



**International Academy for Production Engineering**

**67<sup>th</sup> General Assembly – Lugano – Switzerland - Aug. 20-26 2017**

# **The Application of Computational Fluid Dynamics to Vibratory Finishing Processes**

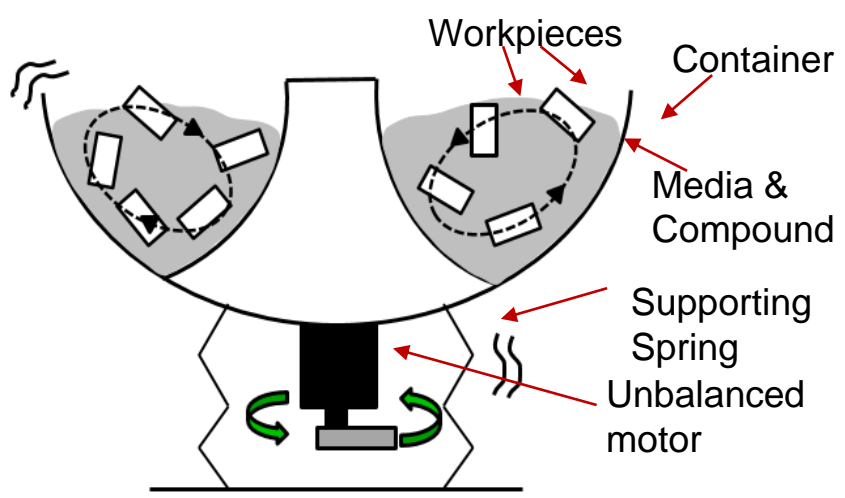
**by**

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

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UNC Charlotte, North Carolina, USA  
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**CIRP Annals - Manufacturing Technology**  
Volume 66, Issue 1, 2017

# Vibratory Finishing



## Applications

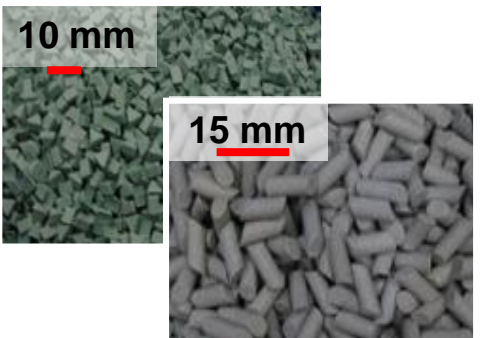
- Deburring
- Cleaning
- Improve surface finish

## Process Dynamics:

- Vibrations ~29 Hz
- Amplitude 2 mm to 6 mm

## Media:

- Plastic
- Ceramic
- Metal
- Organic



## Finding application for:

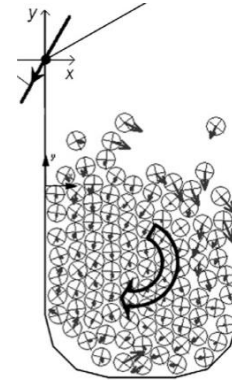
- Orthopedic implants
- Blisks and turbine blades
- Tool finishing

## Dynamics Based approaches

- Hashimoto et al. (2015)

## Discrete Element Modeling approaches

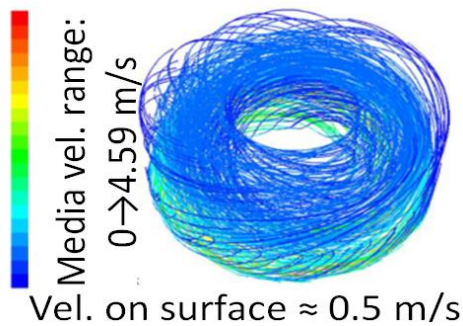
- Naeini et al. (2011)
- Uhlmann et al. (2015)
- Kang et al. (2017)



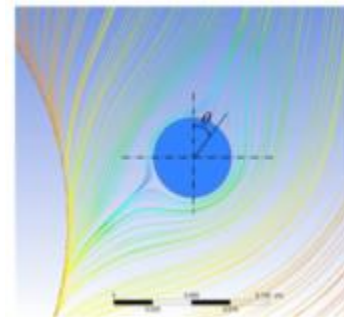
Naeini et al. (2011)

## Continuum based approaches

- Cariapa et al. (2009)
- Wan et al (2012)



Cariapa et al (2009)



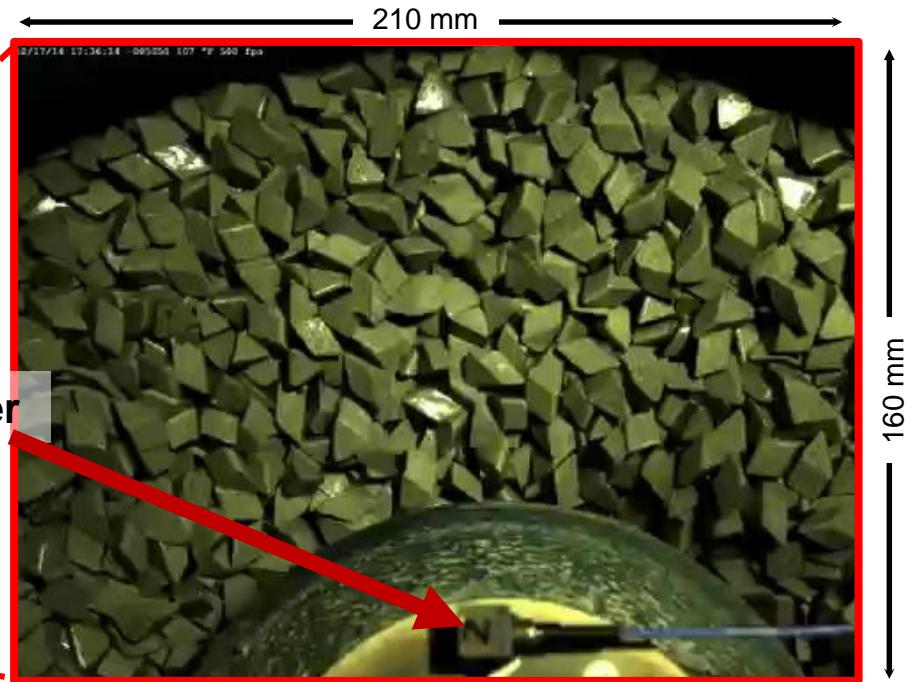
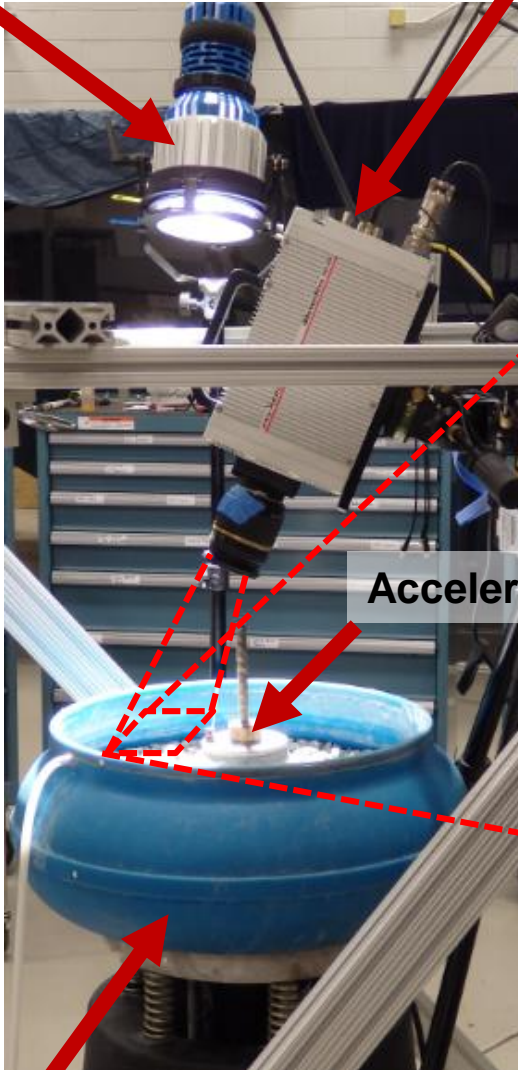
Wan et al (2012)

# Particle Image Velocimetry (PIV)

**Halogen Light:**  
ARRI EB 400/575 D

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

Previous Work



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

**Raytech AV-75 System (Ø 600 mm)**



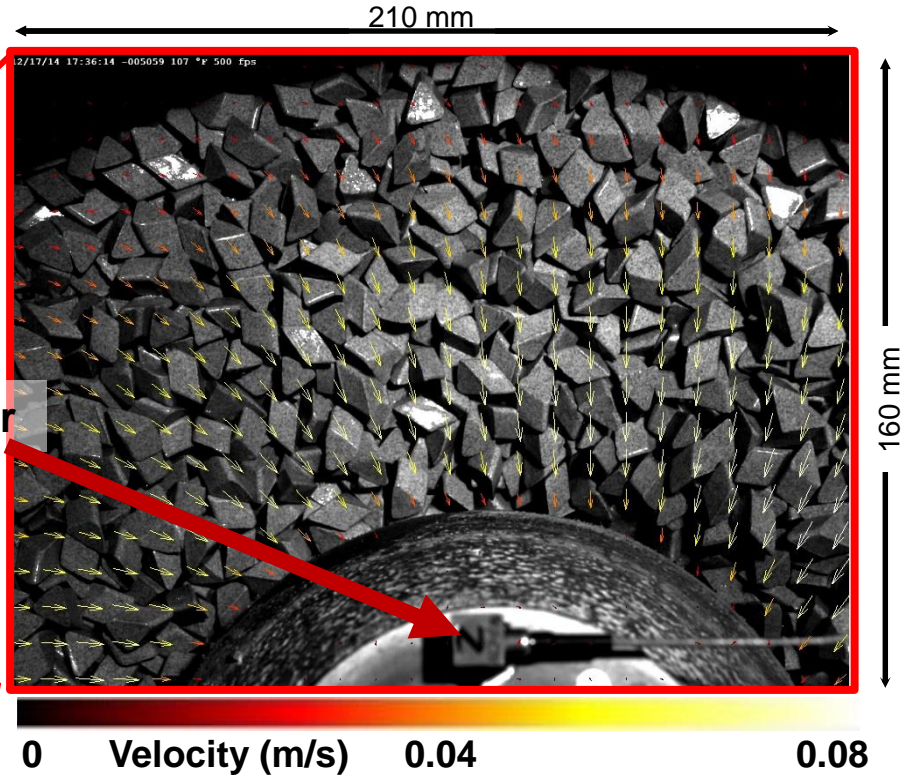
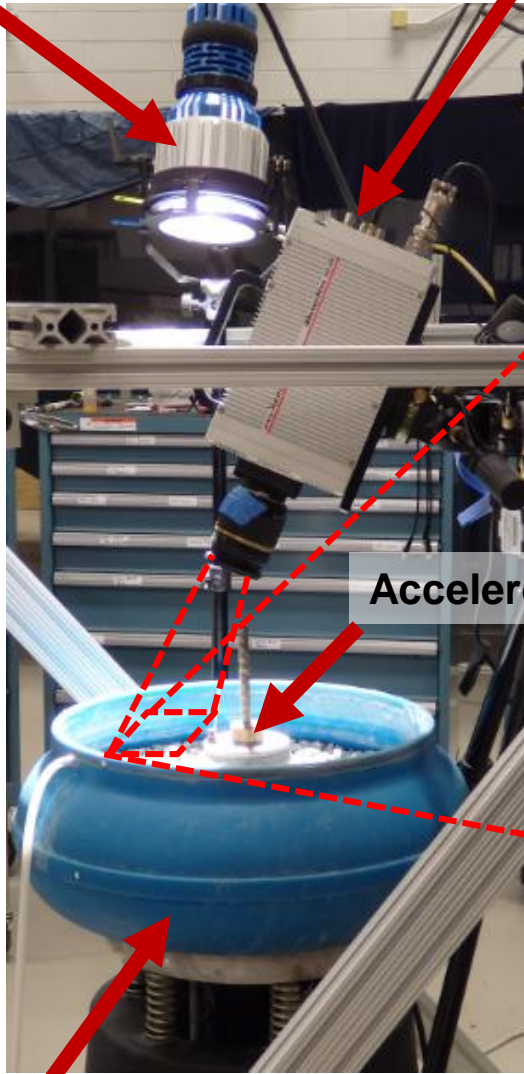
# Particle Image Velocimetry (PIV)

**Halogen Light:**  
ARRI EB 400/575 D

**High Speed Camera:**  
Redlake (Motionextra 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<sup>2</sup> area.*

Previous Work



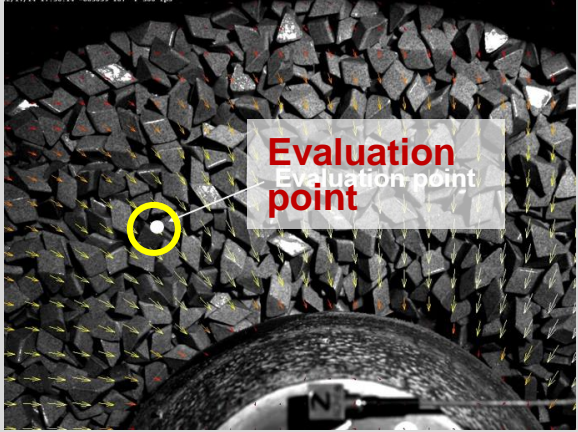
**Operating Conditions:**  
**Motor speed:** 1740 rpm  
**Media:** Ceramic RSG 10/10  
**Compound:** FC FLK (3% vol.)

**Raytech AV-75 System (Ø 600 mm)**

# PIV: The Discrete and Continuous

Previous Work

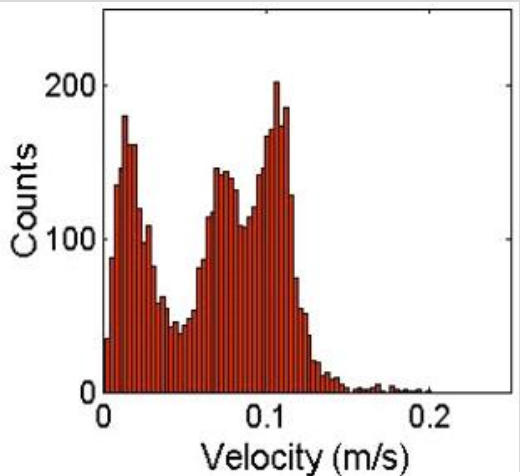
## Continuum nature of media captured



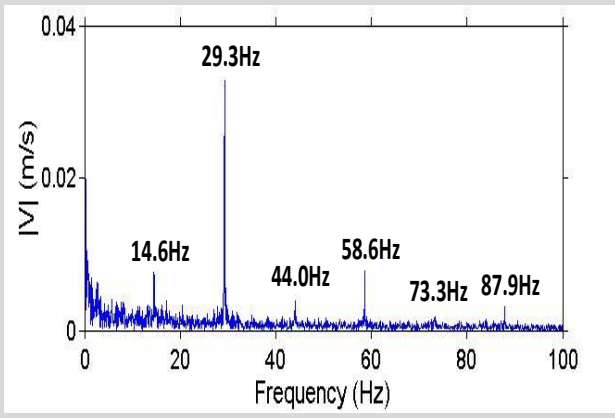
Each velocity vector = averaged velocity  
Based on 5059 vectors (taken over 10.12s)  
Over an 20.25 mm<sup>2</sup> area.

## Discrete nature of media particles

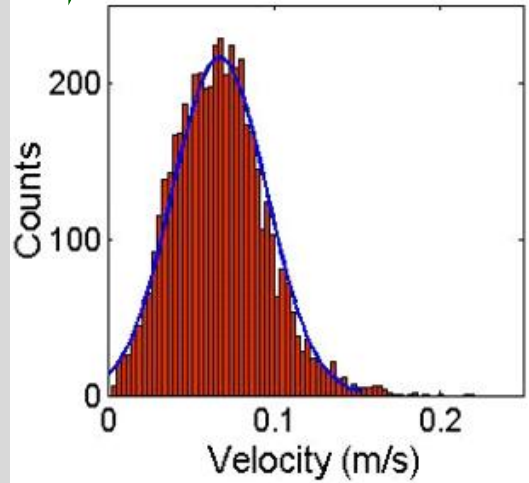
Histogram of Velocity at a single point



Fourier Filter to remove bulk media motion



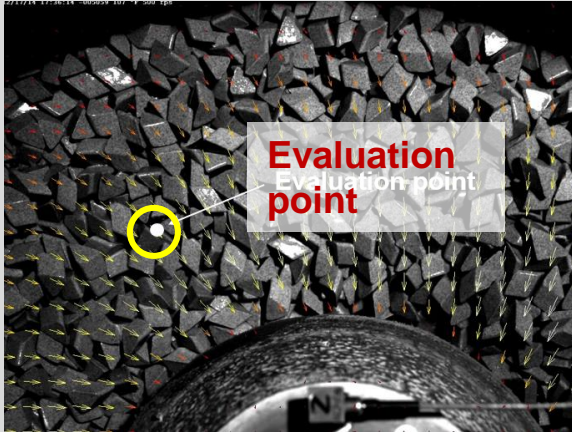
Captures media-media interactions



# 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<sup>2</sup> area.

## Discrete nature of media particles

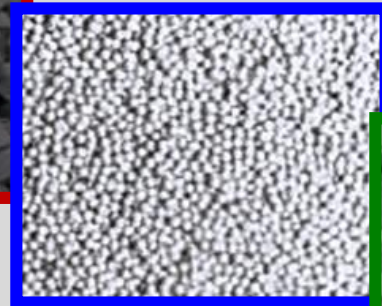
**RSG 10/10**

Char. length  $\approx$  10 mm



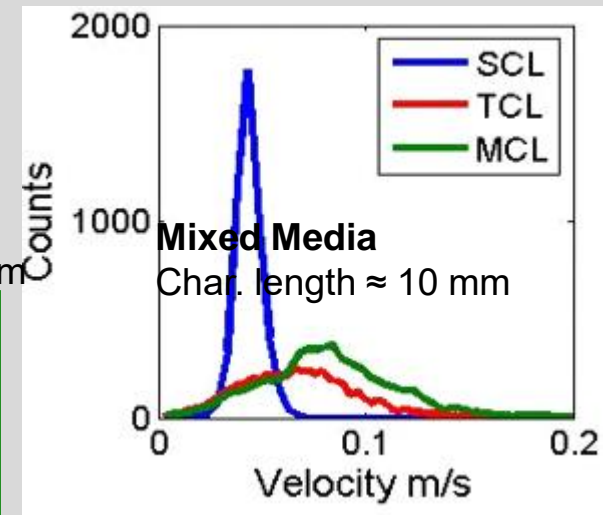
**Spheres**

Char.  $\varnothing$   $\approx$  2 mm



**Mixed Media**

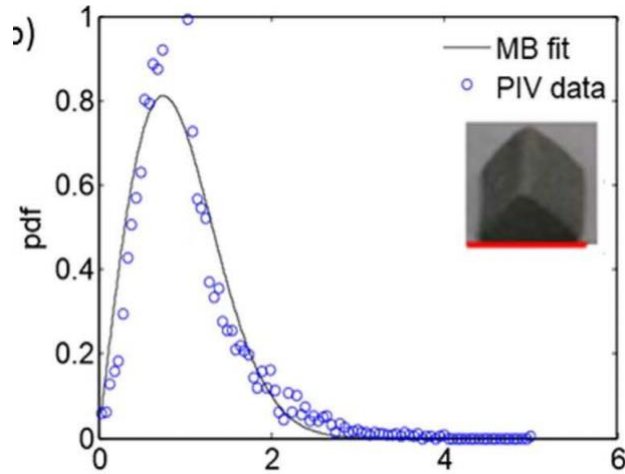
Char. length  $\approx$  10 mm



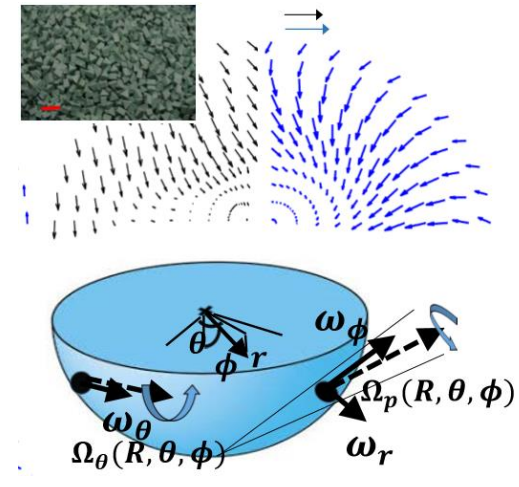


# The physics support Media $\approx$ Fluid

Previous Work



Maxwell-Boltzmann Vel. Distributions  
 $\Downarrow$   
 Hamiltonian



$\sim 10^{-3}$  s Time scales  $\sim 10^0$  s

**Discrete**

**Continuum**

SCIENTIFIC REPORTS

**OPEN** Macroscopic liquid-state molecular hydrodynamics

R. G. Keanini, Peter T. Thack, Eric Pitschke, Hossain Shahin, Jada Shilar, Farhad Anali & Brid Mullany

Received 18 November 2016  
 Accepted 22 December 2016  
 Published 11 January 2017

Experimental evidence and theoretical modelling suggest that planar, confined, high-resolution 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 mirror 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 evolution of collective hydrodynamic modes, and (iii) long-time-scale emergence of continuum, viscous flow. In order to connect directly observable macroscopic granular dynamics to inaccessible single-molecule hydrodynamic hydrodynamic processes, we reuse traditional molecular-dynamics and nonequilibrium statistical-mechanics formalisms, including molecular-systems one self-organization, microscale flow. The presented microscopic models, which appear to be well-suited to general physics, use which other applications from traditional kinetic theory-based, macroscopic statistical-mechanics models, are used to rigorously derive the continuum quantities governing viscous, liquid-like granular flow. The models allow principled, consistent interpretation and prediction of observed equilibrium and non-equilibrium, single-grain, and collective, multiple-grain dynamics.

Molecular hydrodynamics typically uses two approaches to study molecular-scale dynamics in liquids and gases, the first measuring 'light' (optical) or 'high-frequency sound' (acoustic) from an interrogating volume, the second computationally simulating the dynamics of spatially-discrete, N-body systems subject to various forcing mechanisms, and measuring through statistical analysis the properties of the system.

During systems involving single-grain, and other forms of 'single-molecule' (SM) flow, planar-based studies of liquid-state molecular-scale dynamics, by contrast to molecular-scale scattering experiments, this approach to the dynamic observations of single-grain dynamics and corresponding evolution of molecular dynamics (MD) single-grain simulations. Viscous granular systems hold potential as macroscopic analogs for investigating hydrodynamic processes. Viscous granular systems have recently been theorized, for example, between the macroscopic steady-state structure of effectively rigid granular media and the equilibrium structure of molecular liquids<sup>1,2</sup>. These and other studies<sup>3,4</sup> have drawn expected parallels to single-grain granular systems, similar to a dense single-molecule (SM) particle (in MD) simulation, to derive underlying molecular flow<sup>5,6</sup> (note: throughout this paper, 'we use fluid' will refer to, and be used interchangeably with, 'liquid' and 'dense, interacting grain'). We will assume a liquid state when the grain relative concentration function,  $\chi$ , becomes negative and this re-approaches zero at large times, a dimensional indicator of trapped but untrapped particle dynamics<sup>7</sup>. However, 'isolated' (free) and 'particle' will be used to mean, respectively, an interacting fluid<sup>8</sup> or one having high enough density that interparticle interactions – e.g. Coulombic and van der Waals forces – and frictional contact forces to granular liquids – exert a significant influence on single-grain and collective dynamics.

This paper proposes their confined planar high-resolution vibration subject to low-amplitude vibration can serve as experimentally accessible analogs for studying hydrodynamic processes. In order to use analogs to predict, interpret, or expose physical processes in liquid-state molecular systems, two formal correspondences, one experimental and one theoretical, and both holding over a wide range of single-grain and multiple-grain dynamic conditions, must be established. Experimentally, the macroscopic system must, at minimum, exhibit (i) a sustained random or forced flow, macroscopic statistical mechanical equilibrium, and (ii) small, lower nonequilibrium departures from equilibrium that qualitatively mirror, (weakly) nonequilibrium.

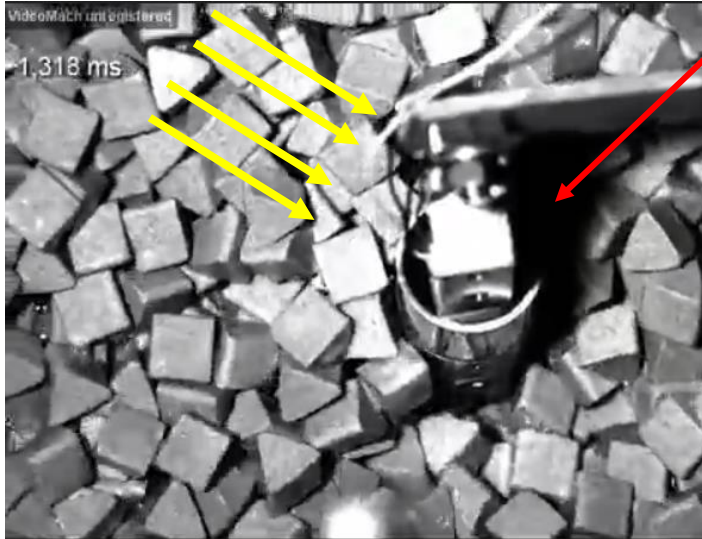
The University of North Carolina at Charlotte, Department of Mechanical Engineering and Engineering Science, Charlotte, NC, 28223, USA. Correspondence and requests for materials should be addressed to R.G.K. (email: keanini@unc.edu)

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

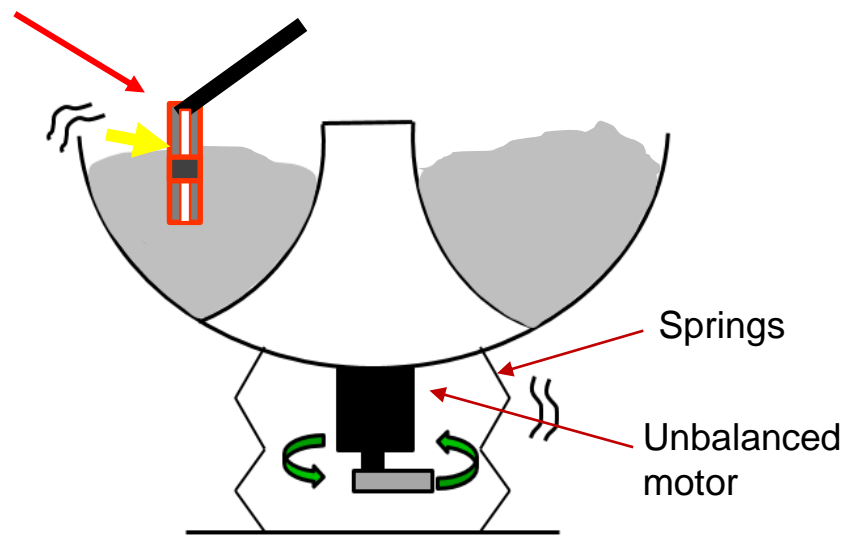


# Effective Viscosity of the Media

Top view of Cylinder in Media



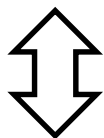
Instrumented  
Cylinder  
Ø 25 mm  
Length ~150mm



Determine Drag Coefficient,  $C_d$

- Drag Force,  $F_d$
- Velocity,  $V$

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



Established  
empirical  
correlations  
(Ossen ...)

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



Ceramic  
 $\mu \approx 6 \text{ kg/ms}$



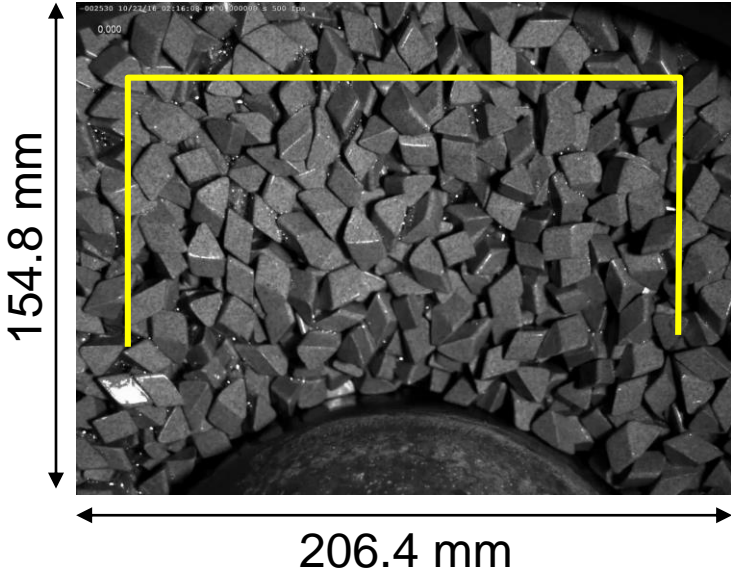
Ceramic  
 $\mu \approx 8 \text{ kg/ms}$



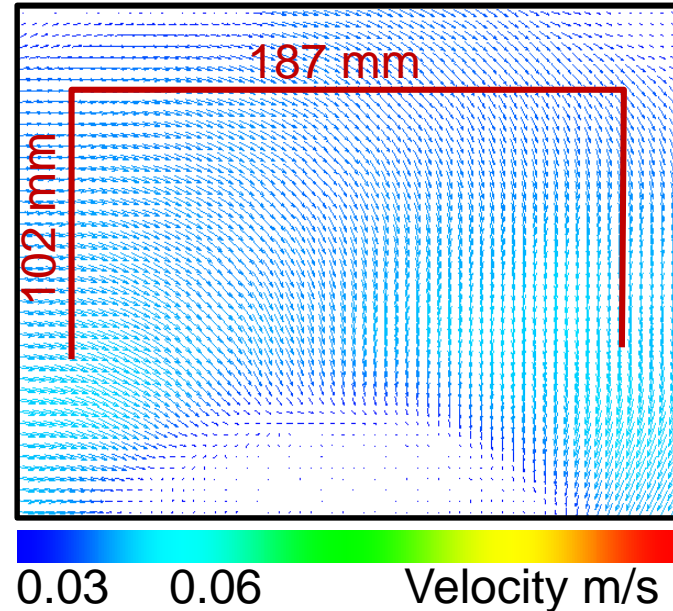
Plastic  
 $\mu \approx 3.5 \text{ kg/ms}$

# PIV data used as CFD input


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



PIV measurement  
Averaged velocity field



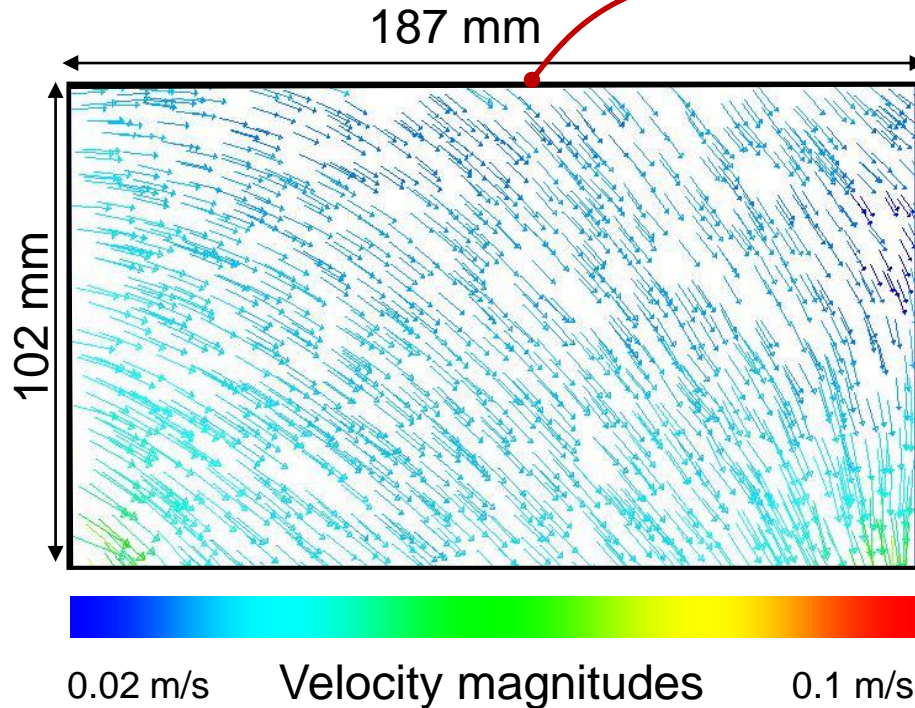
**PIV Velocity Profiles imported into CFD environment**



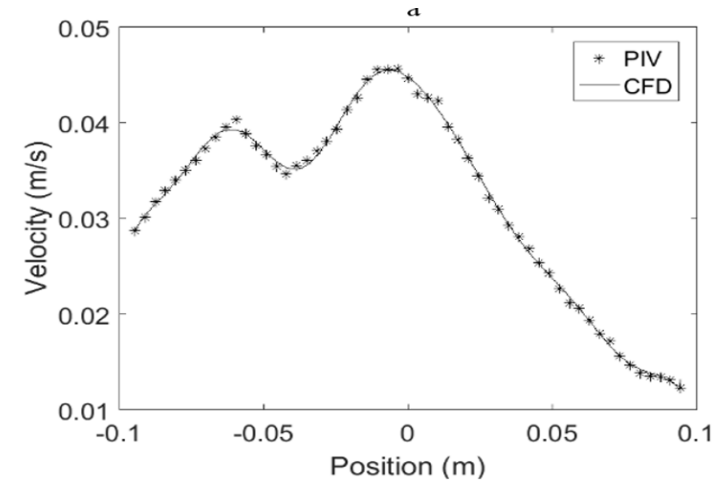
ANSYS

THE C PROGRAMMING LANGUAGE

# 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

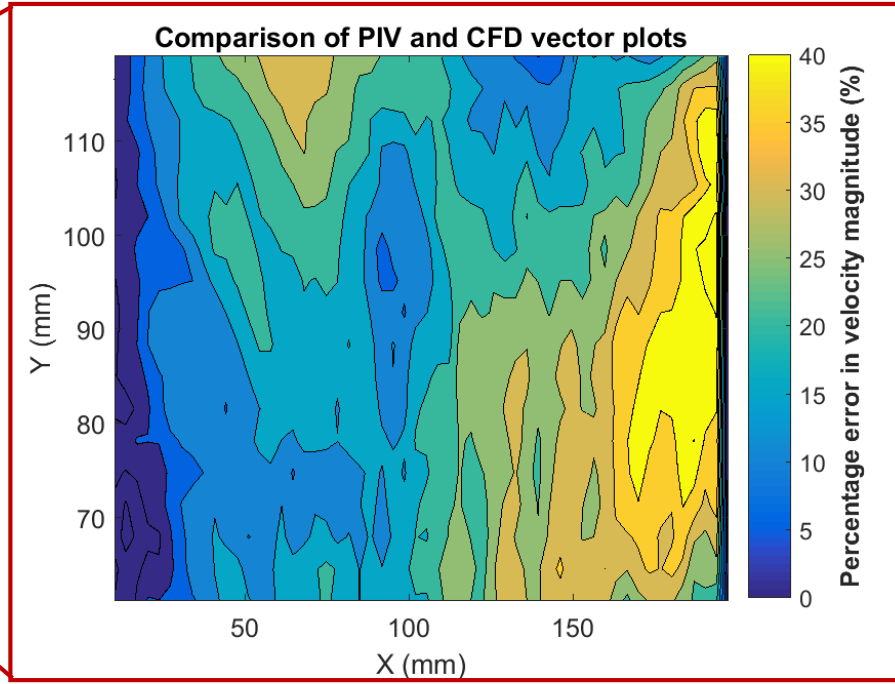
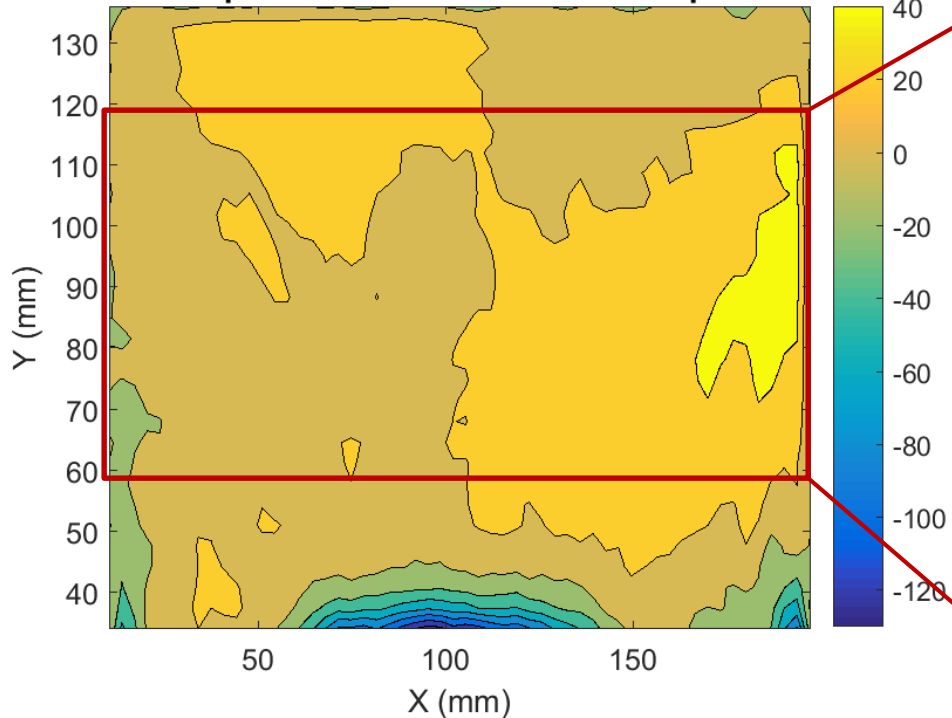
- $\rho = 1350 \text{ kg/m}^3$
- $\mu = 6.02 \text{ Pa}\cdot\text{s}$
- Solution time ~ 1 minute



# Comparison between PIV and CFD

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

Comparison of PIV and CFD vector plots



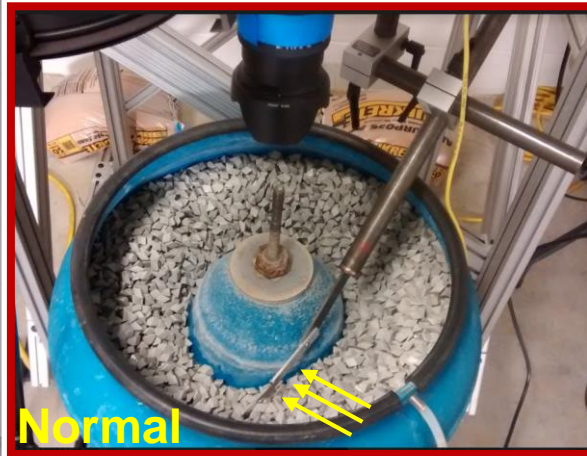
## Main Source of error:

- 2D representation of a complex 3D flow

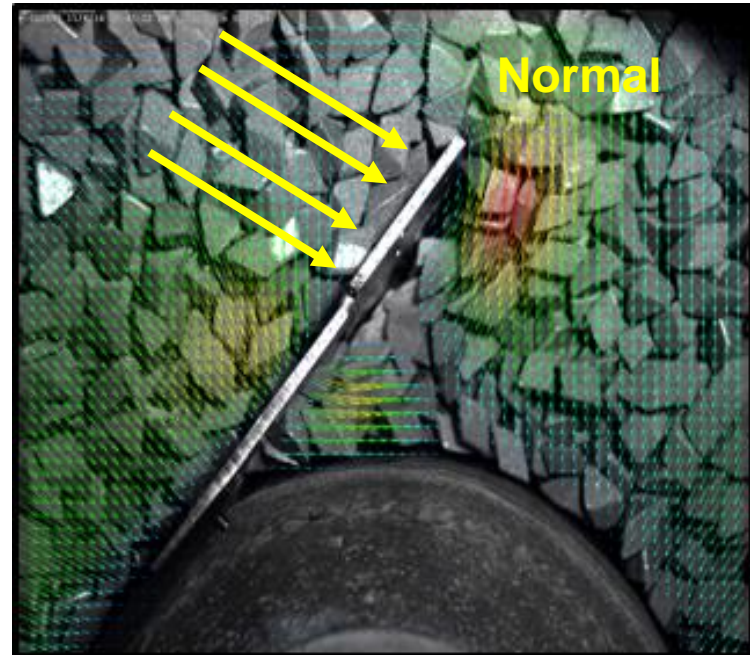
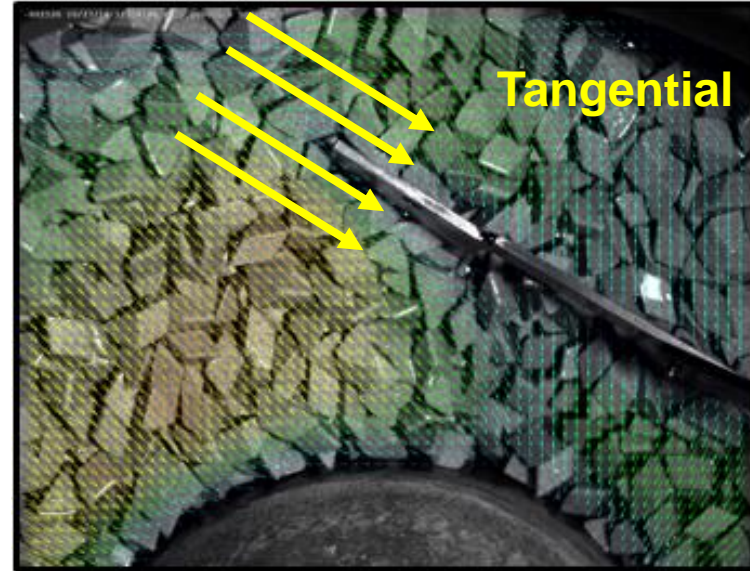
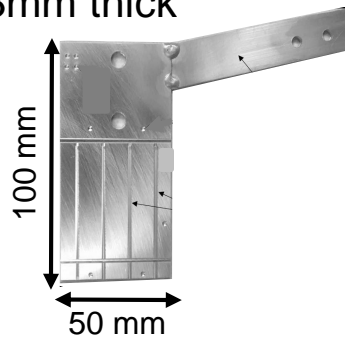
## Sensitivity Analysis:

- Density: 1000 kg/m<sup>3</sup> → 2500 kg/m<sup>3</sup>
- Viscosity: 0.1 → 50 Pa.s
- # elements: 900 → 1.4x10<sup>6</sup> 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



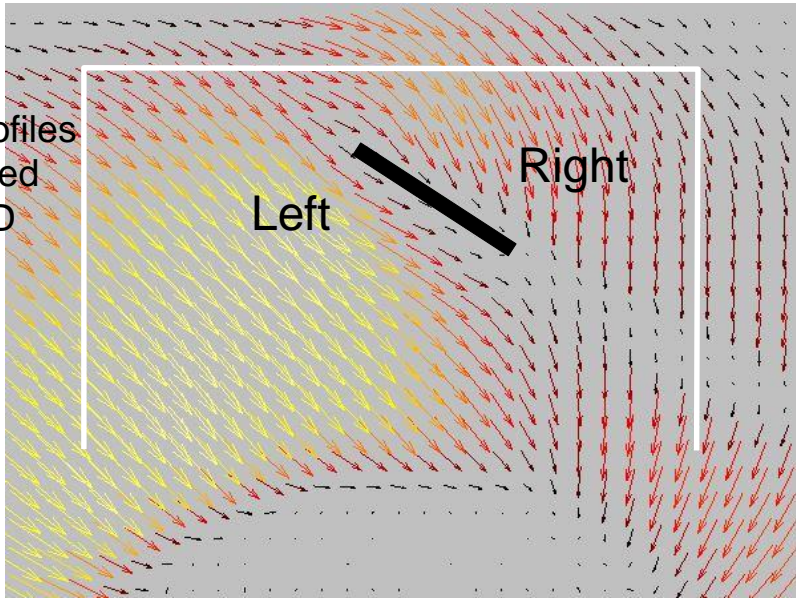
MRRs  
 Surface Alteration



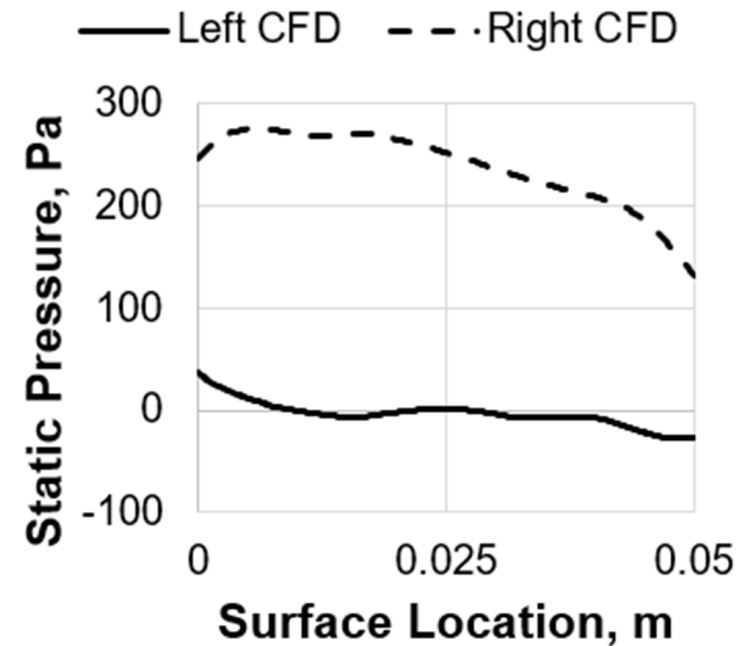
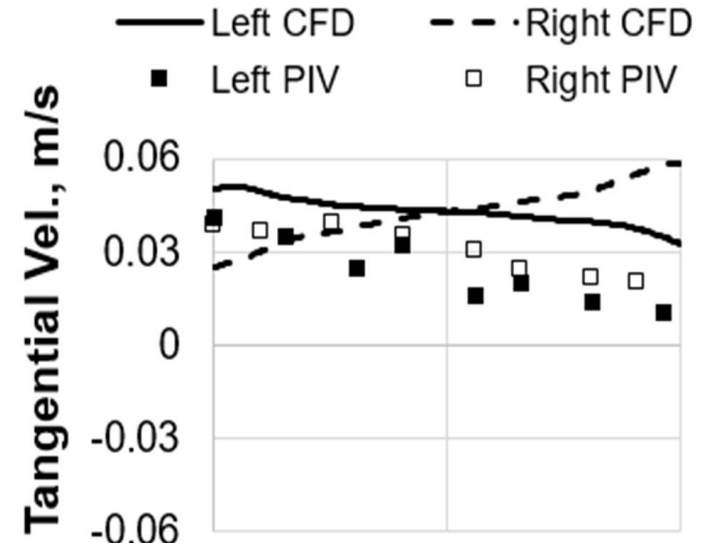
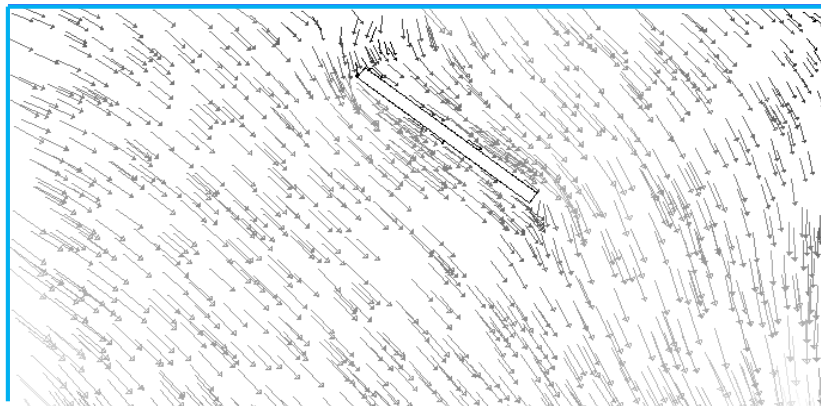
# Flow tangential to workpiece

**Tangential Flow –PIV measured Flow**

PIV profiles extracted for CFD



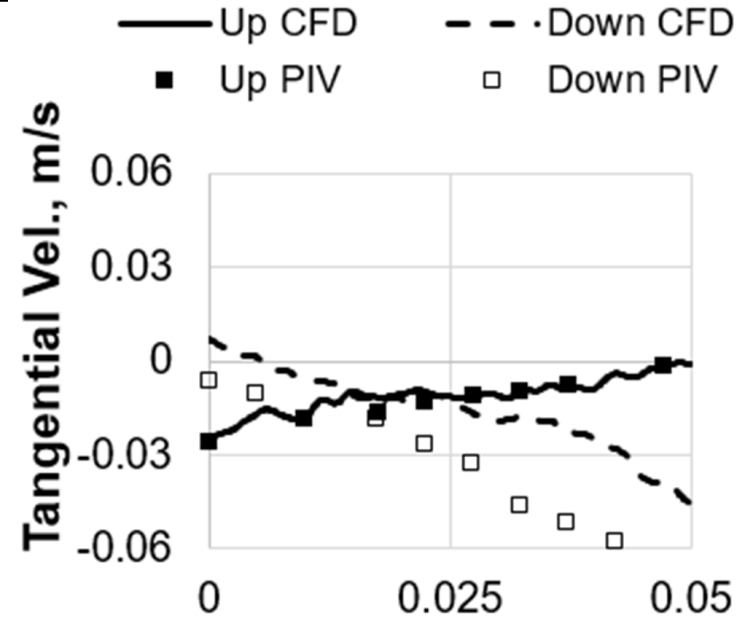
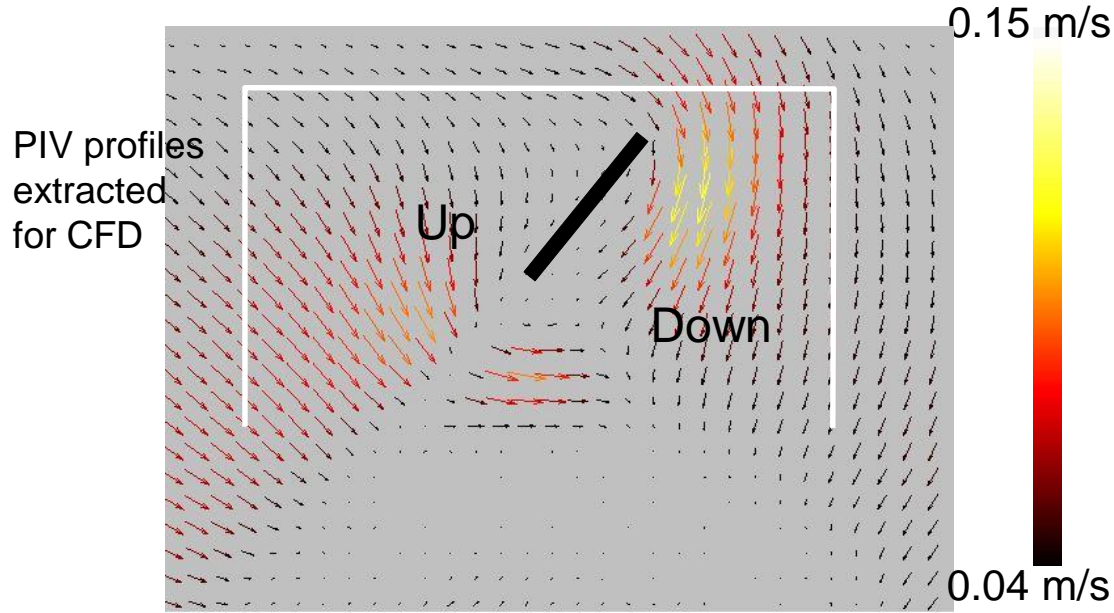
**Tangential Flow –CFD predicted Flow**



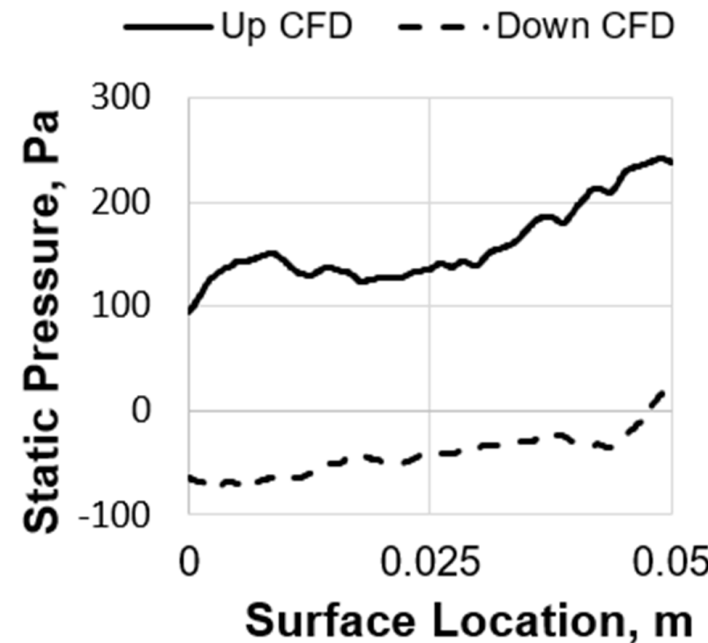
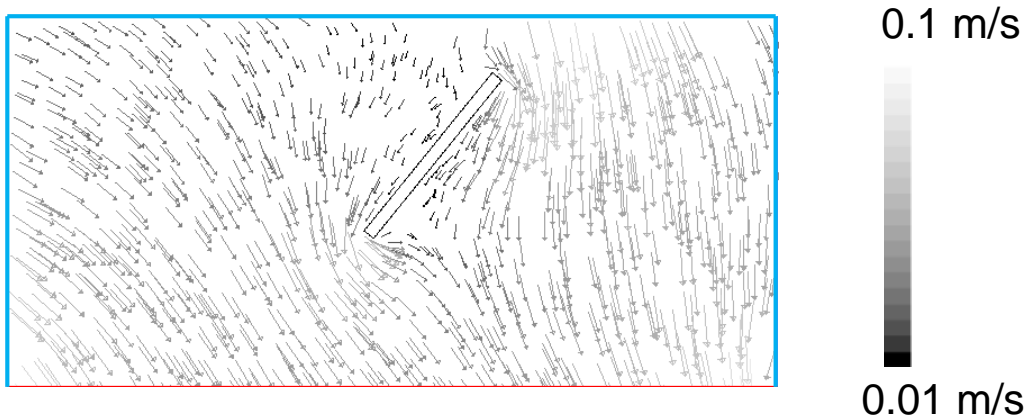


# Flow normal to workpiece

## Tangential Flow –PIV measured Flow

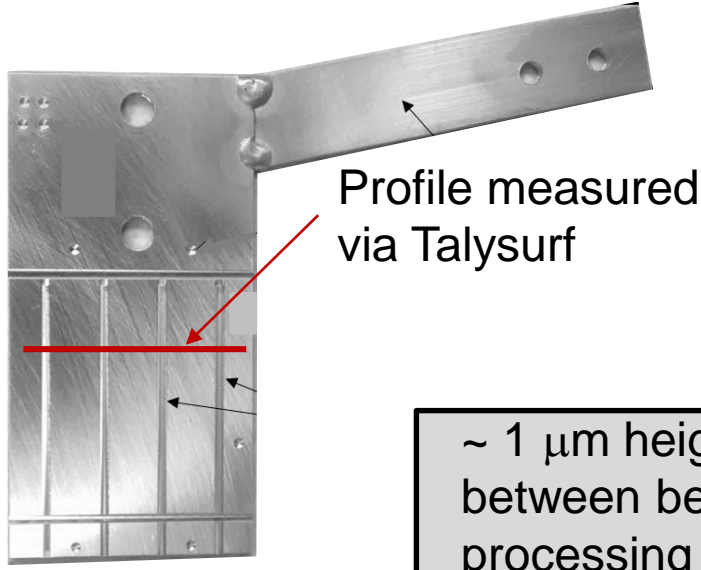


## Tangential Flow –CFD predicted Flow



# Quantification of the Workpiece

Material Removal



## Material removal rate:

- Four slots milled
  - 2 mm wide
  - 100  $\mu\text{m}$  deep
- Base of slot protected via epoxy
- Profile measured pre, and post

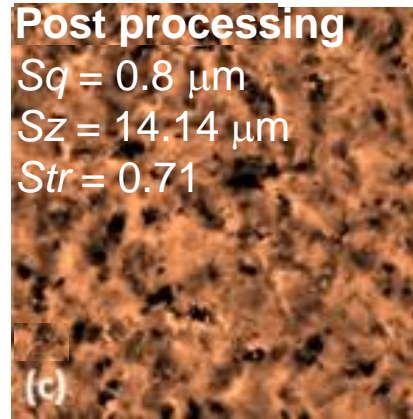
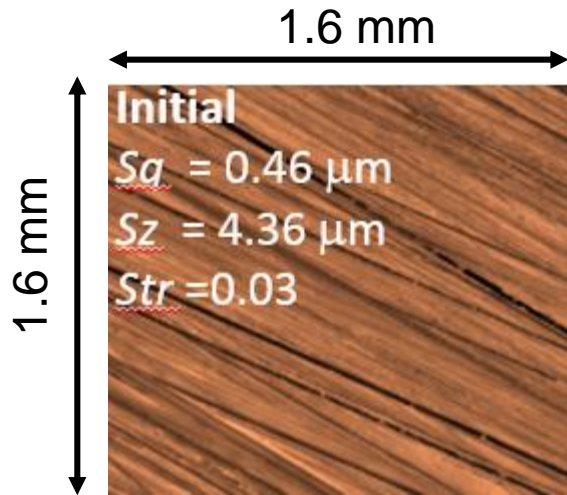


~ 1  $\mu\text{m}$  height difference between before and after processing



- Low MR
- Surface modification via deformation

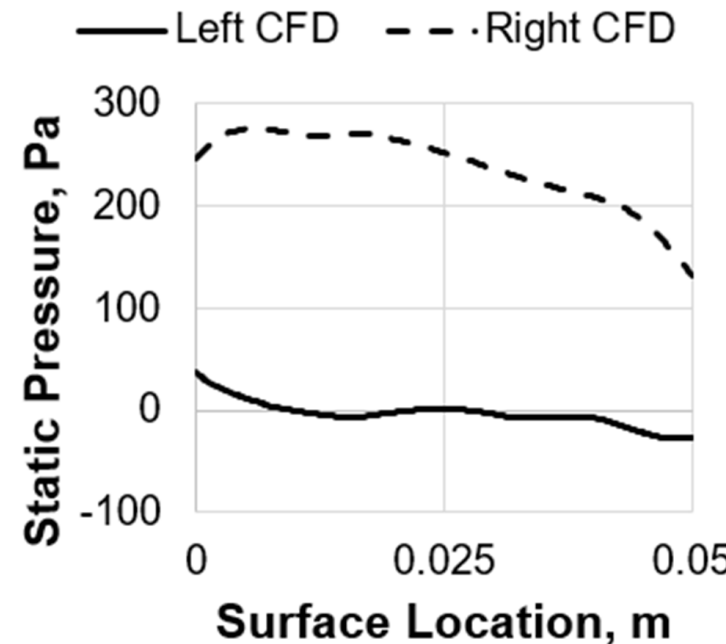
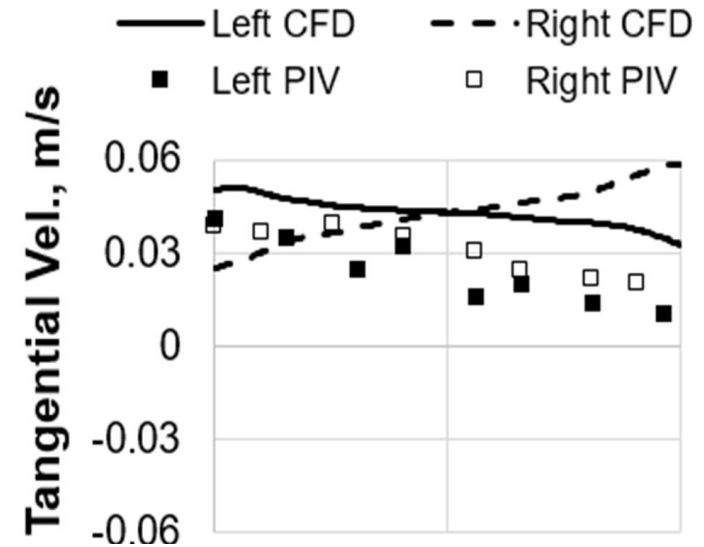
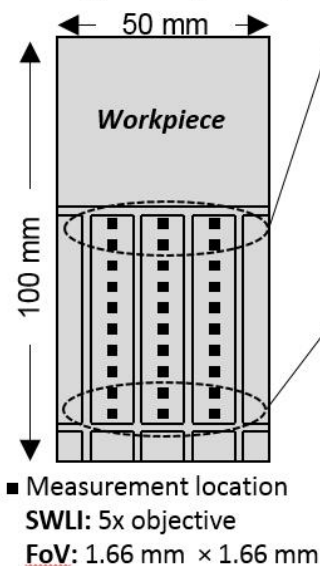
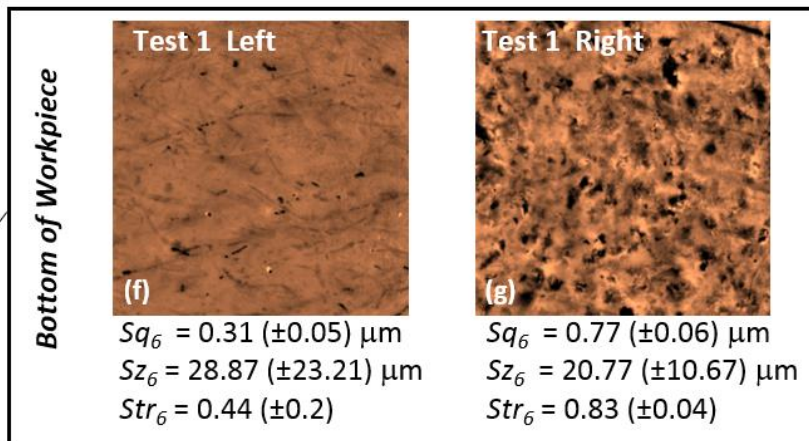
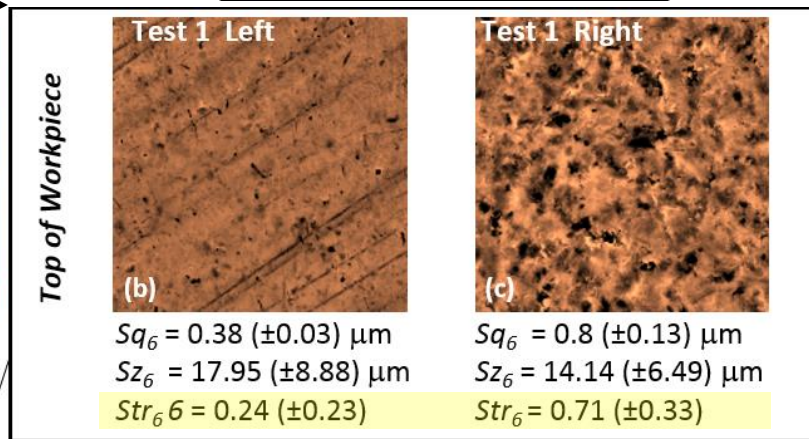
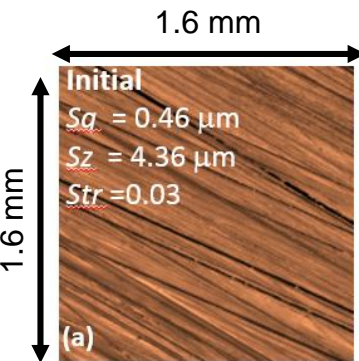
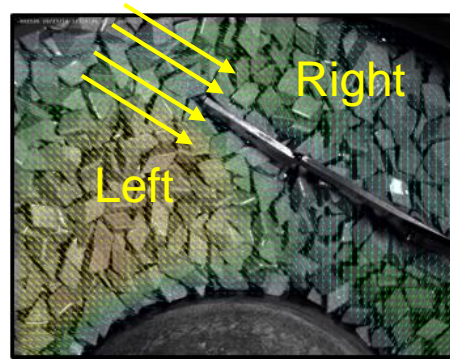
Surface Finish, SWLI 5x



Texture aspect ratio, **Str**

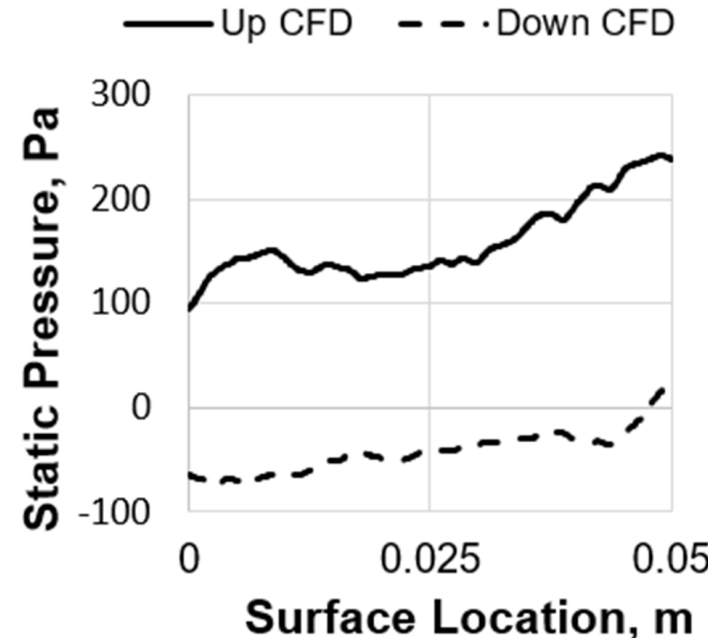
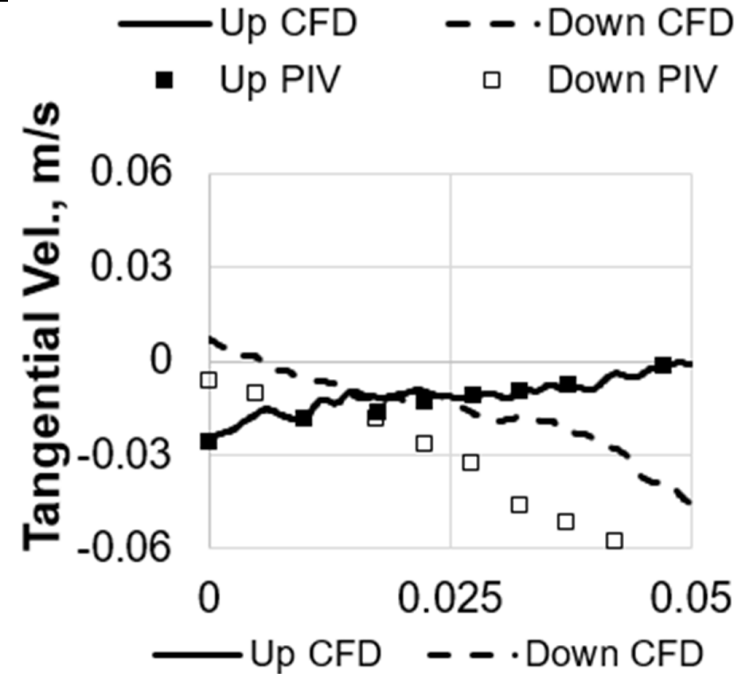
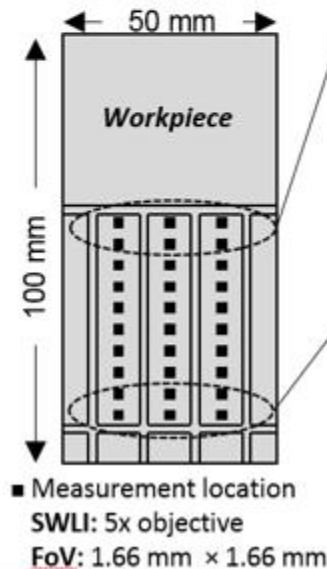
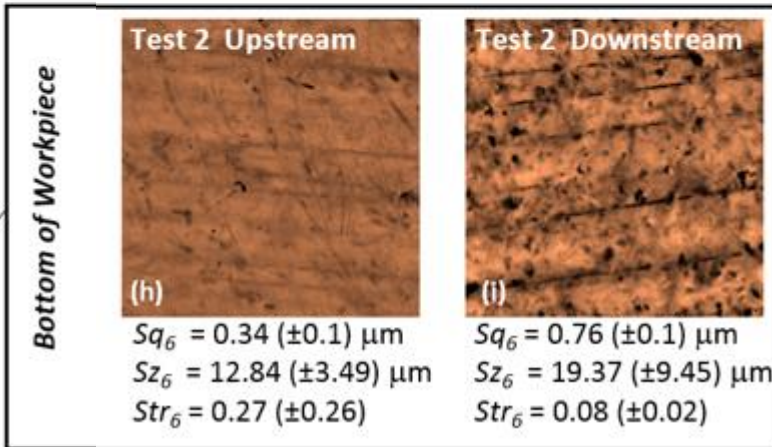
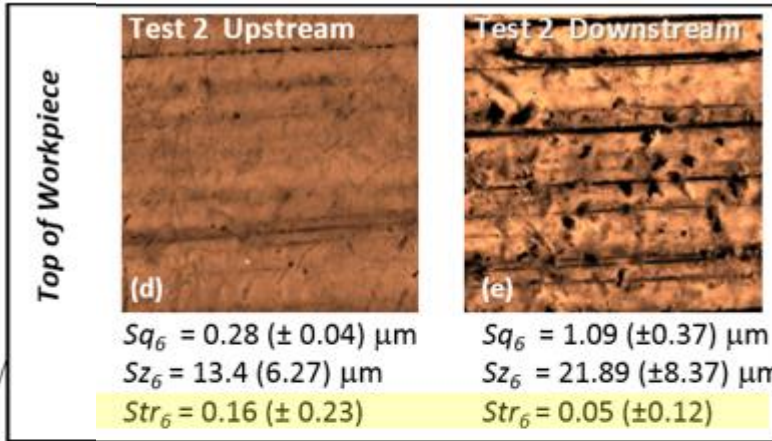
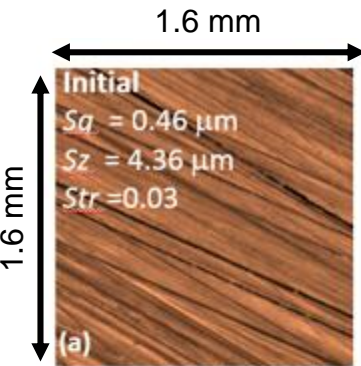
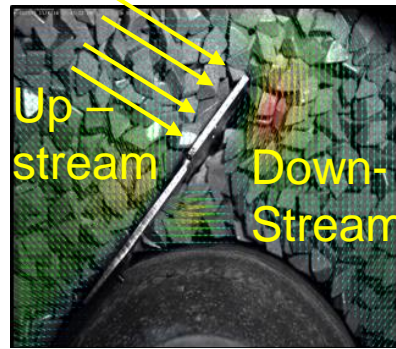
- $Str = 0$  Anisotropic surface
- $Str = 1$  Isotropic surface

# Tangential Flow – post processing

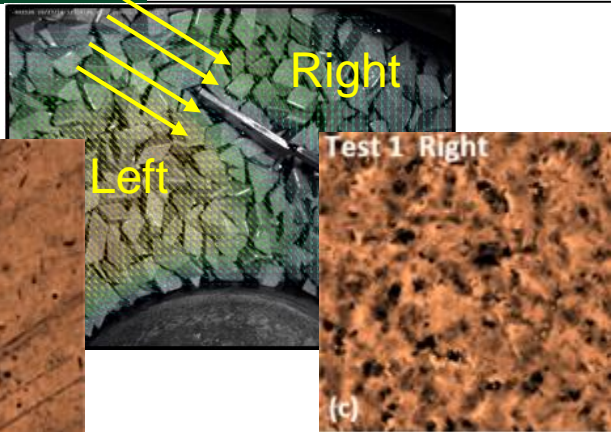




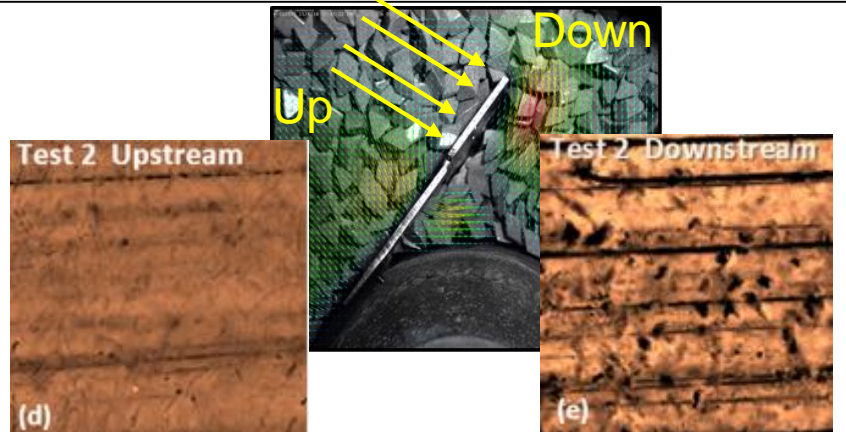
# Normal flow - post processing



# Comparing the results



Low pressure      High pressure  
Comparable velocities



High pressure      Low pressure  
Lower ← Velocity → higher



**Process vibrations should not be neglected!**

## 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 NSF's IRD program



- 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
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