High-Fidelity Single Particle Property Measurements: Building Blocks for Particle Flow Modeling Validation

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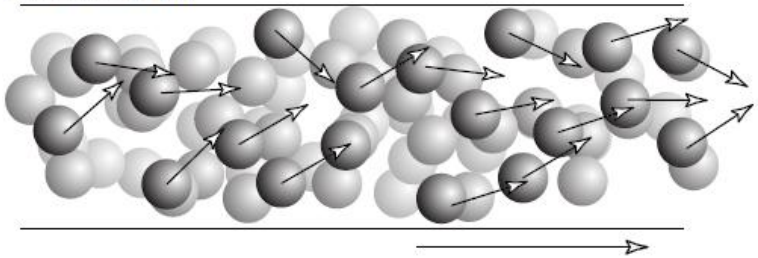
May 22-24, 2012

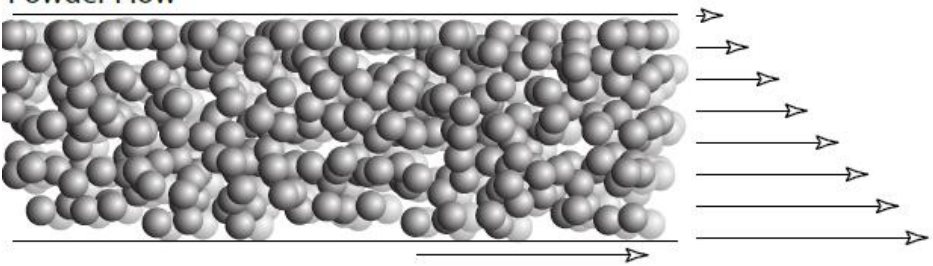
Particle Flow & Tribology Laboratory

Core competencies

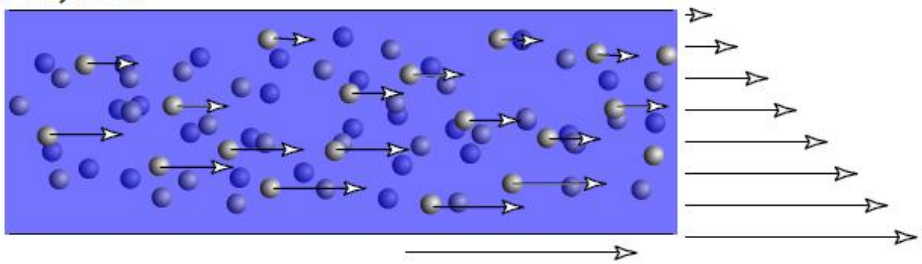
Granular Flow



Powder Flow



Slurry Flow

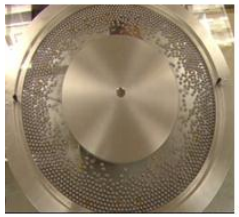


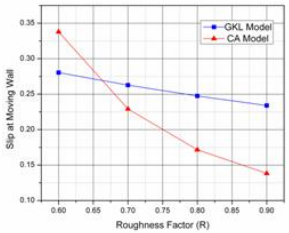
What is tribology?

Tribology is the study of interacting surfaces and the resulting friction, wear, and lubrication

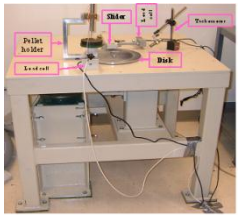
Research strengths

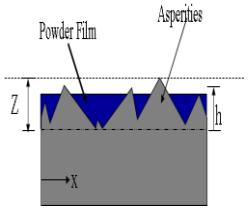
Experiments | Simulations | Predictions

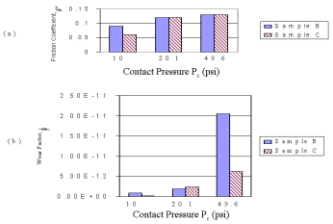




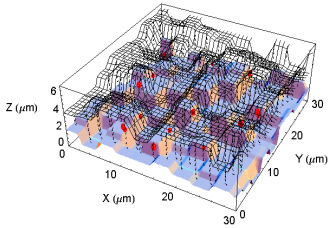
Granular flows

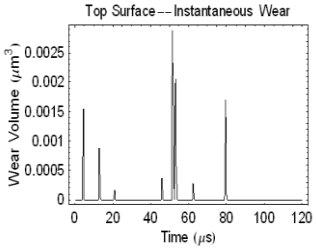






Powder lubrication





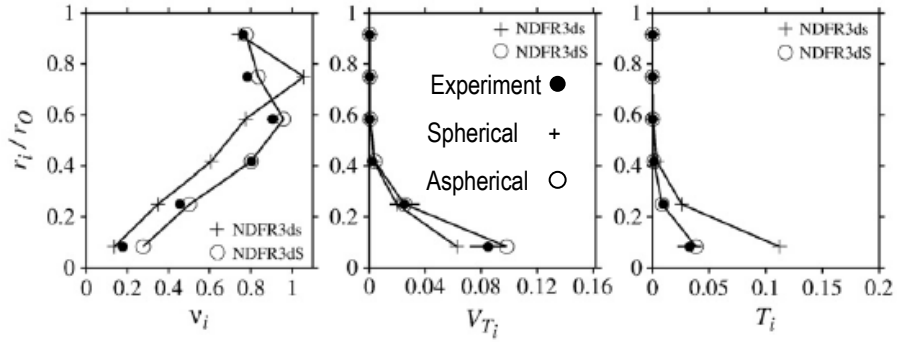
Slurry

Outline

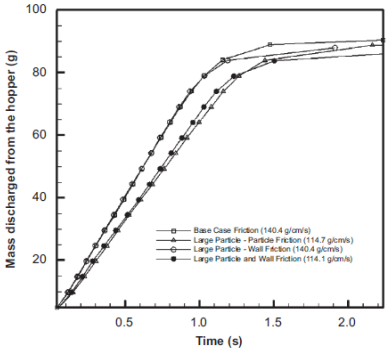
- Motivation
- Objective
- Coefficient of Restitution Testing
- Coefficient of Friction and Wear Testing
- Conclusions

Motivation

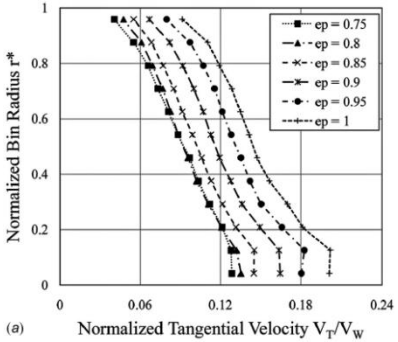
Accuracy of Models Depends on Accuracy of Single Particle Parameters



McCarthy et al. (2010)



Anand et al. (2008)



Marinack and Higgs (2011)

Objective

- **Coordinate single particle interaction measurements to granular flows.**
  - Perform and evaluate detailed experimental studies which examine the coefficient of friction, particle *wear*, and surface metrology of individual granules undergoing sliding against a rotating disk.

Coefficient of Restitution Testing

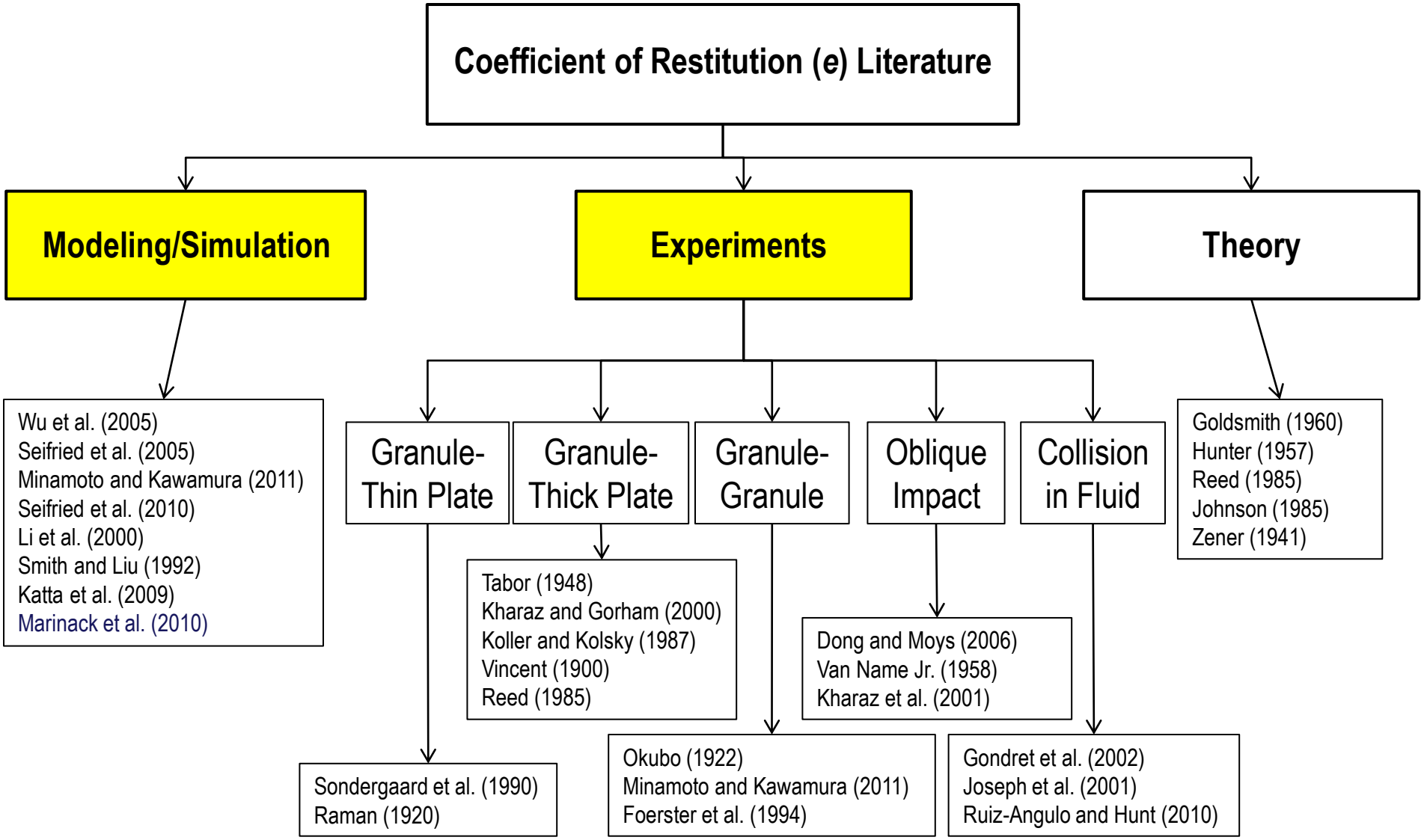
Coefficient of Restitution, e

- **Measure of the elasticity of normal collision between two objects**
  - e = 0: Perfectly inelastic (plastic), KE is completely dissipated
  - e = 1: Perfectly elastic, KE is completely conserved

- **Ratio of post-collision relative velocity to pre-collision relative velocity between the colliding materials**

$$e = \frac{-(v_{1f} - v_{2f})}{v_{1i} - v_{2i}} = \frac{v_{2f} - v_{1f}}{v_{1i} - v_{2i}}$$

Background


Coefficient of Restitution (e) Literature
Modeling/Simulation
Experiments
Theory
Wu et al. (2005)
Seifried et al. (2005)
Minamoto and Kawamura (2011)
Seifried et al. (2010)
Li et al. (2000)
Smith and Liu (1992)
Katta et al. (2009)
Marinack et al. (2010)
Granule-Thin Plate
Granule-Thick Plate
Granule-Granule
Oblique Impact
Collision in Fluid
Goldsmith (1960)
Hunter (1957)
Reed (1985)
Johnson (1985)
Zener (1941)
Tabor (1948)
Kharaz and Gorham (2000)
Koller and Kolsky (1987)
Vincent (1900)
Reed (1985)
Dong and Moys (2006)
Van Name Jr. (1958)
Kharaz et al. (2001)
Sondergaard et al. (1990)
Raman (1920)
Okubo (1922)
Minamoto and Kawamura (2011)
Foerster et al. (1994)
Gondret et al. (2002)
Joseph et al. (2001)
Ruiz-Angulo and Hunt (2010)

Background

Coefficient of Restitution (*e*) Literature

Modeling/Simulation

Wu et al. (2005)
Seifried et al. (2005)
Minamoto and Kawamura (2011)
Seifried et al. (2010)
Li et al. (2000)
Smith and Liu (1992)
Katta et al. (2009)
Marinack et al. (2010)

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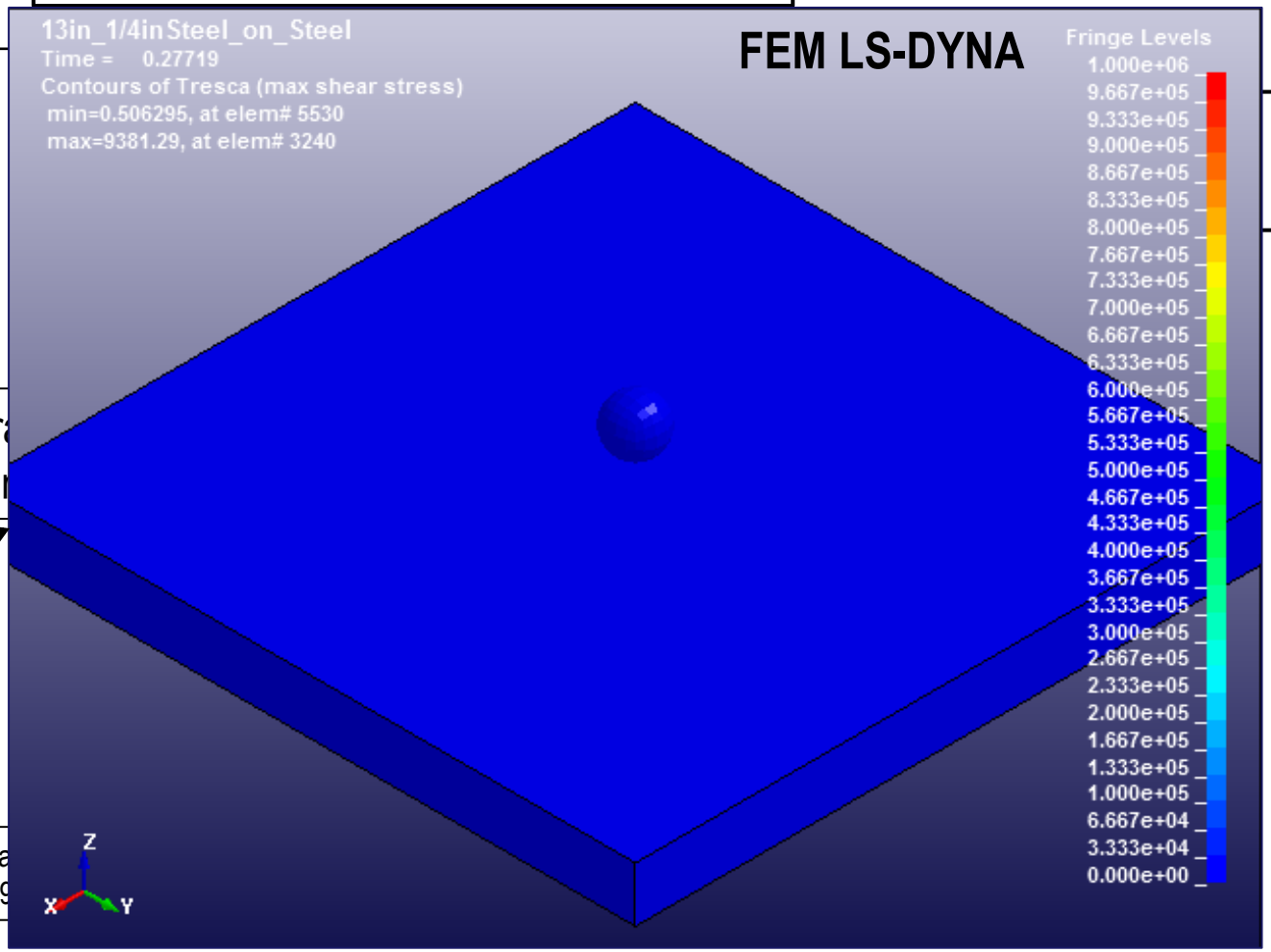
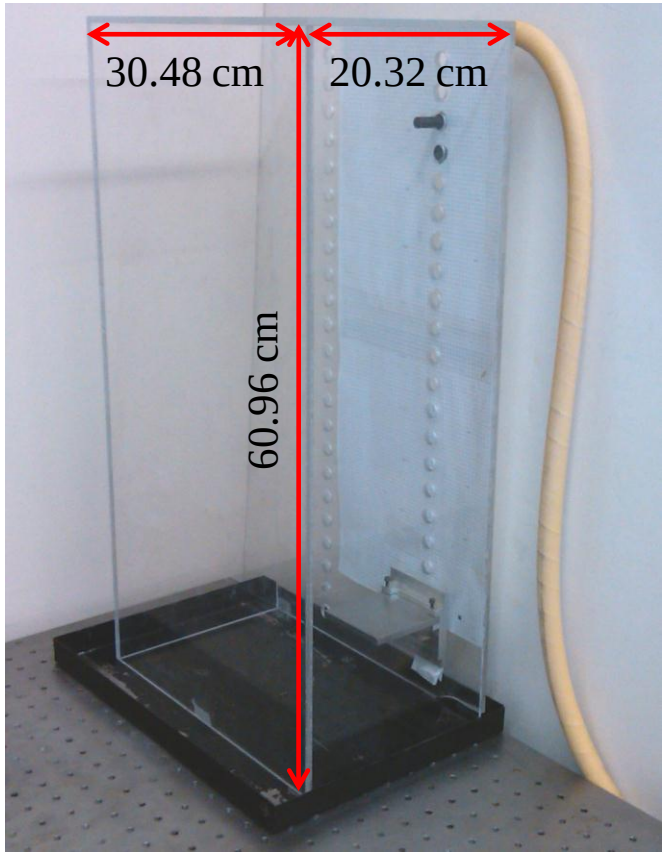
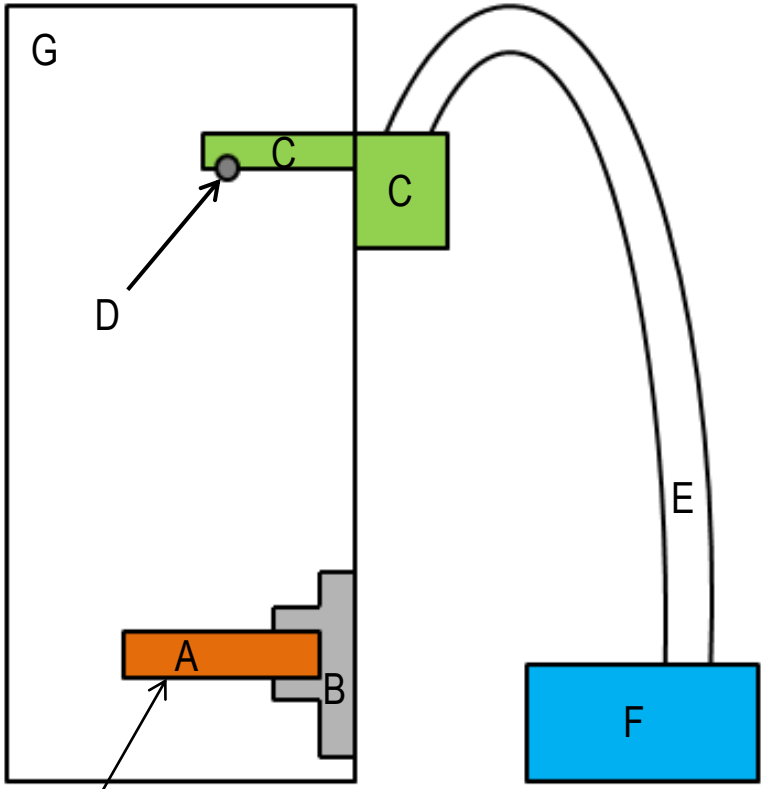
Raman (19



Experimental Setup: COR Testing

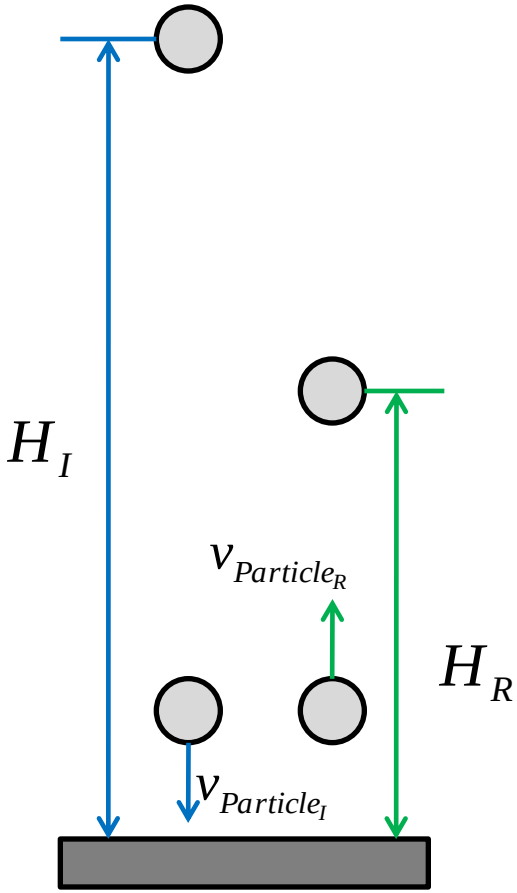


A: Plate:
B: Plate holder
C: Particle holder
D: Particle
E: Air hose
F: Air pump
G: Plexiglas casing



7.62cm x 7.62 cm x 0.635 cm
(3 in. x 3 in. x 0.25 in.)

Calculating Particle-Wall Collision e



$$e = \frac{\cancelto{0}{v_{Plate_R}} - v_{Particle_R}}{v_{Particle_I} - \cancelto{0}{v_{Plate_I}}}$$

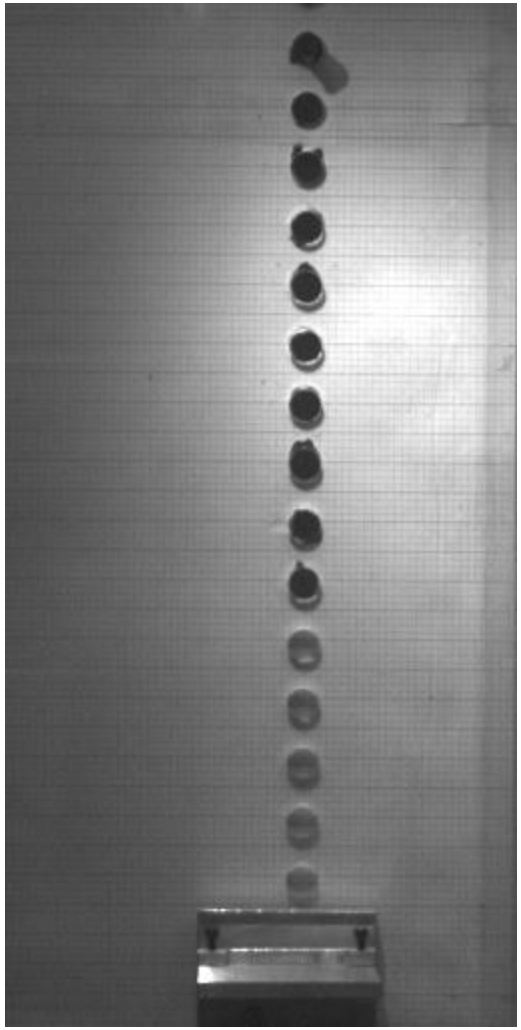
$$e = \frac{-v_{Particle_R}}{v_{Particle_I}}$$

$$v_{Particle_I} = -\sqrt{2gH_I}$$

$$v_{Particle_R} = \sqrt{2gH_R}$$

$$e = \frac{-\sqrt{2gH_R}}{-\sqrt{2gH_I}} = \sqrt{\frac{2gH_R}{2gH_I}} = \boxed{e = \sqrt{\frac{H_R}{H_I}}}$$

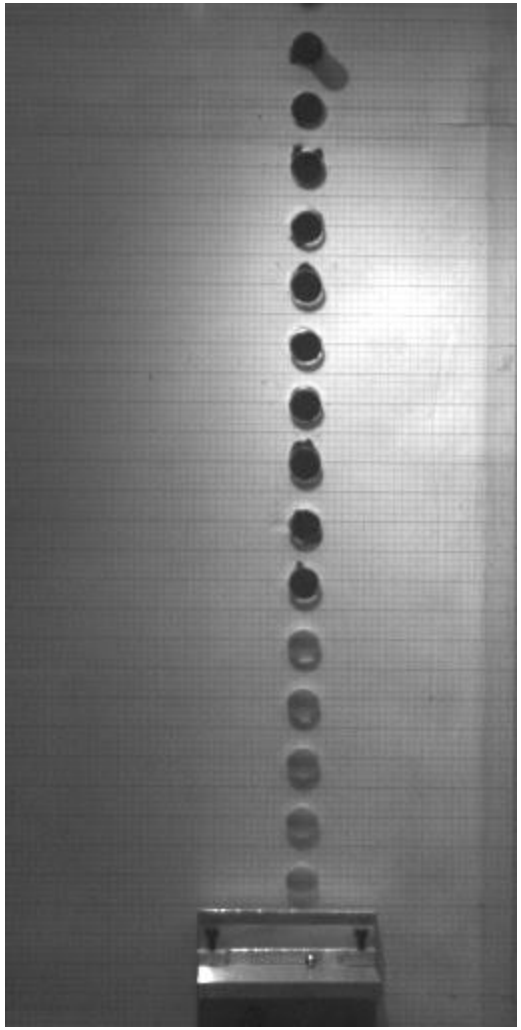
Experimental Processing



Frame 0300

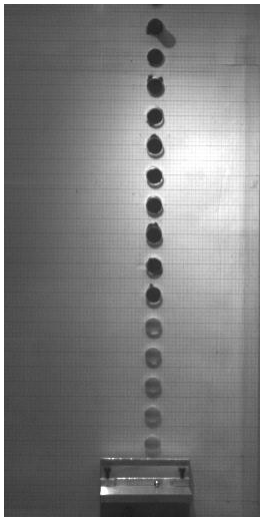
Impact
Image

Experimental Processing



Frame 1099

Impact Image

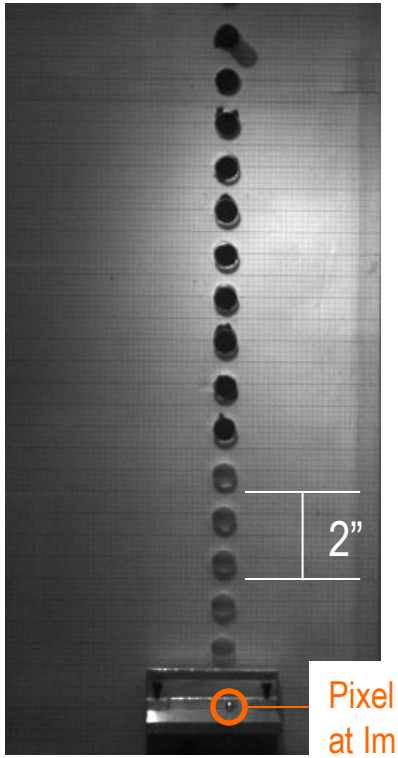


Frame 1099

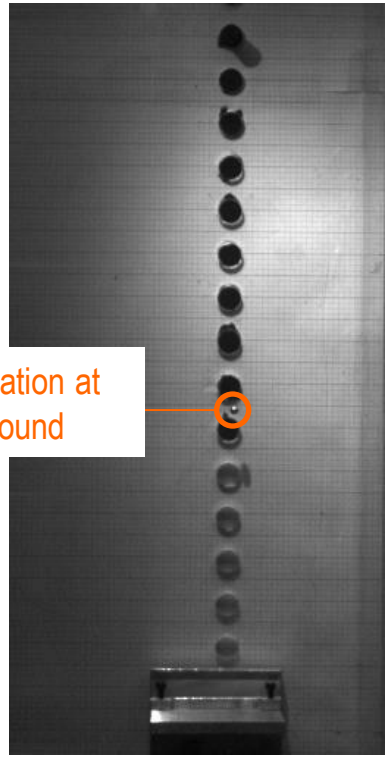
Rebound Image

Experimental Processing

Impact Image



Rebound Image



$$H_R = \left(pixel_{rebound} - pixel_{impact}\right)\frac{inch}{pixel}$$

$$e = \sqrt{\frac{H_R}{H_I}}$$

- **6 Different Heights (Impact Velocities)**
  - 22.86 cm – 48.26 cm (9 in. – 19 in.)
  - 2.14 m/s - 3.10 m/s

$$v_{Particle_I} = -\sqrt{2gH_I}$$

- **6 Trials at each Height**

Experimental Results: Size Study

- 0.476 cm (3/16 in.) Diameter Particles
- 0.635 cm (1/4 in.) Diameter Particles
- Size Comparison

Experimental Results: Size Study

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- 0.635 cm (1/4 in.) Diameter Particles
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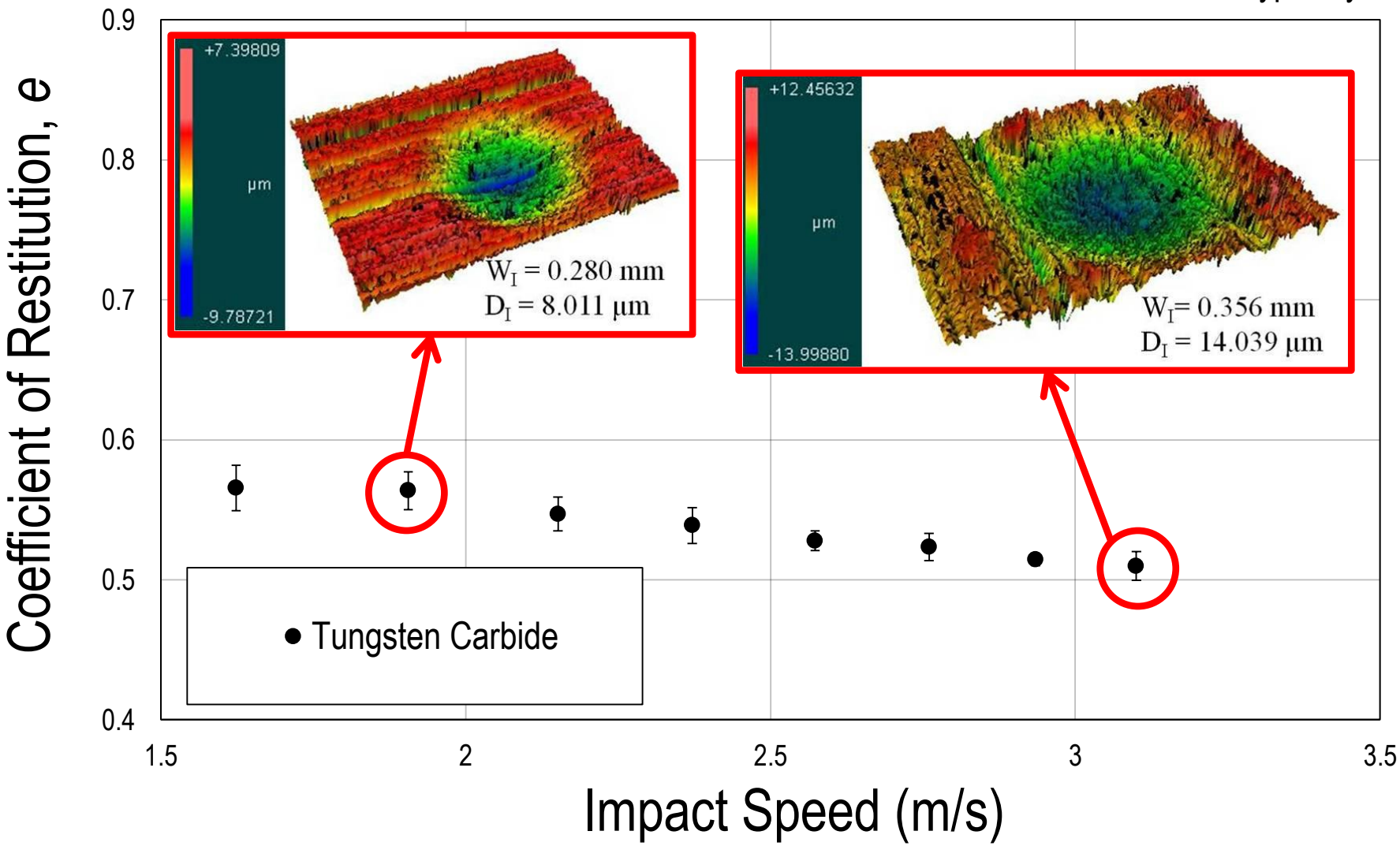
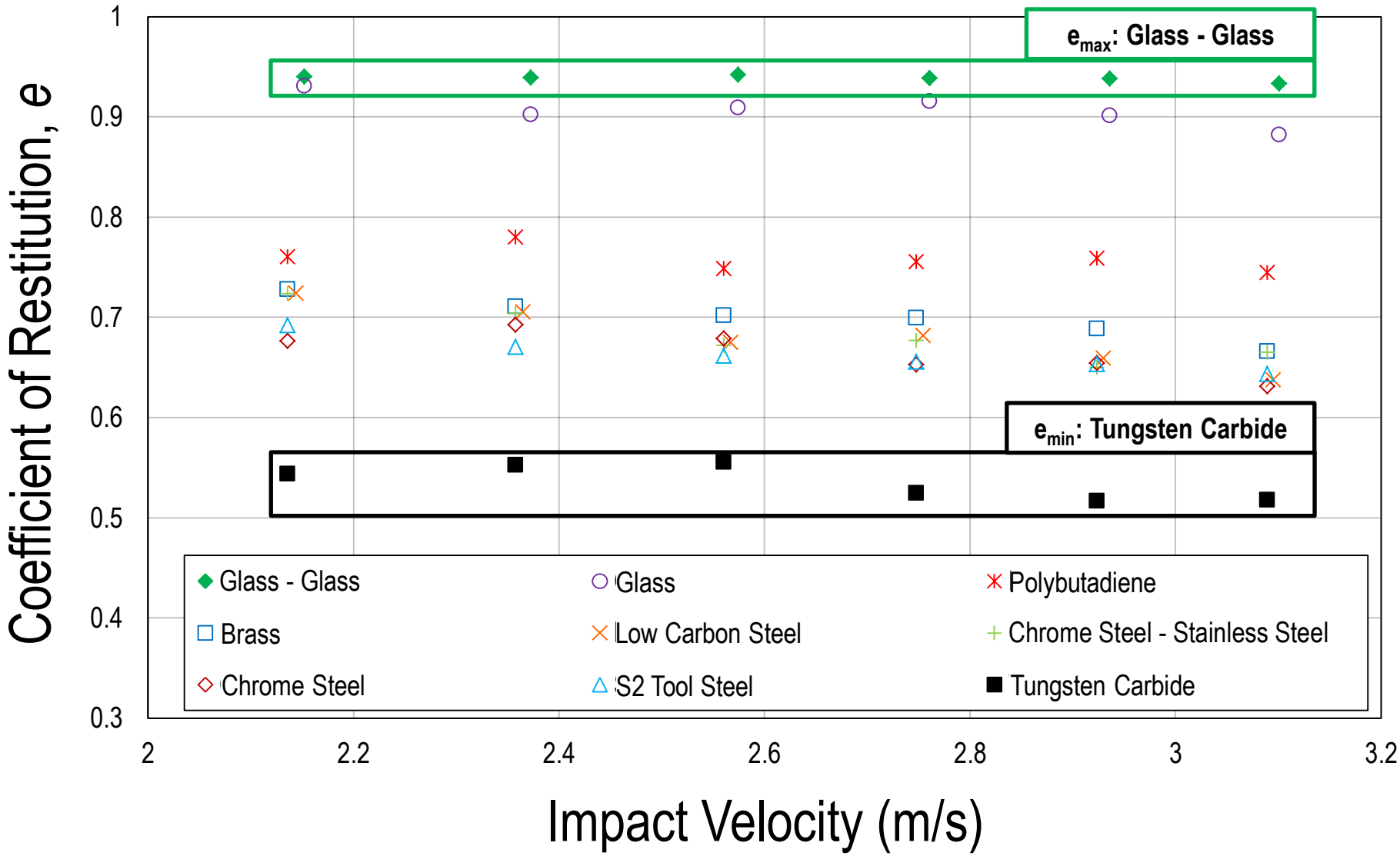
COR: Representative Results

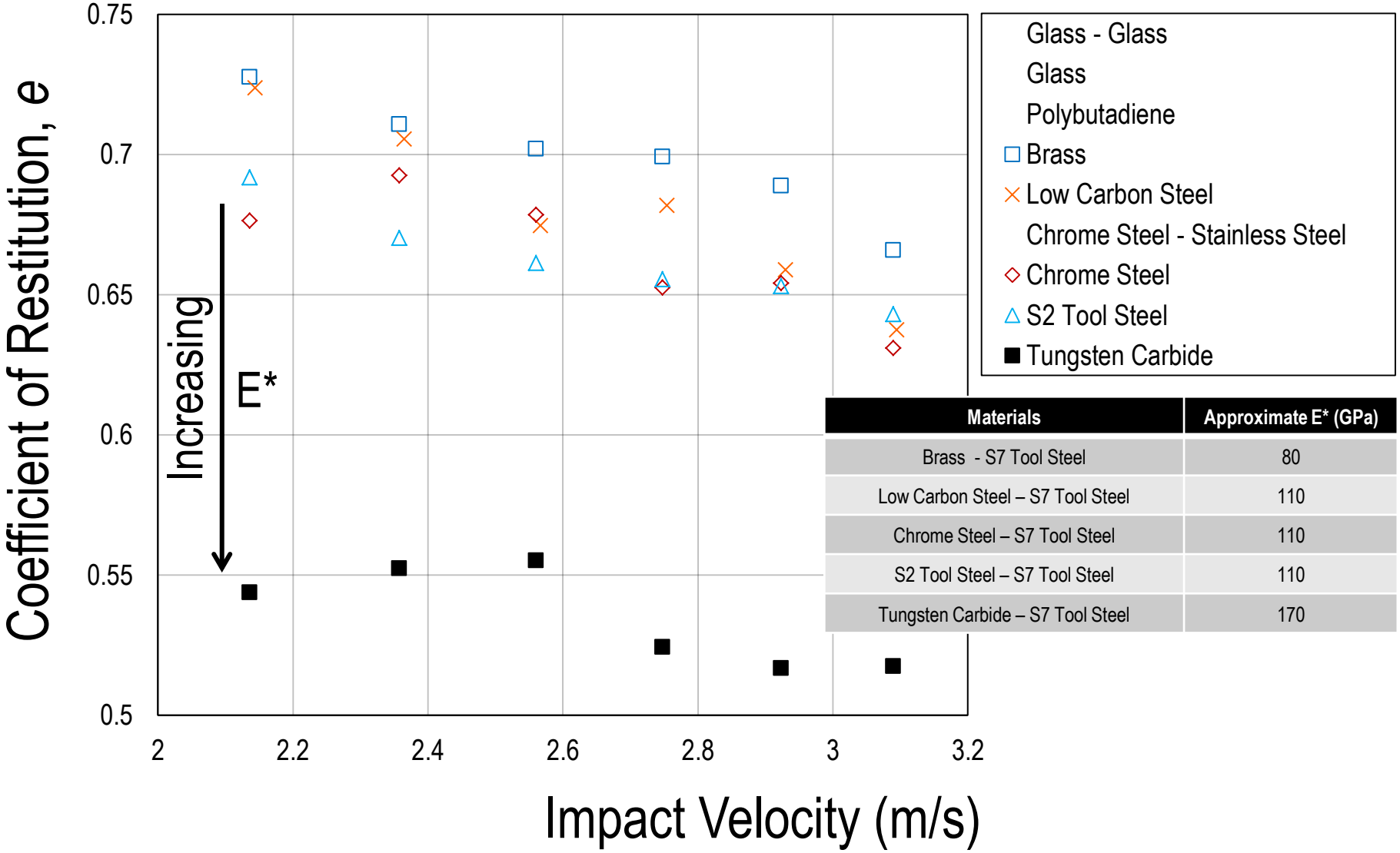
*Plates typically steel



Various Material Combinations



Contact Modulus (E*) Trend

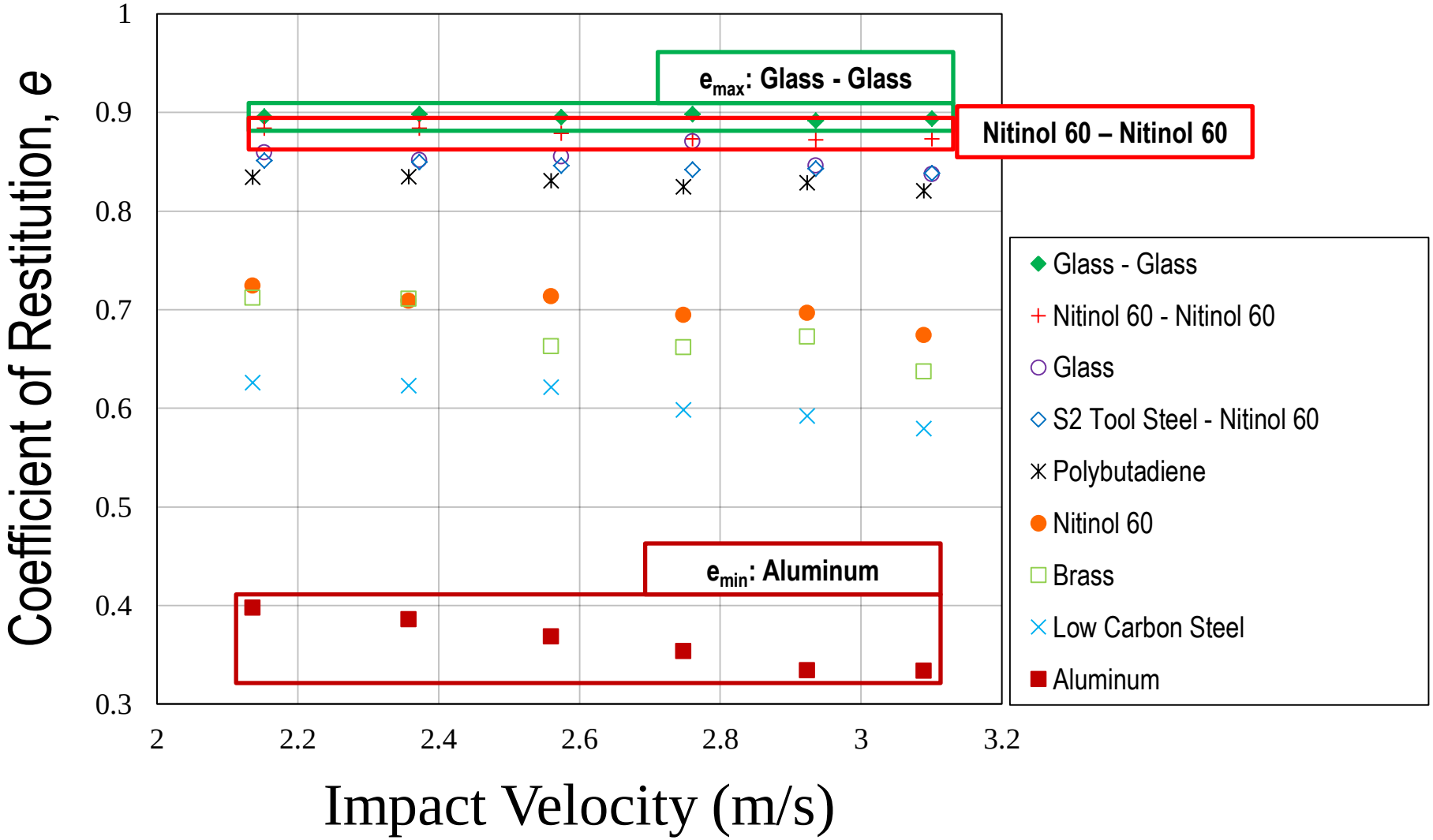


Materials	Approximate E* (GPa)
Brass - S7 Tool Steel	80
Low Carbon Steel – S7 Tool Steel	110
Chrome Steel – S7 Tool Steel	110
S2 Tool Steel – S7 Tool Steel	110
Tungsten Carbide – S7 Tool Steel	170

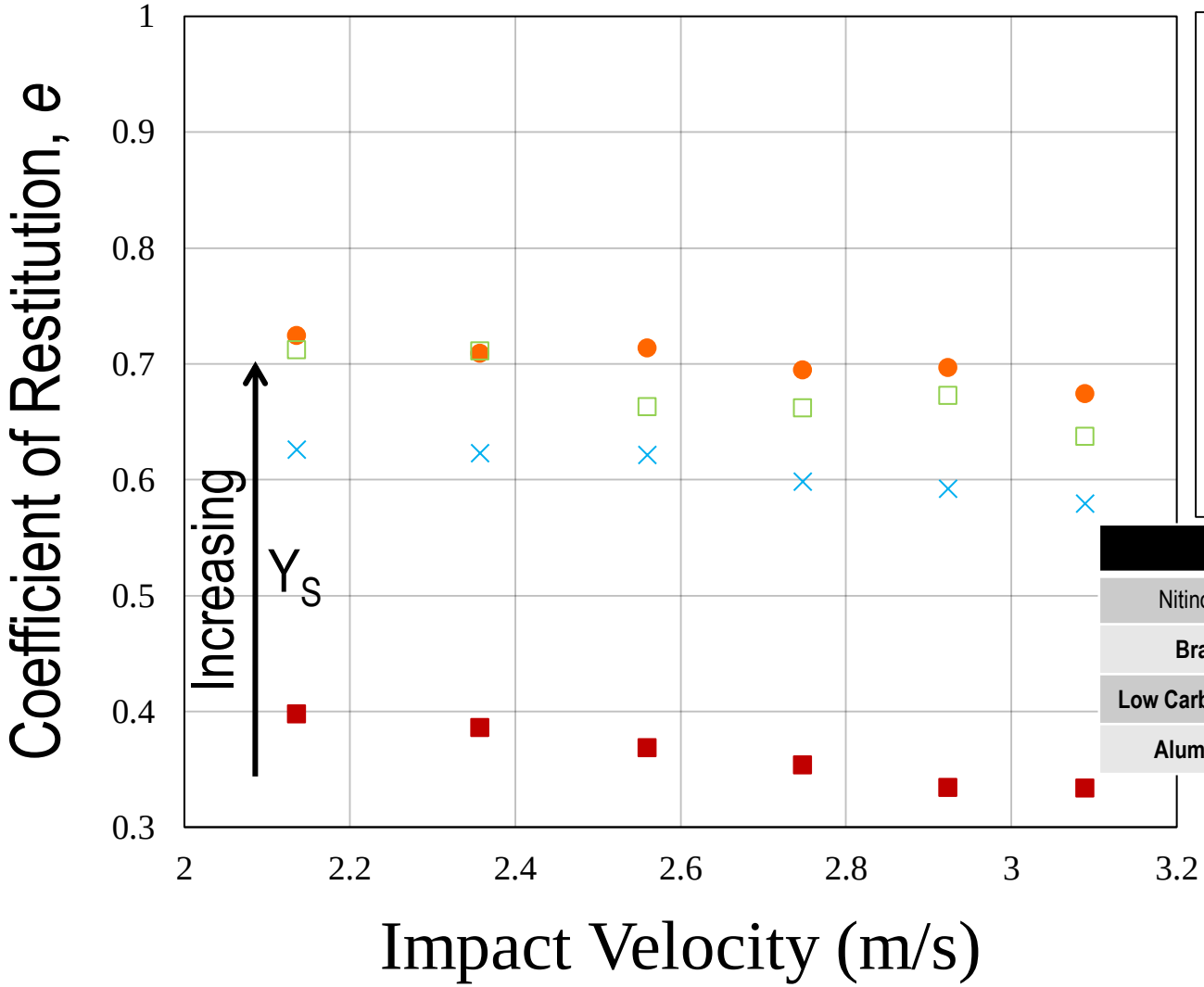
Experimental Results: Size Study

- 0.476 cm (3/16 in.) Diameter Particles
- 0.635 cm (1/4 in.) Diameter Particles
- Size Comparison

Various Material Combinations

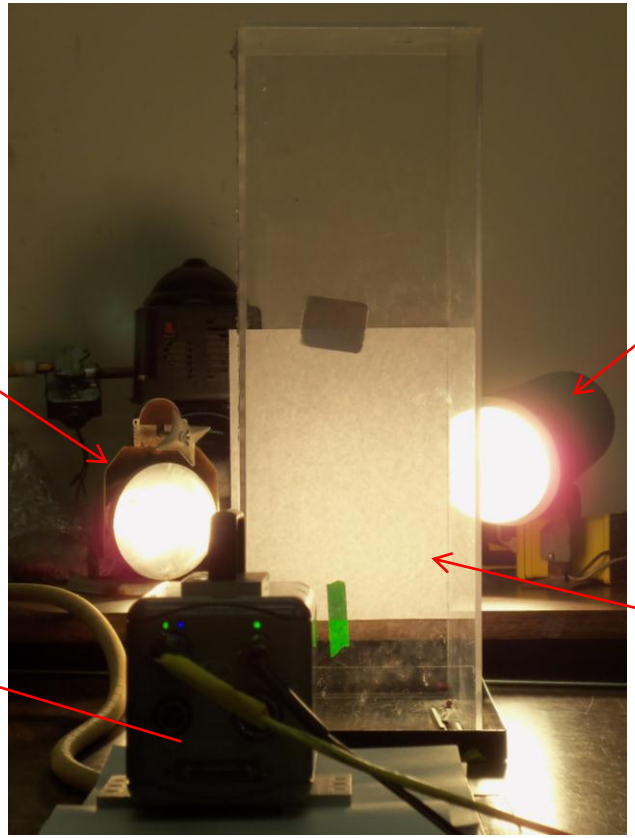


Yield Strength (Y_s) Trend

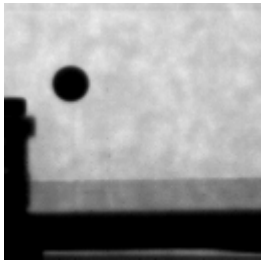


Materials	Approximate Y_S (MPa)
Nitinol 60 – **S7 Tool Steel**	550
Brass – S7 Tool Steel	390
Low Carbon Steel – S7 Tool Steel	300
Aluminum – S7 Tool Steel	100

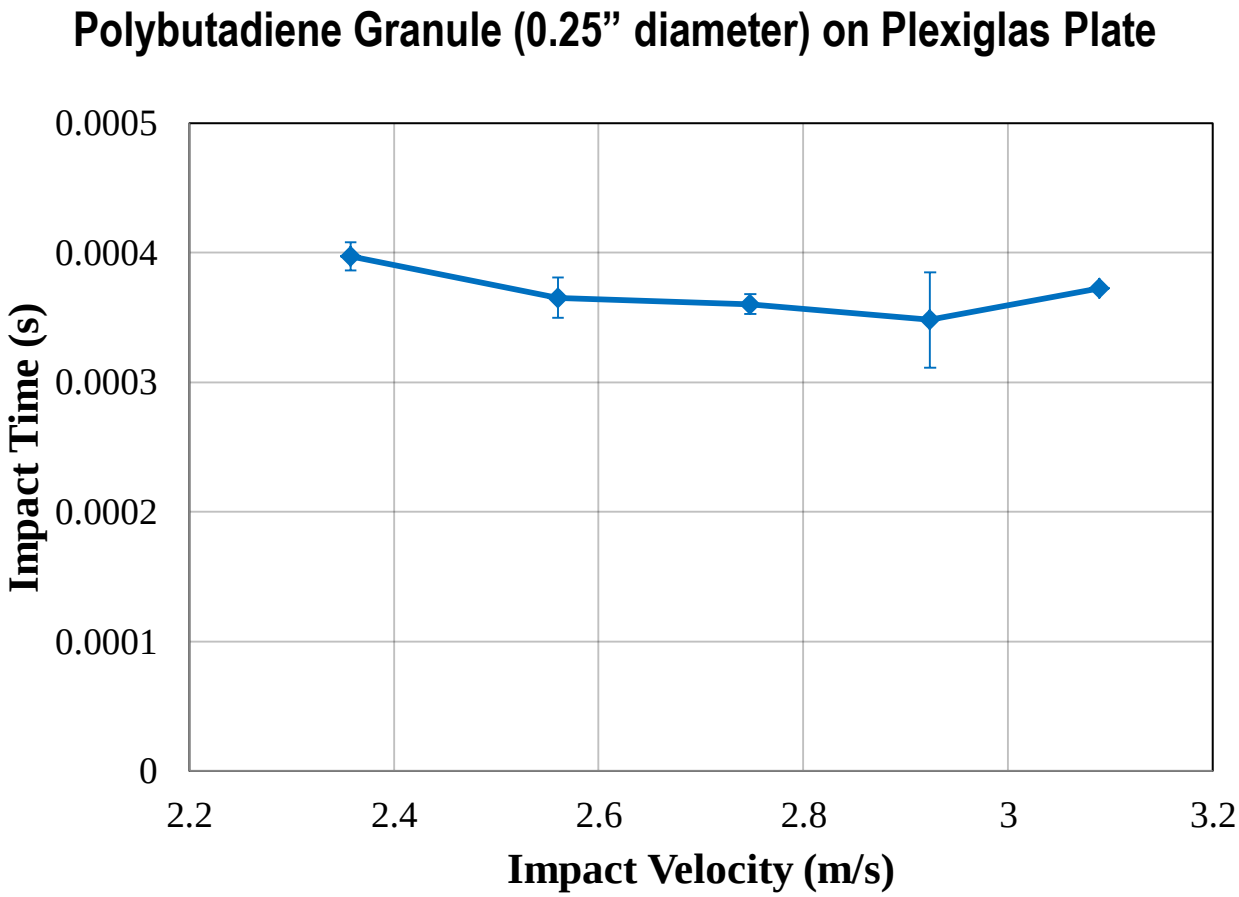
Impact Time: Experimental Setup



Impact Time: Results

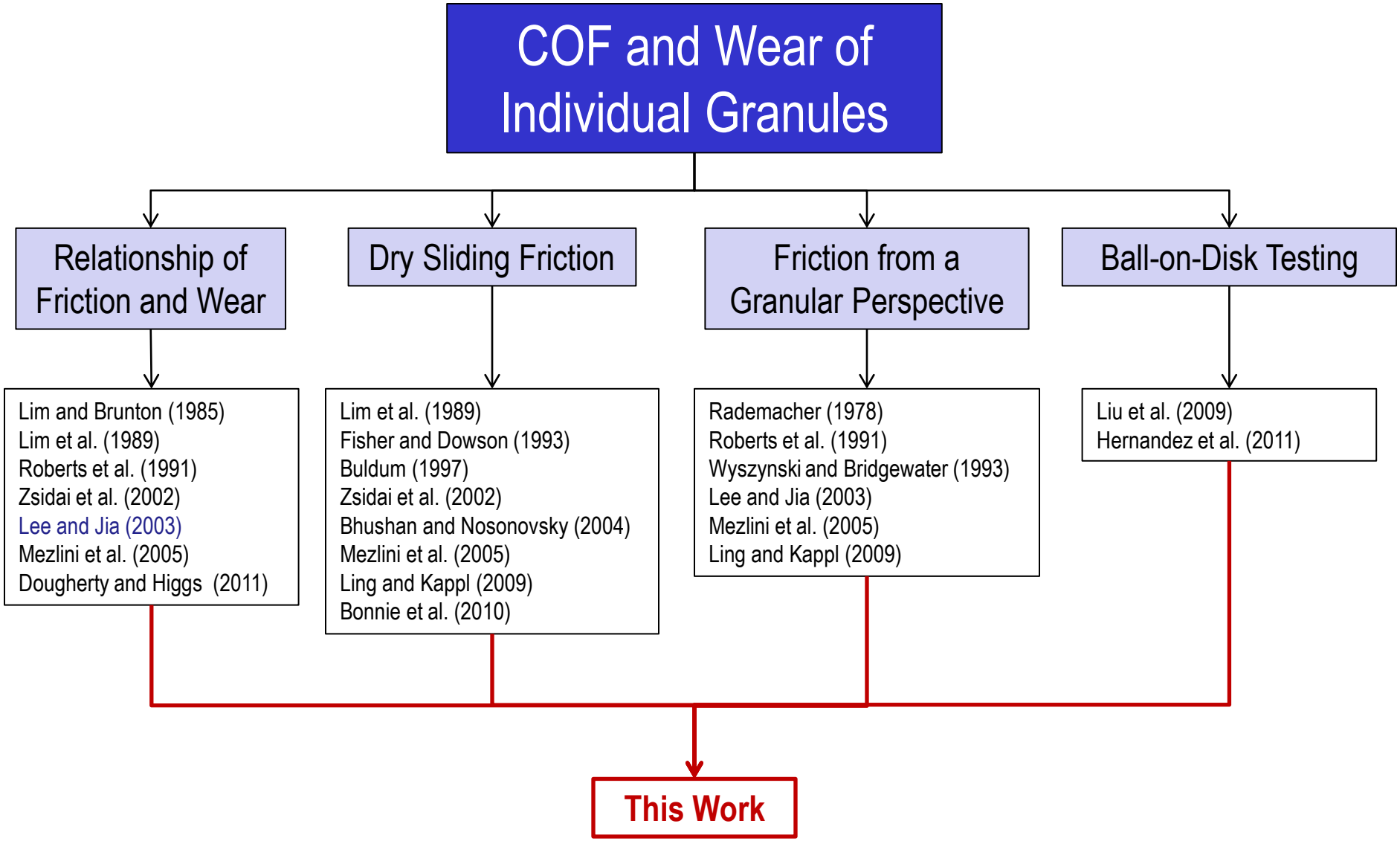


68,000 fps



Single Particle Friction and Wear Testing

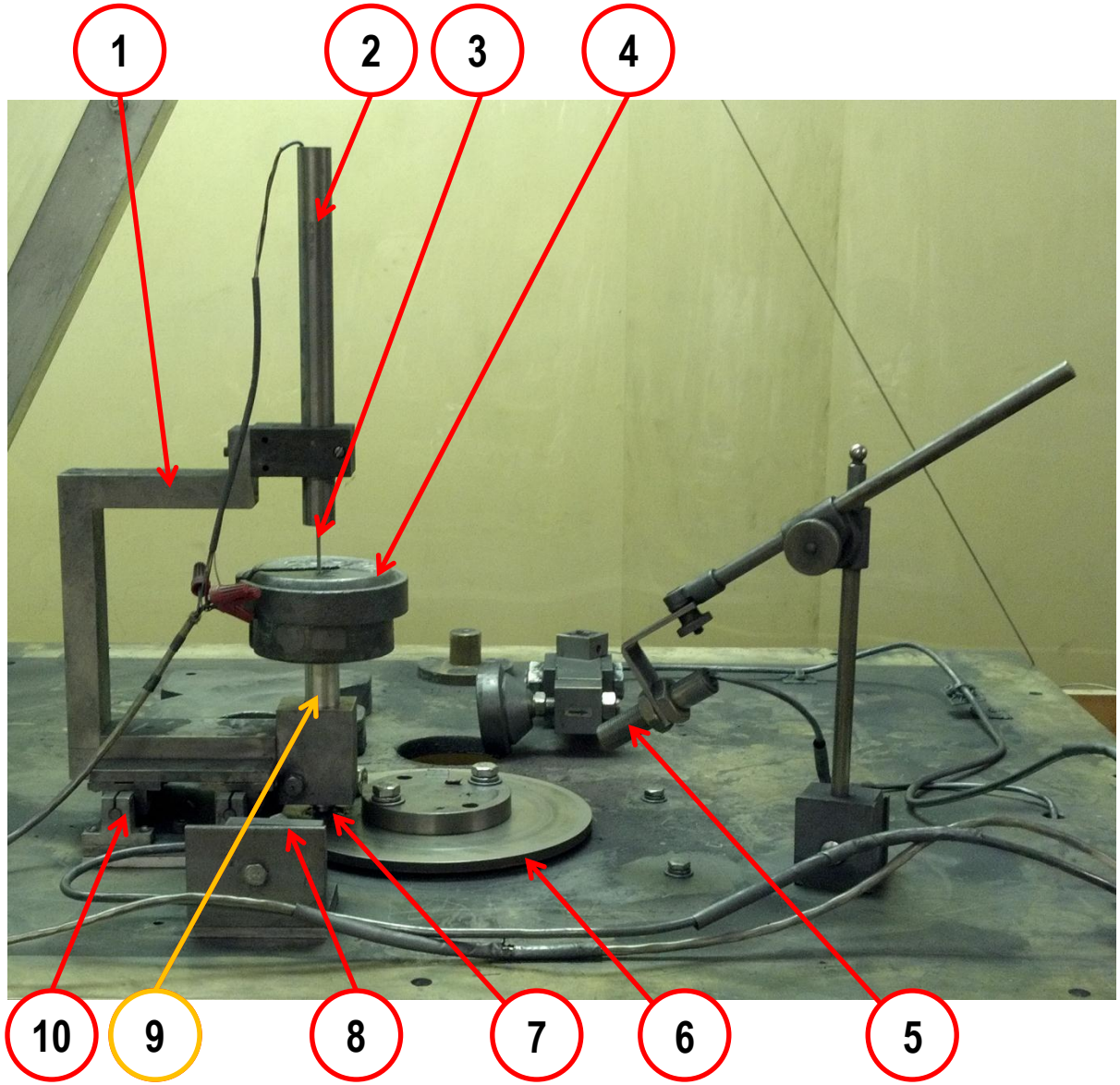
Background


COF and Wear of Individual Granules
Relationship of Friction and Wear
Dry Sliding Friction
Friction from a Granular Perspective
Ball-on-Disk Testing
Lim and Brunton (1985)
Lim et al. (1989)
Roberts et al. (1991)
Zsidai et al. (2002)
Lee and Jia (2003)
Mezlini et al. (2005)
Dougherty and Higgs (2011)
Lim et al. (1989)
Fisher and Dowson (1993)
Buldum (1997)
Zsidai et al. (2002)
Bhushan and Nosonovsky (2004)
Mezlini et al. (2005)
Ling and Kappl (2009)
Bonnie et al. (2010)
Rademacher (1978)
Roberts et al. (1991)
Wyszynski and Bridgewater (1993)
Lee and Jia (2003)
Mezlini et al. (2005)
Ling and Kappl (2009)
Liu et al. (2009)
Hernandez et al. (2011)
This Work

Experimental Setup and Processing

Single particle wear and friction

Tribometer: Granule-on-Disk



1) Loading piece holder
2) LVDT
3) LVDT probe
4) Applied load
5) Tachometer
6) Disk
7) Granule
8) Granule load cell
9) Granule loading piece
10) Linear slider bearing

Experimental Parameters

Experimental Parameter	Value / Input
Granule Material	Brass
	Cellulose Acetate
	Glass
	S2 Tool Steel
	Tungsten Carbide
Granule Diameter	4.76 mm (3/16 inches)
Disk Material	Stainless Steel
Speed	3 m/s
	4 m/s
	5 m/s
Load	1 lb. (1.298 lbs.)
	3 lbs. (3.298 lbs.)
	5 lbs. (5.298 lbs.)

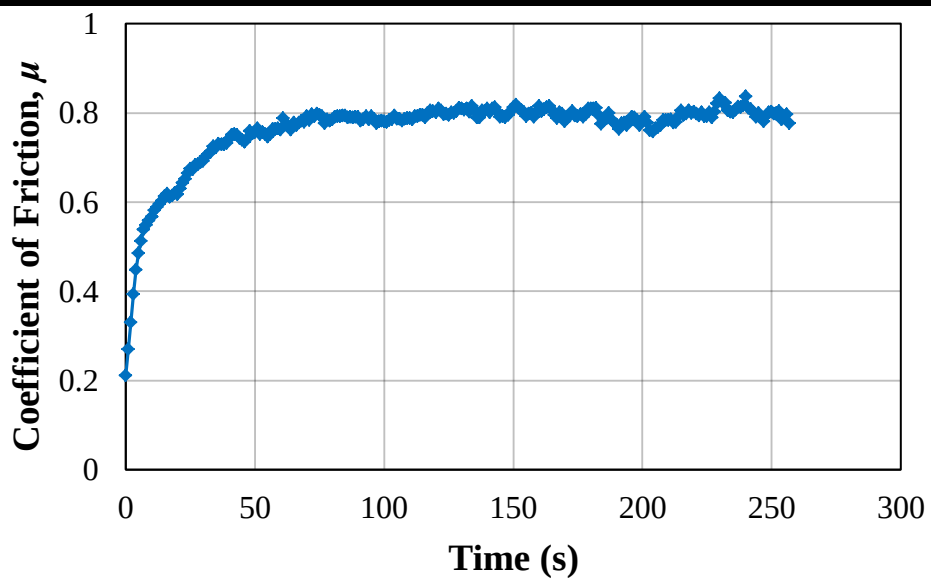
Friction Results

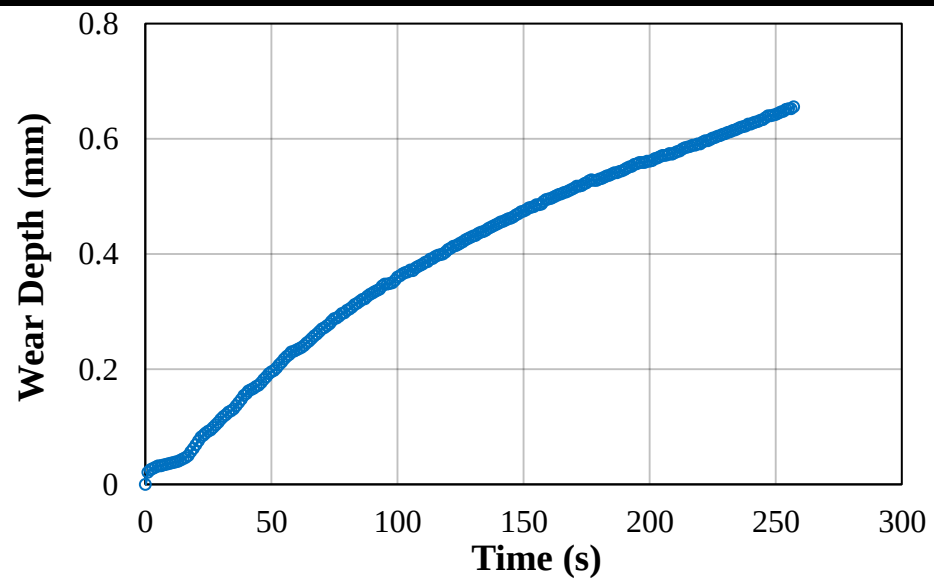
- Representative Results: Brass (4 m/s ; 1 lb.)
- Varying Speed Studies
  - (1) Brass, (2) Cellulose Acetate, (3) Glass
- Varying Load Studies
  - (1) Glass, (2) S2 Tool Steel
- Varying Material Studies
  - (1) 4 m/s ; 1 lb.

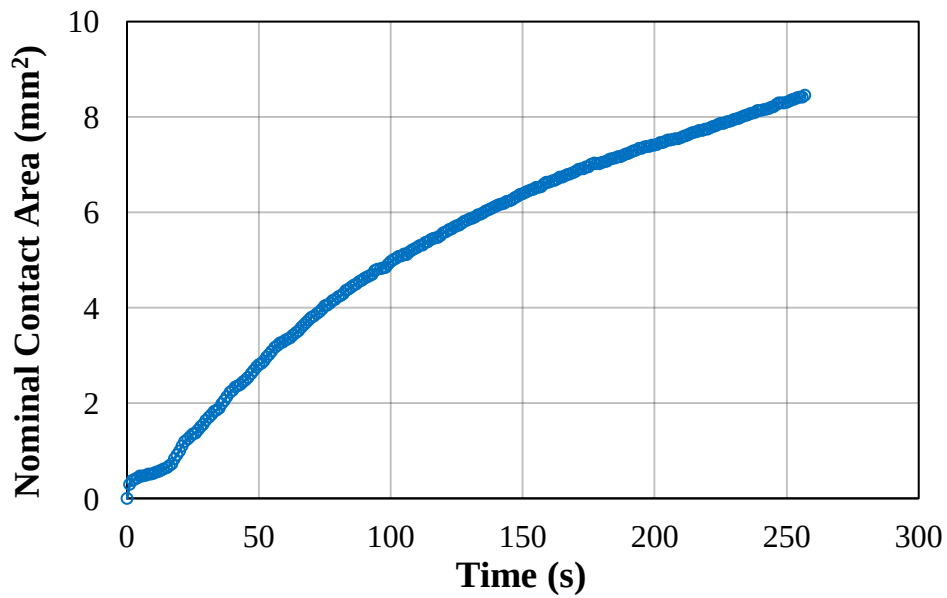
Friction & Wear Results

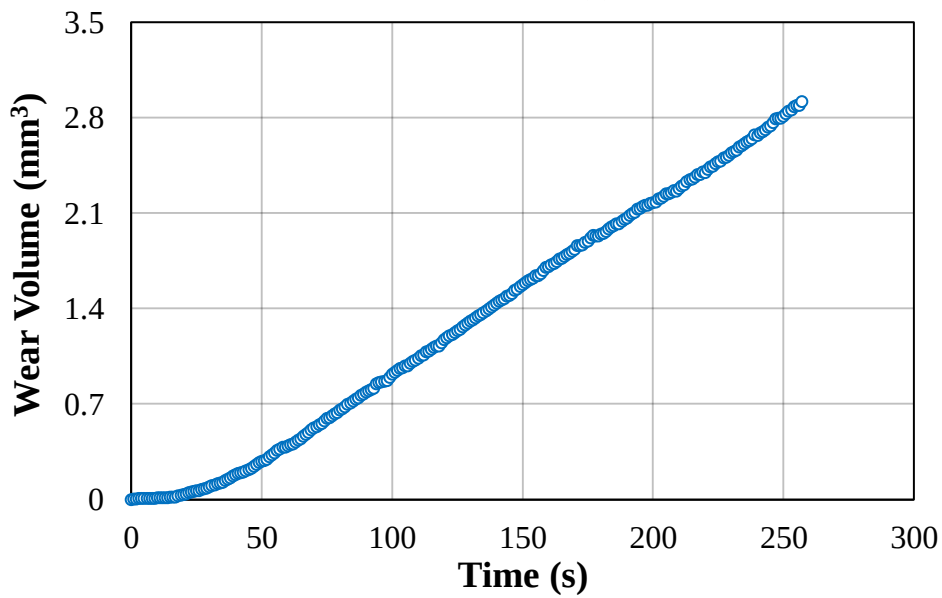
- Representative Results: Brass (4 m/s ; 1 lb.)
- Varying Speed Studies
  - (1) Brass, (2) Cellulose Acetate, (3) Glass
- Varying Load Studies
  - (1) Glass, (2) S2 Tool Steel
- Varying Material Studies
  - (1) 4 m/s ; 1 lb.

Brass: Speed = 4 m/s ; Applied Load = 1 lb.

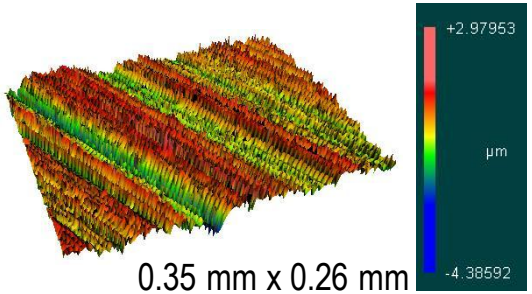
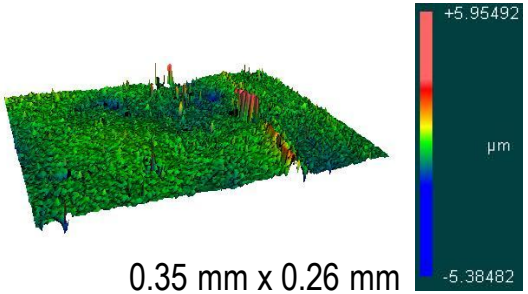
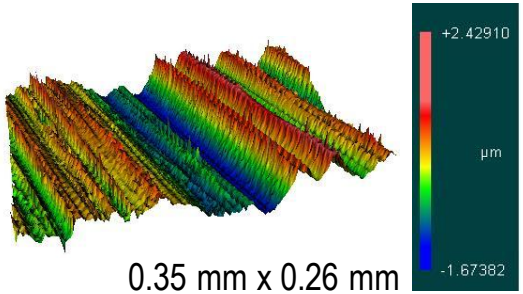








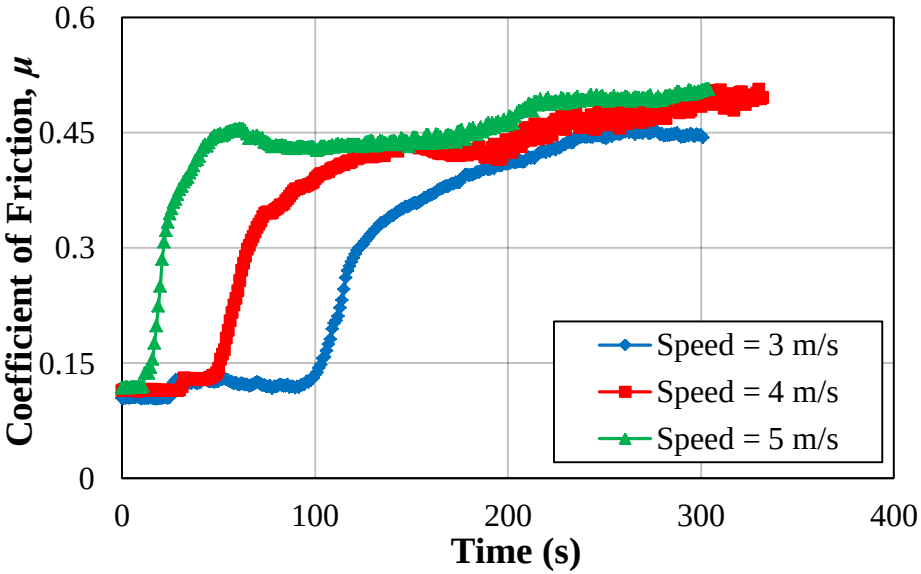
Brass: Speed = 4 m/s ; Applied Load = 1 lb.

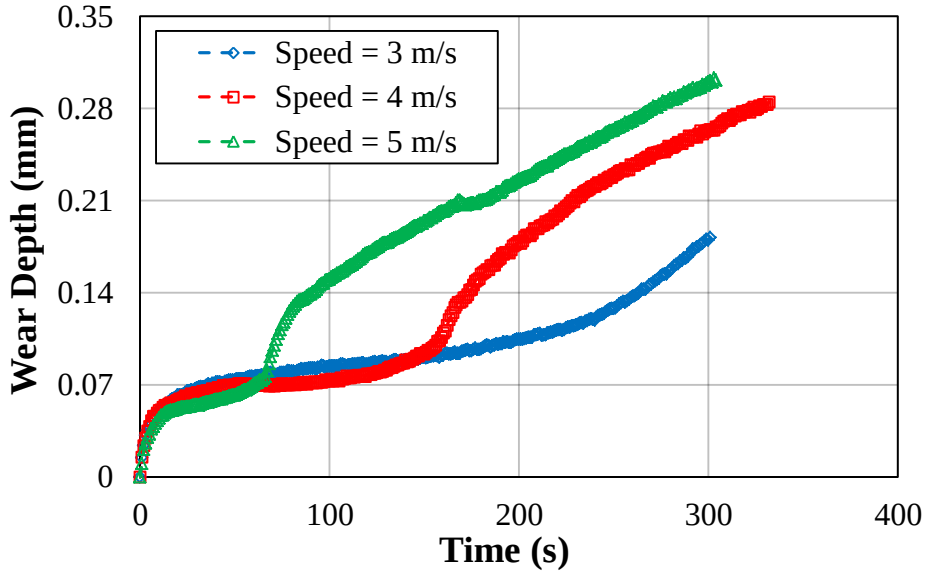
Granule Material	Stainless Steel Disk Before	Granule Before	Granule After
Brass	 0.35 mm x 0.26 mm	 0.35 mm x 0.26 mm	 0.35 mm x 0.26 mm
	R_a = 0.493 µm	R_a = 0.312 µm	R_a = 0.416 µm

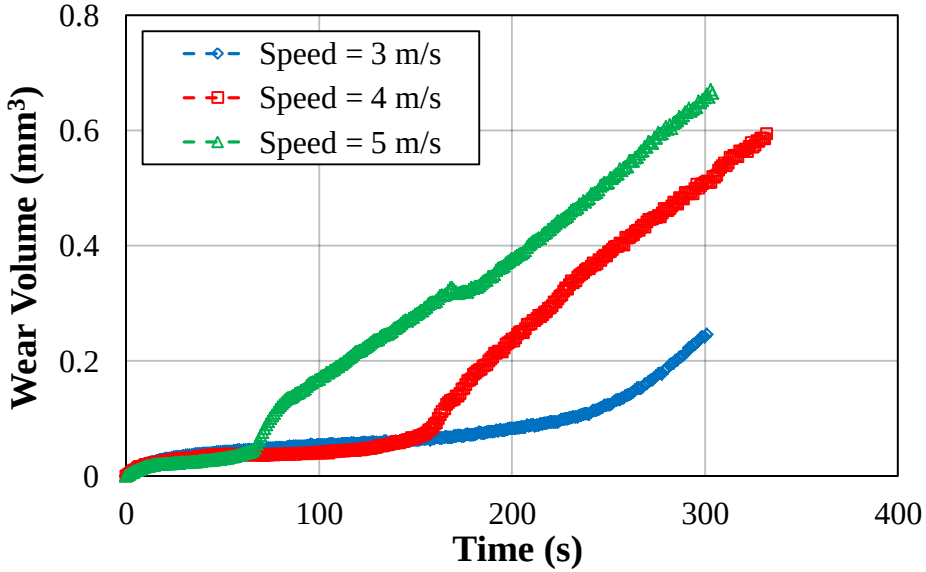
Results

- Representative Results: Brass (4 m/s ; 1 lb.)
- Varying Speed Studies
  - (1) Brass, (2) Cellulose Acetate, (3) Glass
- Varying Load Studies
  - (1) Glass, (2) S2 Tool Steel
- Varying Material Studies
  - (1) 4 m/s ; 1 lb.

Cellulose Acetate: Applied Load = 1 lb.

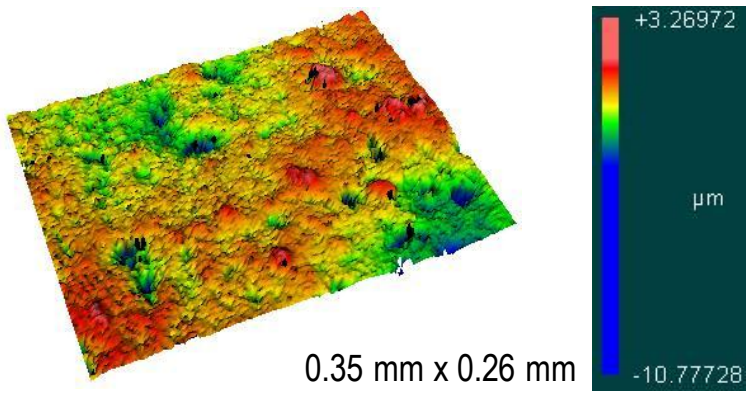






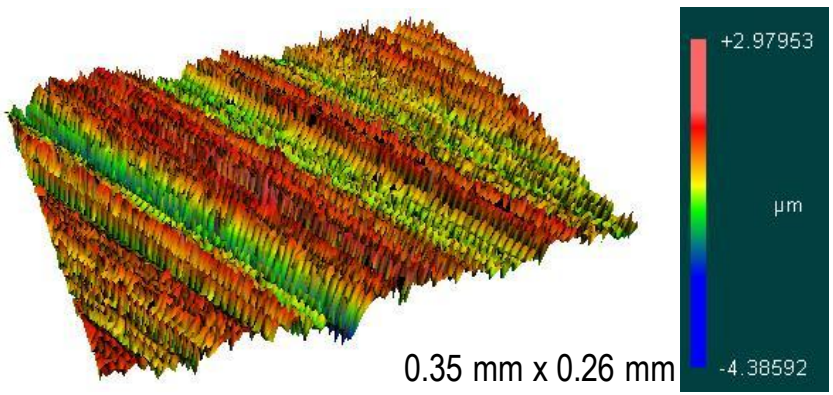
Cellulose Acetate: Applied Load = 1 lb.

Granule Before



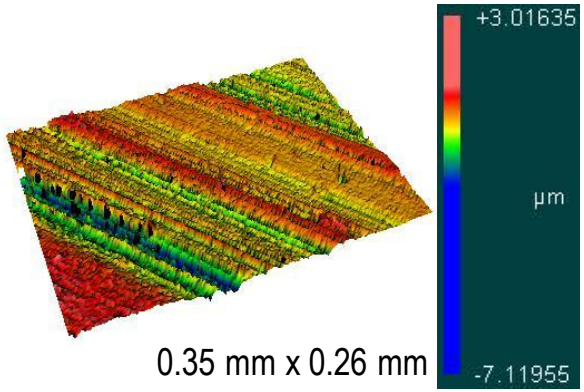
R_a = 0.509 µm

Stainless Steel Disk Before



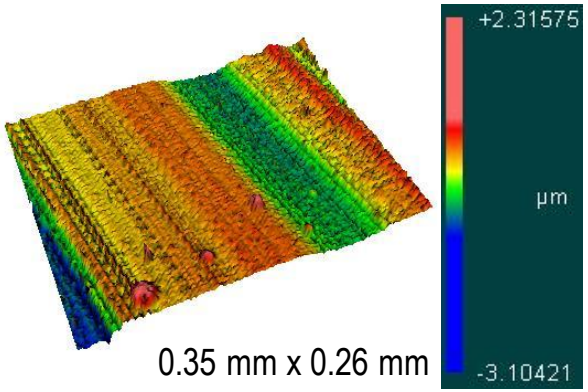
R_a = 0.493 µm

Granule After: 3 m/s



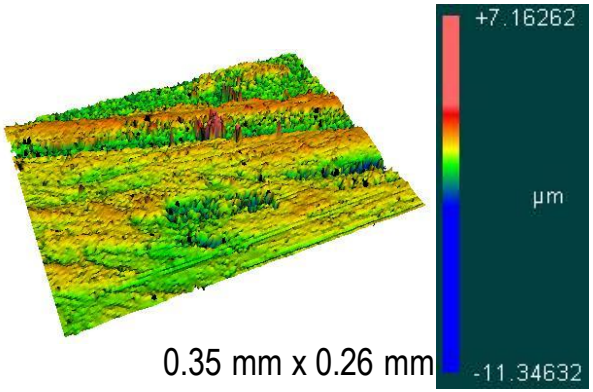
R_a = 0.339 µm

Granule After: 4 m/s



R_a = 0.303 µm

Granule After: 5 m/s

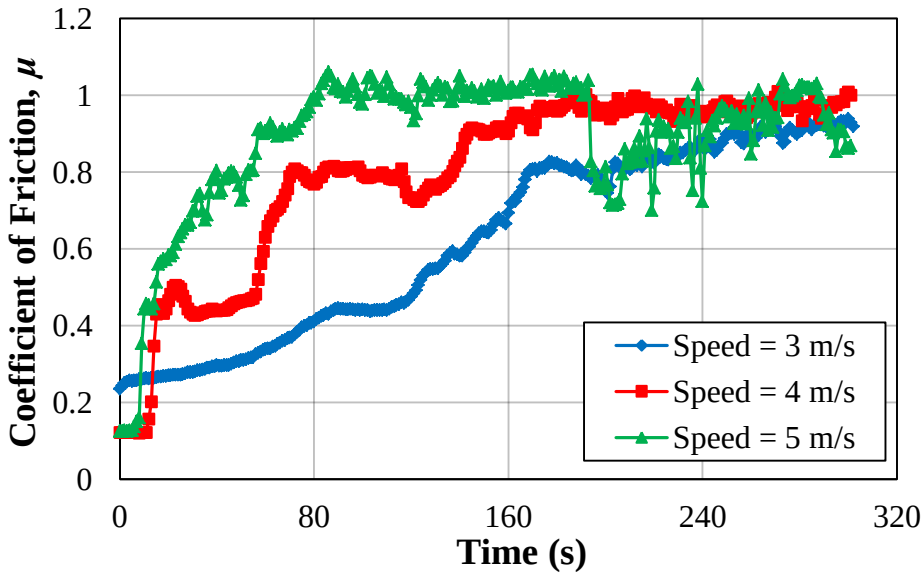


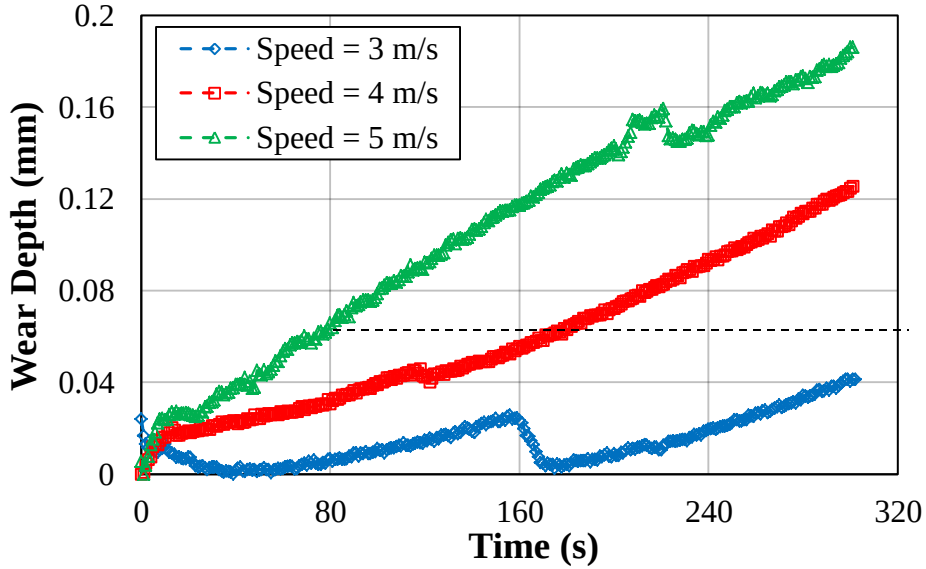
R_a = 0.498 µm

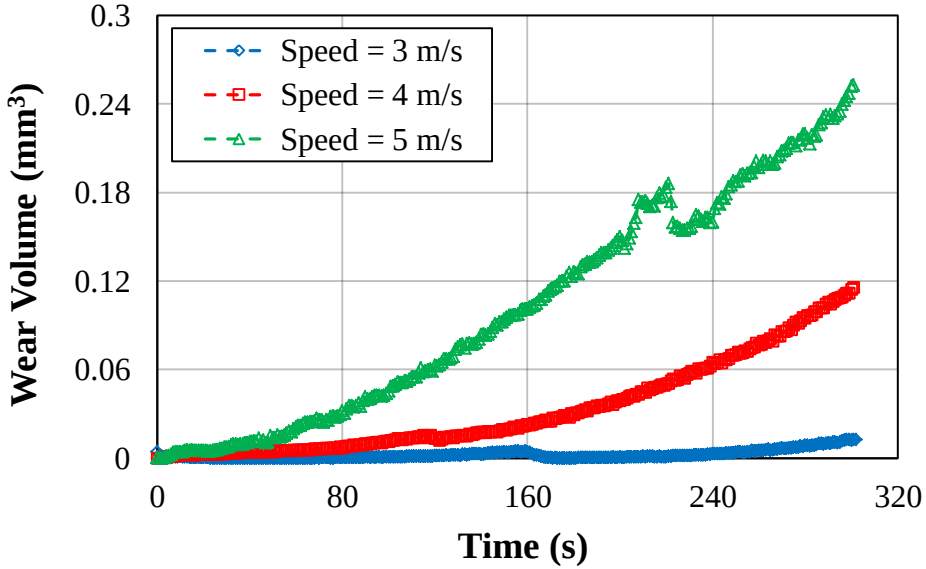
Results

- Representative Results: Brass (4 m/s ; 1 lb.)
- Varying Speed Studies
  - (1) Brass, (2) Cellulose Acetate, (3) Glass
- Varying Load Studies
  - (1) Glass, (2) S2 Tool Steel
- Varying Material Studies
  - (1) 4 m/s ; 1 lb.

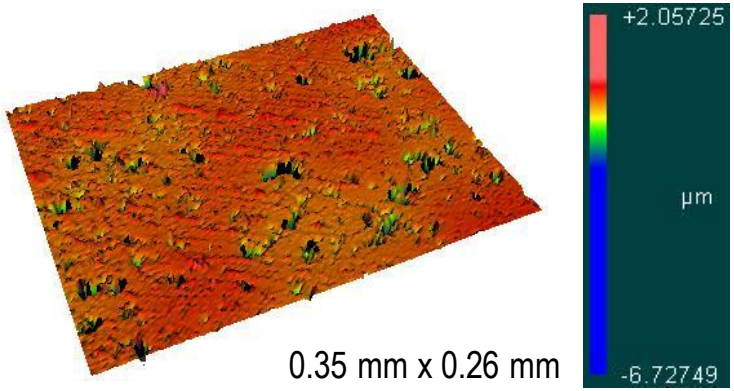
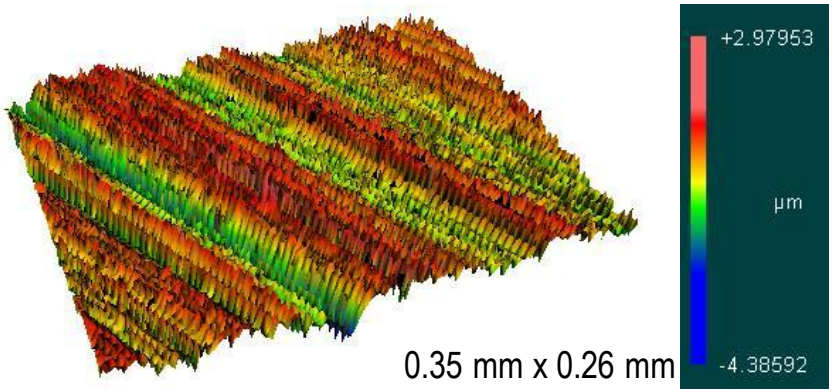
Speed varying tests (Glass: Applied Load = 1 lb.)

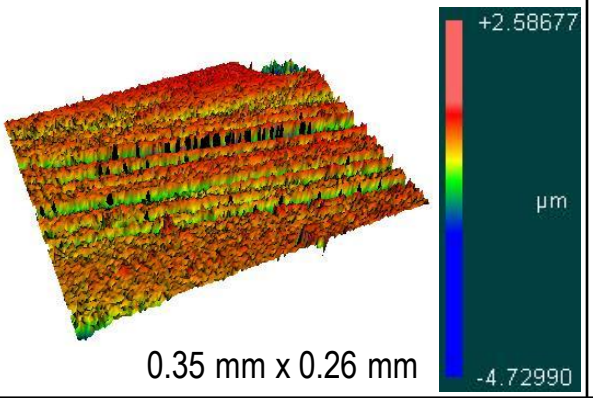
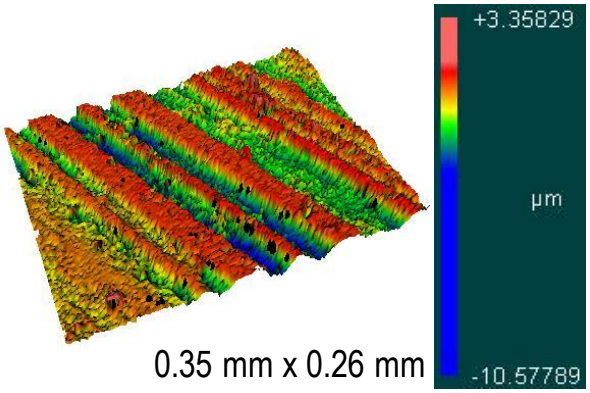
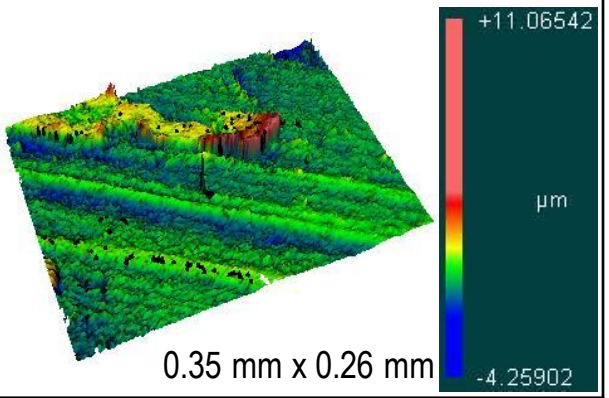






Speed varying tests (Glass: Applied Load = 1 lb.)

Granule Before	Stainless Steel Disk Before
	
R_a = 0.128 µm	R_a = 0.493 µm

Granule After: 3 m/s	Granule After: 4 m/s	Granule After: 5 m/s
		
R_a = 0.314 µm	R_a = 0.725 µm	R_a = 0.502 µm

Conclusions

Conclusions

- **Obtained coefficient of restitution (COR) and coefficient of friction (COF), wear, and surface roughness measurements for single granules.**

- **COR experimental results showed:**
  - Increase in e for decrease in E^*
  - Increase in e for increase in Y_S
  - Decrease in e for increased *d/t* ration

- **COR FEM modeling results showed:**
  - Decrease in *e* for increased particle radius (same as experiments).
  - Decrease in *e* for increased particle density.
  - Increase in *e* for increase in Y_S.

Acknowledgements

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- Patrick Dougherty (Interferometer).
- Members of the PFTL.

Thank You!

Questions?