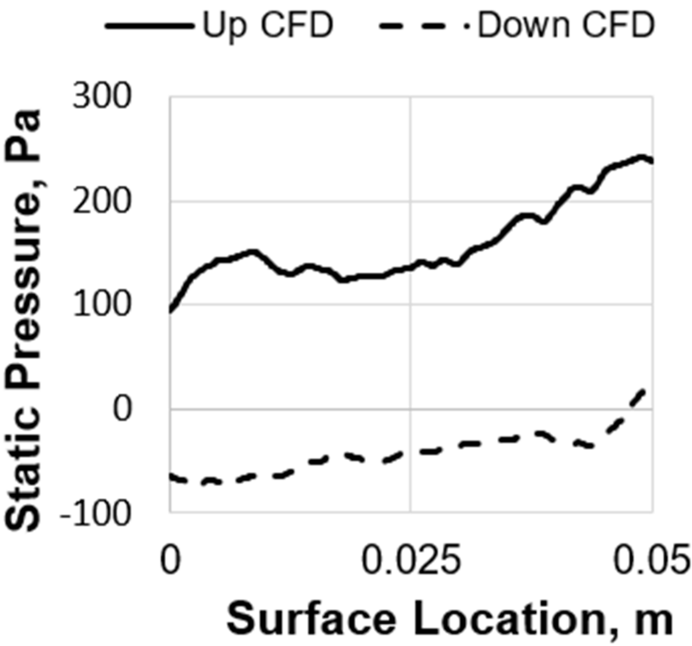


Test 2 Upstream	Test 2 Downstream
Sq_6 = 0.28 (± 0.04) µm	Sq_6 = 1.09 (±0.37) µm
Sz_6 = 13.4 (6.27) µm	Sz_6 = 21.89 (±8.37) µm
Str_6 = 0.16 (± 0.23)	Str_6 = 0.05 (±0.12)

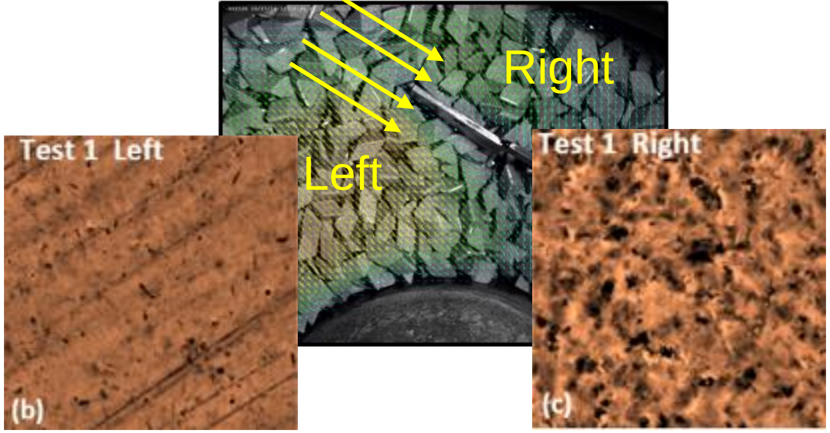


Test 2 Upstream	Test 2 Downstream
Sq_6 = 0.34 (±0.1) µm	Sq_6 = 0.76 (±0.1) µm
Sz_6 = 12.84 (±3.49) µm	Sz_6 = 19.37 (±9.45) µm
Str_6 = 0.27 (±0.26)	Str_6 = 0.08 (±0.02)





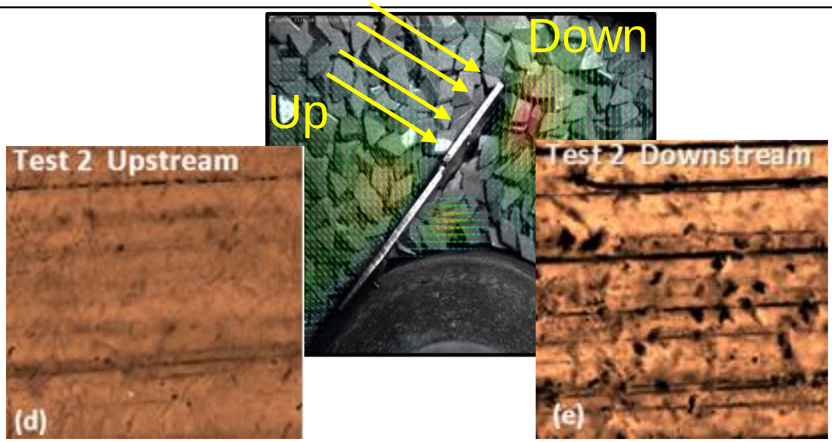
Comparing the results



Low pressure

High pressure

Comparable velocities



High pressure

Low pressure

Lower ←Velocity→ higher

Process vibrations should not be neglected!

Summary

Summary …

- A 2D CFD model provides useful insights on 3D complex flow about a workpiece
  - CFD predicted velocities are comparable to PIV measured values
  - CFD provides new insights on local pressure field variations

- Combining knowledge of process vibrations with CFD predicted velocity and pressure fields offers explanations for process induced topographies.

Going forward…

- A fully successful model will combine;
  - Continuum mechanics
  - Process vibrations
  - Media packing density

Acknowledgements:

Partial funding via the Office of Naval Research (ONR N00014-15-1-0020) and NSFs IRD program

References

- Hashimoto, F., Johnson, S. P., 2015, Modeling of vibratory finishing machines, CIRP Annals Manufacturing Technology, 64:345-348.

- S.E. Naeini, J.K. Spelt, development of single cell bulk circulation in granular media in a vibrating bed, Powder technology, 211, pp. 176-186, 2011

- Eckart Uhlmann, Alexander Eulitz*, Arne Dethlefs, A., Discrete Element Modelling of Drag Finishing, Procedia CIRP, 31:369-374, 2015

- Young Sup Kang, Fukuo Hashimoto (1), Stephen P. Johnson, Jerry P. Rhodes , Discrete element modeling of 3D media motion in vibratory finishing process, CIRP Annals Manufacturing Technology, 66/1/2017

- V. Cariapa, H. Park, J. Kim, C. Cheng, A. Evaristo, Development of a metal removal model using spherical ceramic media in a centrifugal disk mass finishing machine, International Journal of Advanced Manufacturing Technology, 39, pp.92-106, 2008

- Wan, S., T. Sato, and A. Hartawan. Vibratory finishing of immobilized cylinders. in Advanced Materials Research. Trans Tech Publ. 2013