Integrated Surface Engineering for Improving Energy Efficiency

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Agreements 16226 & 16710

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Aaron Yocum, NTEL, Project monitor

Outline

- Purpose of work
- Barriers
- Approach
- Performance measure and accomplishments
- Technology transfer
- Publications/Patents
- Plans for next fiscal year
- Summary

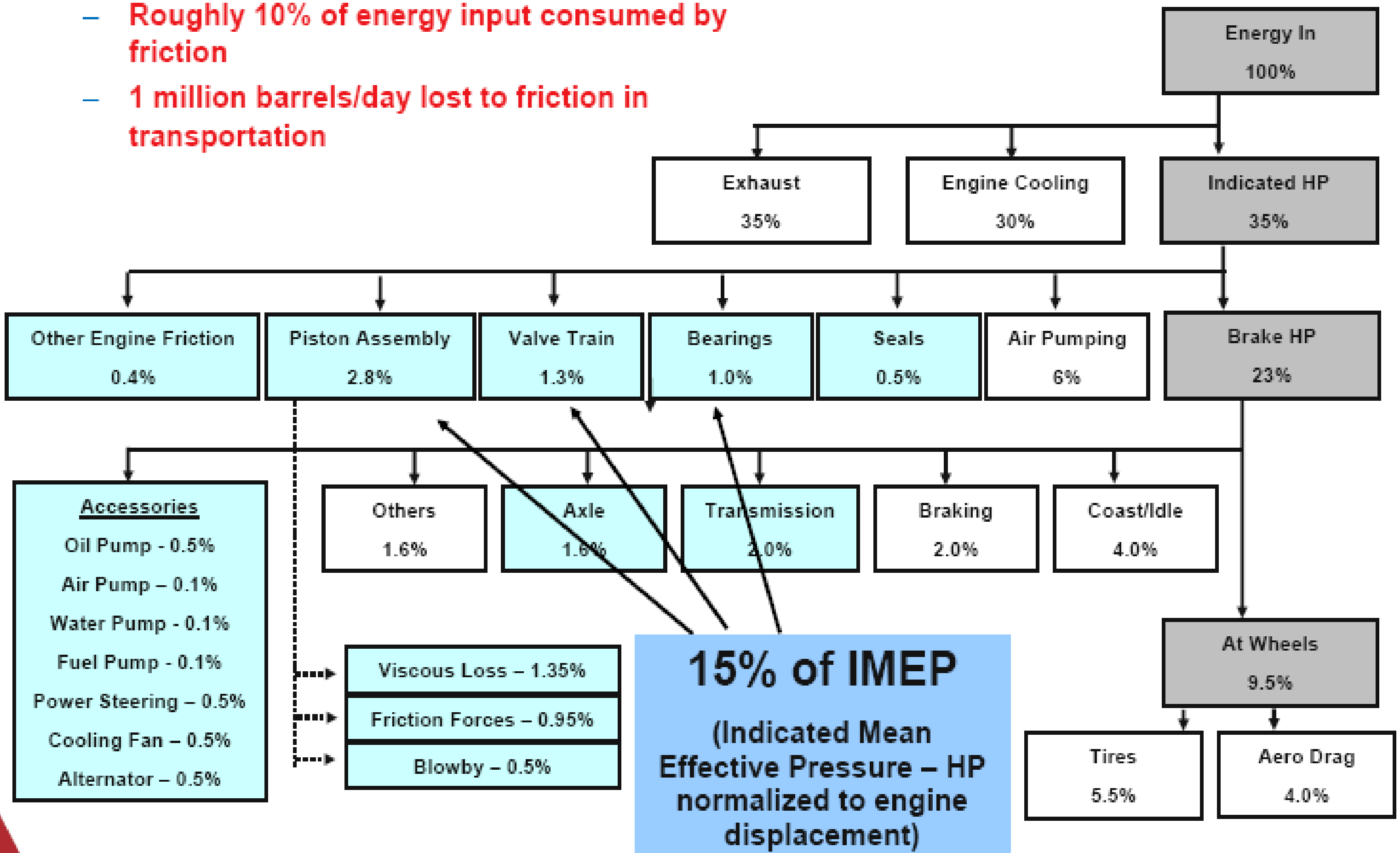
Purpose of work

The central idea is to create a surface that has 1) multiscale surface textural patterns; 2) ultra-thin compliant hard film to protect the textures; 3) strongly bonded friction reduction chemical film (nanocomposite). This should create a surface technology that can significantly reduce parasitic friction losses and save energy in all contacting surfaces in automobile and truck applications

Develop an integrated surface technology (including surface textures, protective coating, surface chemistry) to significantly reduce energy losses between contact surfaces in engines to improve energy efficiency and reduce fuel consumption, thereby achieving petroleum conservation and displacement

More Energy is Lost to Friction Than Delivered to the Wheel

- Energy Map- Passenger Vehicle EPA Cycle
  - Roughly 10% of energy input consumed by friction
  - 1 million barrels/day lost to friction in transportation



Relevance to DOE goals

- This project addresses friction reduction in various engine components where parasitic energy losses are occurring such as bearings, piston-liner interfaces, transmissions, cams, etc.
- Texturing and surface modification technology have the potential of reducing the parasitic losses by at least 5% while improving durability significantly by preventing seizure and scoring
- We are working with Caterpillar, Timken, United Technology, Crane Packing and other smaller engine manufacturers to develop this technology
- It also enables the utilization of light weight materials which may not have the necessary contact properties for wide spread use in engine applications.
- It also has the potential of reducing wind resistance by controlling the aerodynamics of cars and trucks

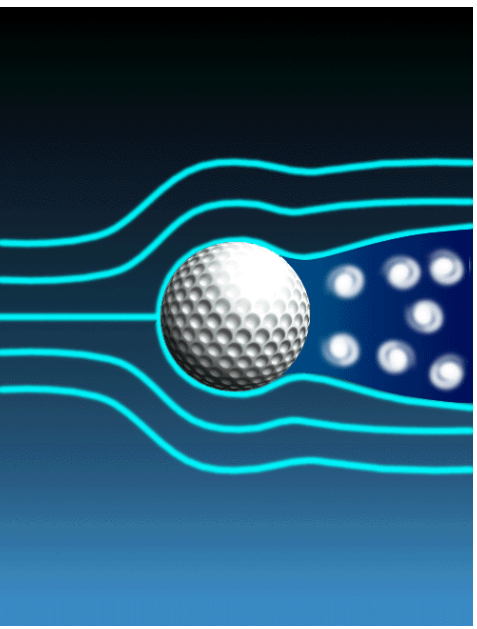
Barriers to commercialization

- Lack of theory and understanding of how surface textures control/reduce friction (surface texture is an art based on trial and error)
- Demonstrated success for conformal contacts such as seals using dimples works only under low load high speed conditions
- Cost effectiveness of texturing (additional cost & processing vs performance enhancement)
- Fabrication cost and ease of texturing on actual engine parts

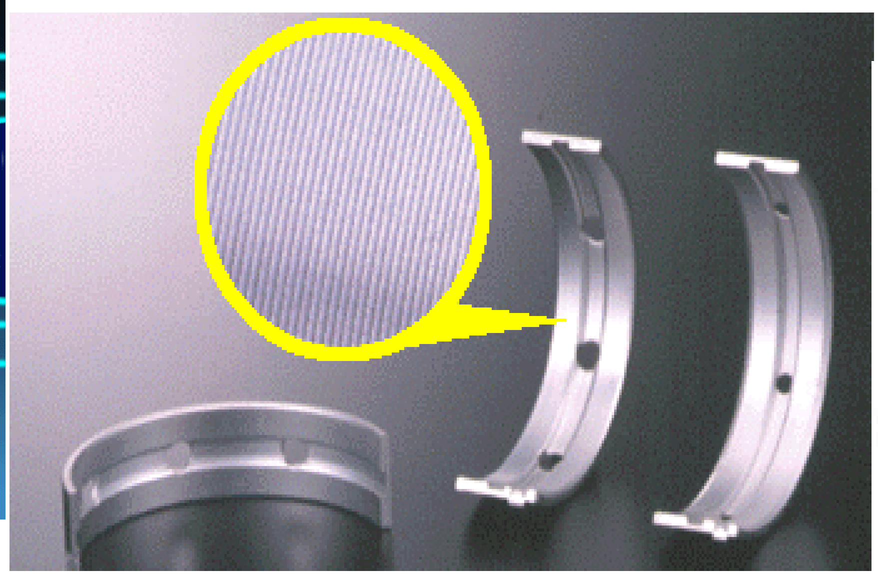
Approaches

- Conduct control experiments to understand the basic mechanisms of friction reduction under various loads and speeds
- Develop models to describe the process in order to estimate the extent of benefits
- Develop fabrication techniques to make textures on steel surface
- Develop concepts and chemistry to protect the textures under high load wearing conditions
- Component testing to validate models
- Implementation of technology with industrial partners

Surface texturing + Protective film + Surface chemistry
to reduce friction for engine components from
hydrodynamics (high speed low load)
to
boundary lubrication (low speed low load) conditions

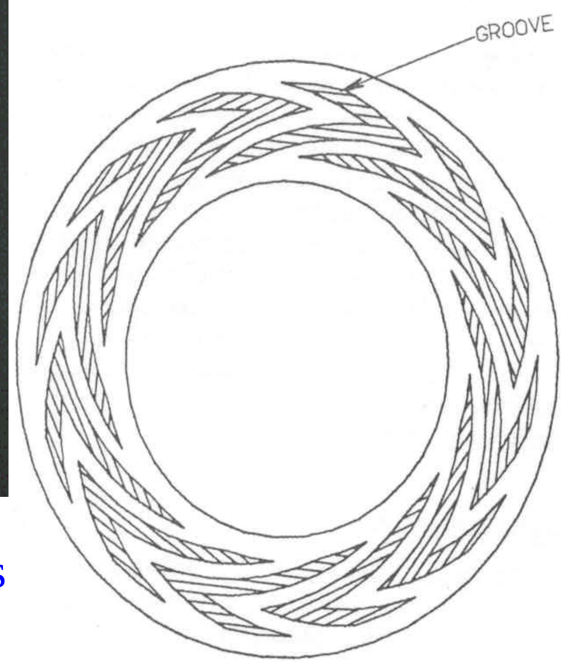


Aerodynamic lift



Bearing contact under lubricated conditions

Liquid retention &
residence time control



Surface texturing

A physical/chemical way to change the contact interface by fabricating specific geometric features (lines, grooves, dimples) into the surface to induce or enhance the following known effects:

- Hydrodynamic fluid lift under high speed low load
- Wear particle trapping (minimize third body abrasion)
- Lubricant reservoir (prevent seizure and lubricant starvation)

In our work, we have discover additional mechanisms to reduce friction:

- Cavitation induced pressure lift
- Reverse flow inside the dimple creating lift force
- Hydrostatic lift force from compression of liquid trapped inside the textures

The use of surface texture to control interfacial friction

Current state-of-the-art surface texture friction reduction technology as a function of speed and load

Load \ Speed	Low	Medium	High
Low			Regime I: seals, thrust bearings
Medium		Regime II: roller lifters	
High	Regime III: hydraulic motors, gears, transmission		

- I. High speed, low load: hydrodynamic effects, demonstrated success in seals
- II. High-medium speed, medium load: combining effects of hydrodynamics and contact mechanics; increases friction
- III. Low-medium speed, high load: combining effects of contact mechanics, lubricant compressibility, and wear particle trapping, feasibility not yet shown

Region I: High speed, low load conditions

Steel on steel

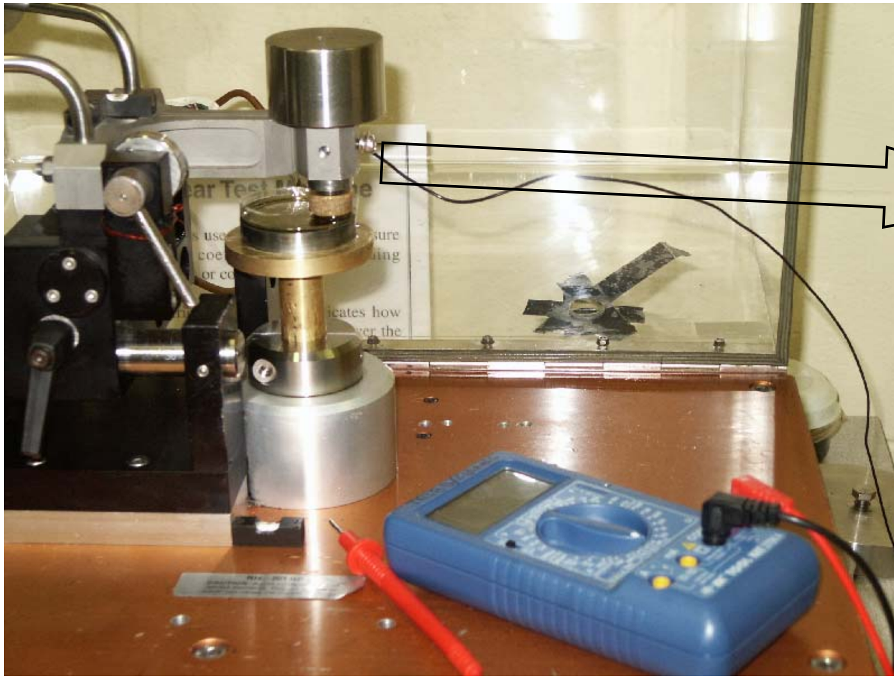
- Apparent contact pressure: 1-2 MPa
- Asperity contact pressure ~ 80-100 MPa
- Speed: 0.02 – 0.2 m/s
- Continuous fluid film within the contact

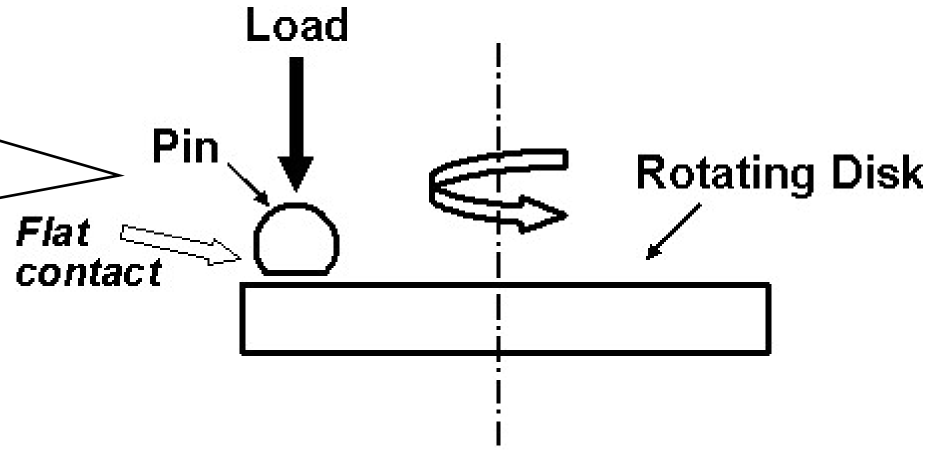
- Watching for mixed lubrication regime transition behavior to hydrodynamic
  - Critical load texture fails
  - Critical velocity for texture to function

Experimental procedure

Flat pin

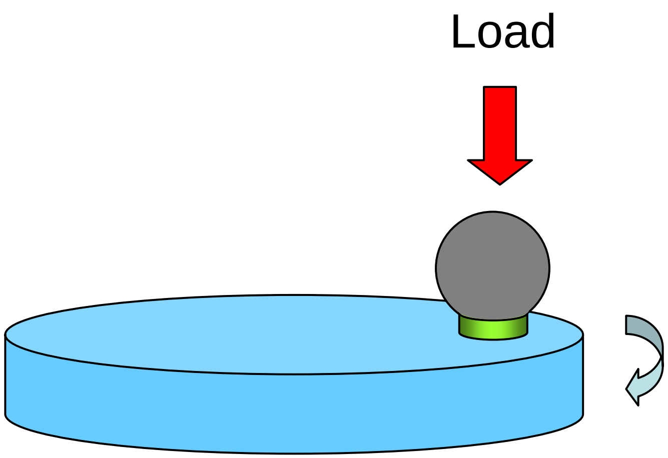
Pin-on-disk fric. machine





Review

Modified flat-on-disk test conditions



Material: steel/steel

Diameter of small disk: 6.35 mm

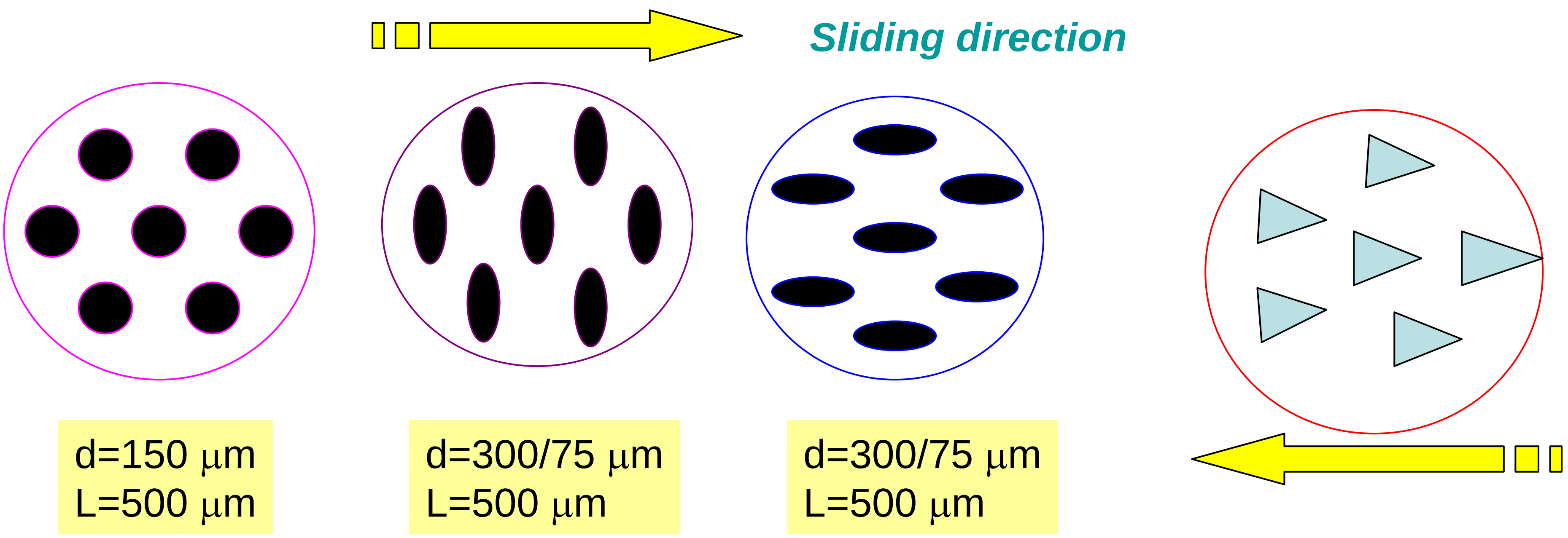
Load range: 1-35 N
Pressure: 0.03-1.1 MPa
Speed range: 0.023-0.23 m/s

Lubricant: purified parafin oil
(Saybolt number 125/135)

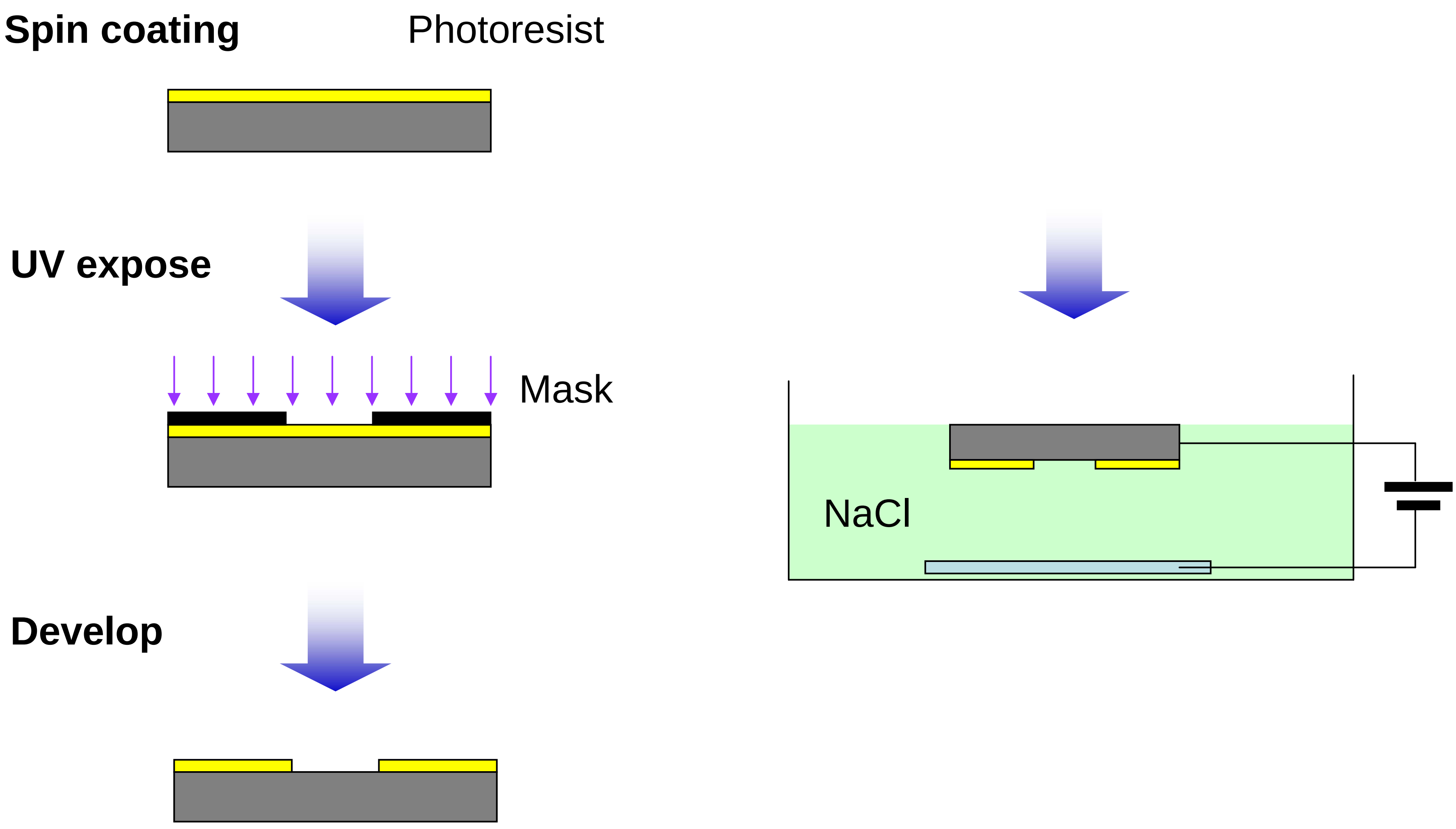
Temperature: room temperature

NIST study: The effect of shape, distribution

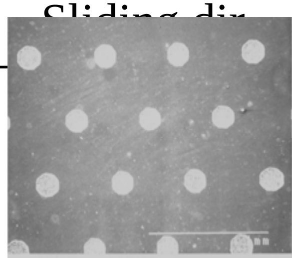
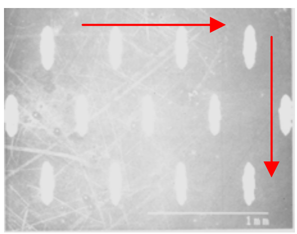
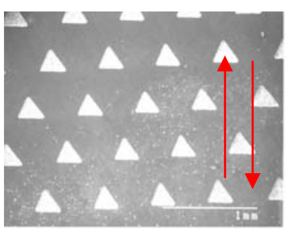
with same number, same area density, different shape and distribution at low loads and high speeds



Micro-lithograph and Electrochemical etching



Features of surface texture:

	Pattern & Sliding dir.	Dimension (μm)	Depth (μm)	Pitch (μm)	Area of a dimple (μm^2)	Area density (%)
Circle		**150**	8	500	17671	7
Ellipse		**300/75**	8	500	17671	7
Triangle		**187**	8	500	17671	7

Same

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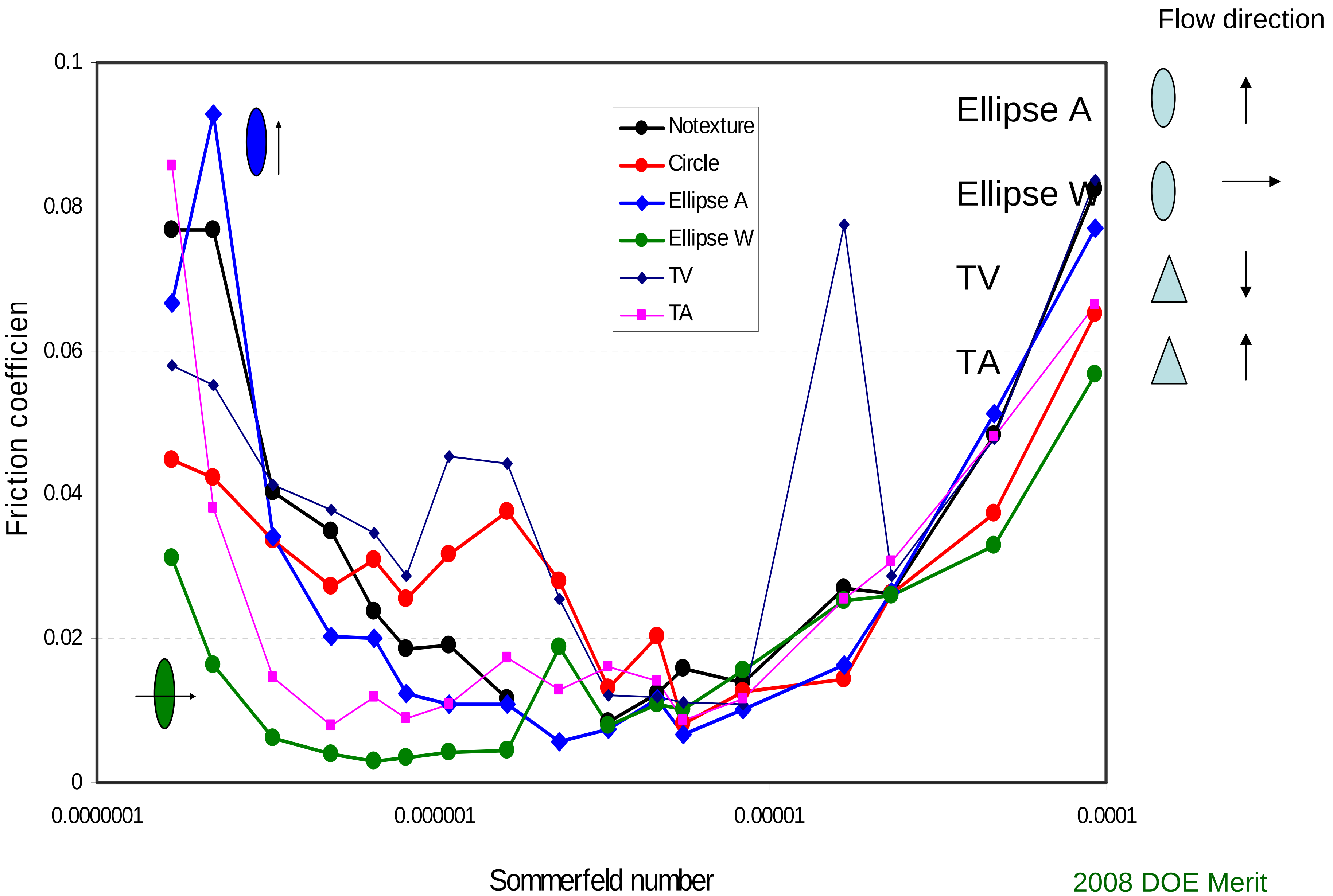
Effect of geometry on transition from mixed lubrication to hydrodynamic lburication



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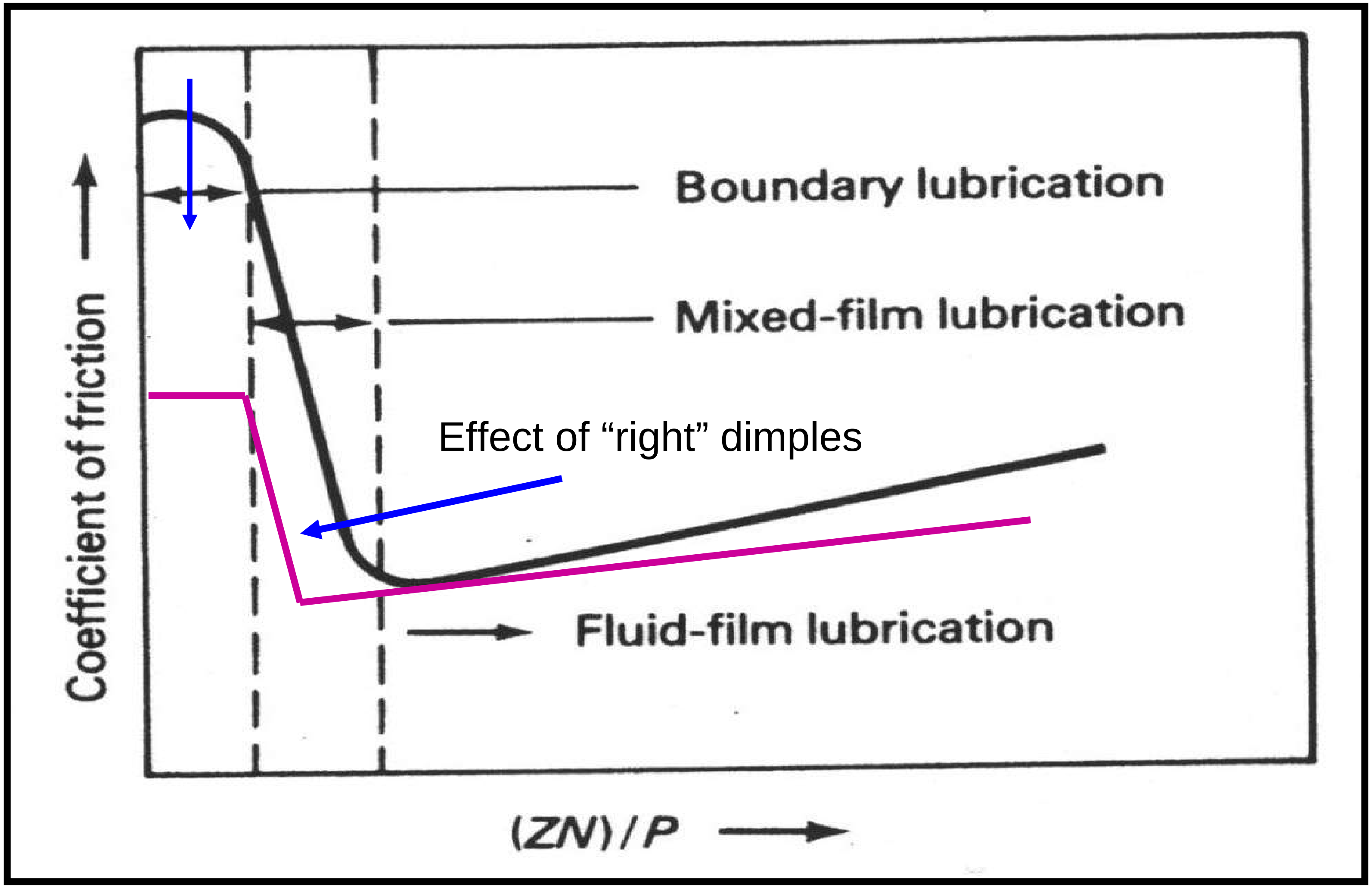
Under the right conditions dimples move Stribeck curve left and the top down

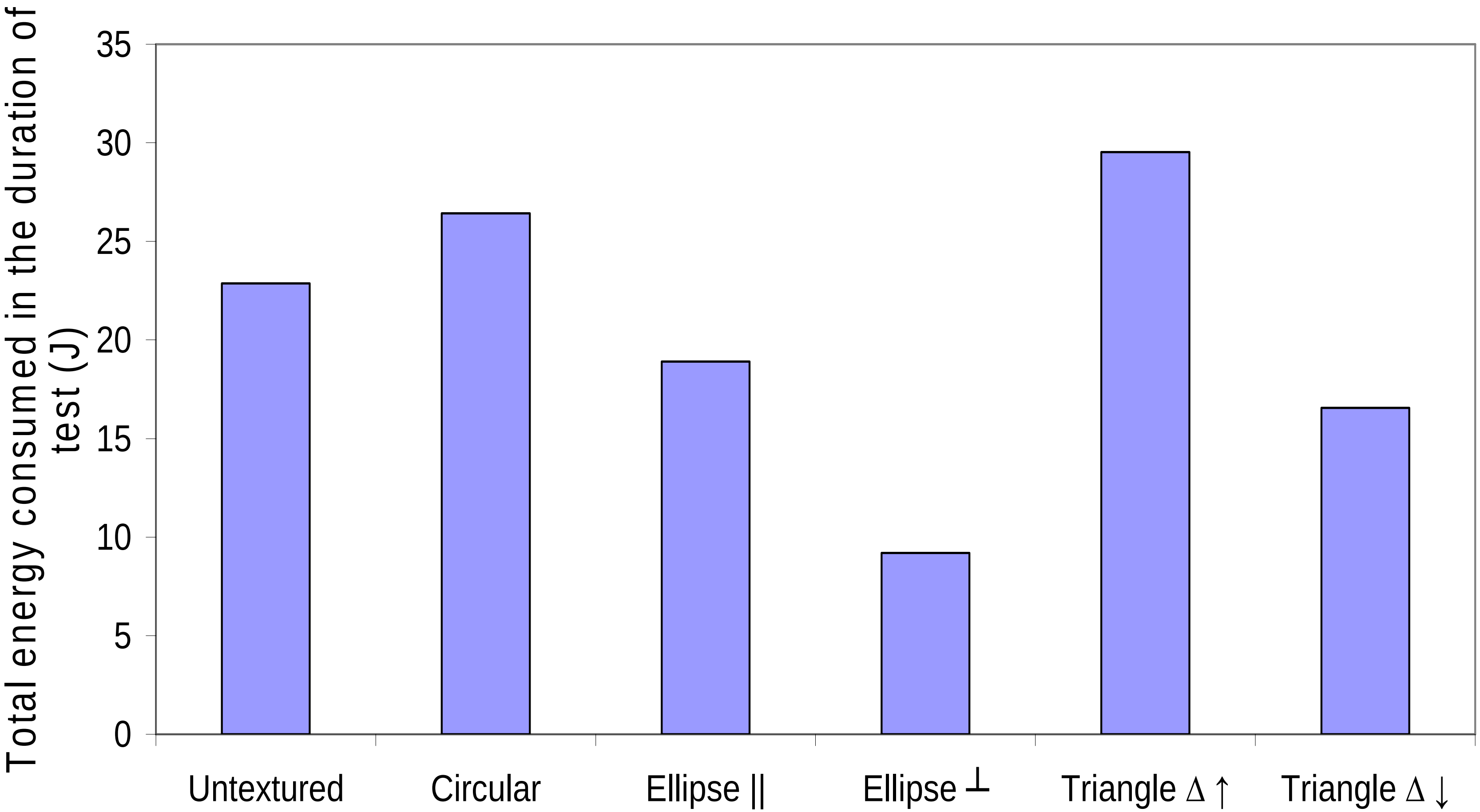


(or: viscosity x velocity x width/ load)

Effect of surface texture on Stribeck curve

Comparison of the energy consumed during the test

Etotal = $\sum i$ (load) $\sum j$ (speed) friction force ij ×sliding distance ij



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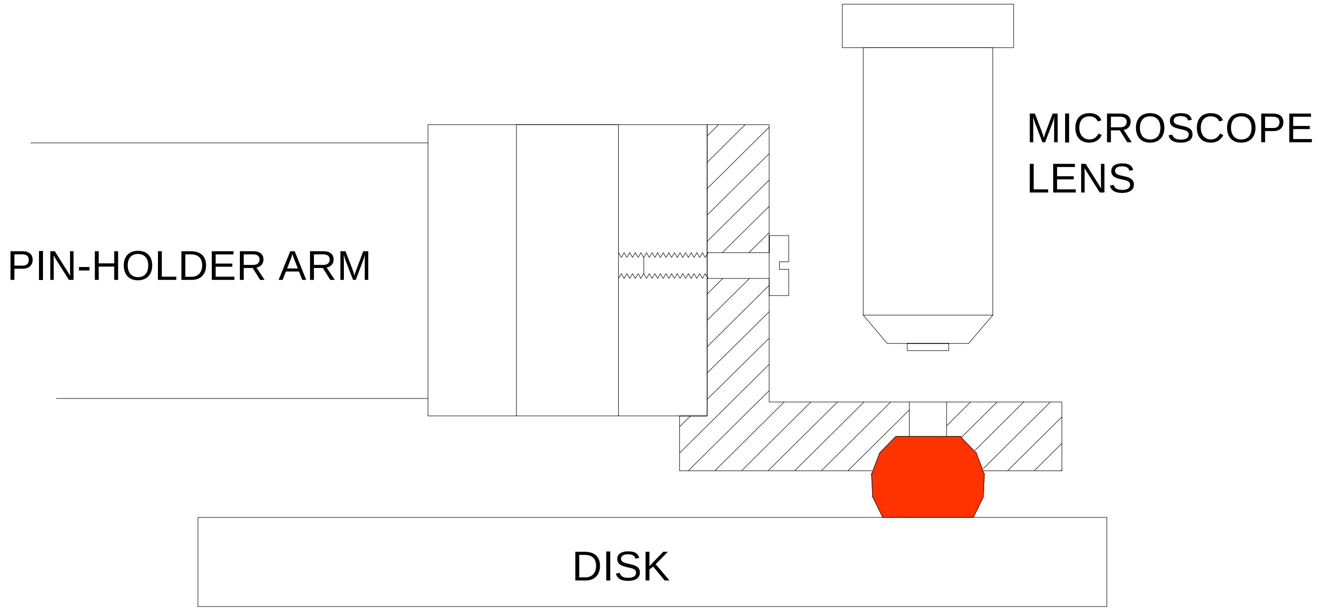
What is the friction reduction mechanism?

- Set up an in situ apparatus to observe the flow patterns of a single dimple to see how the dimple functions
- Use a high speed video camera to record the flow patterns under different speeds and loads

Pin-on-Disk Adapted to Observe Cavitation at Texture Features

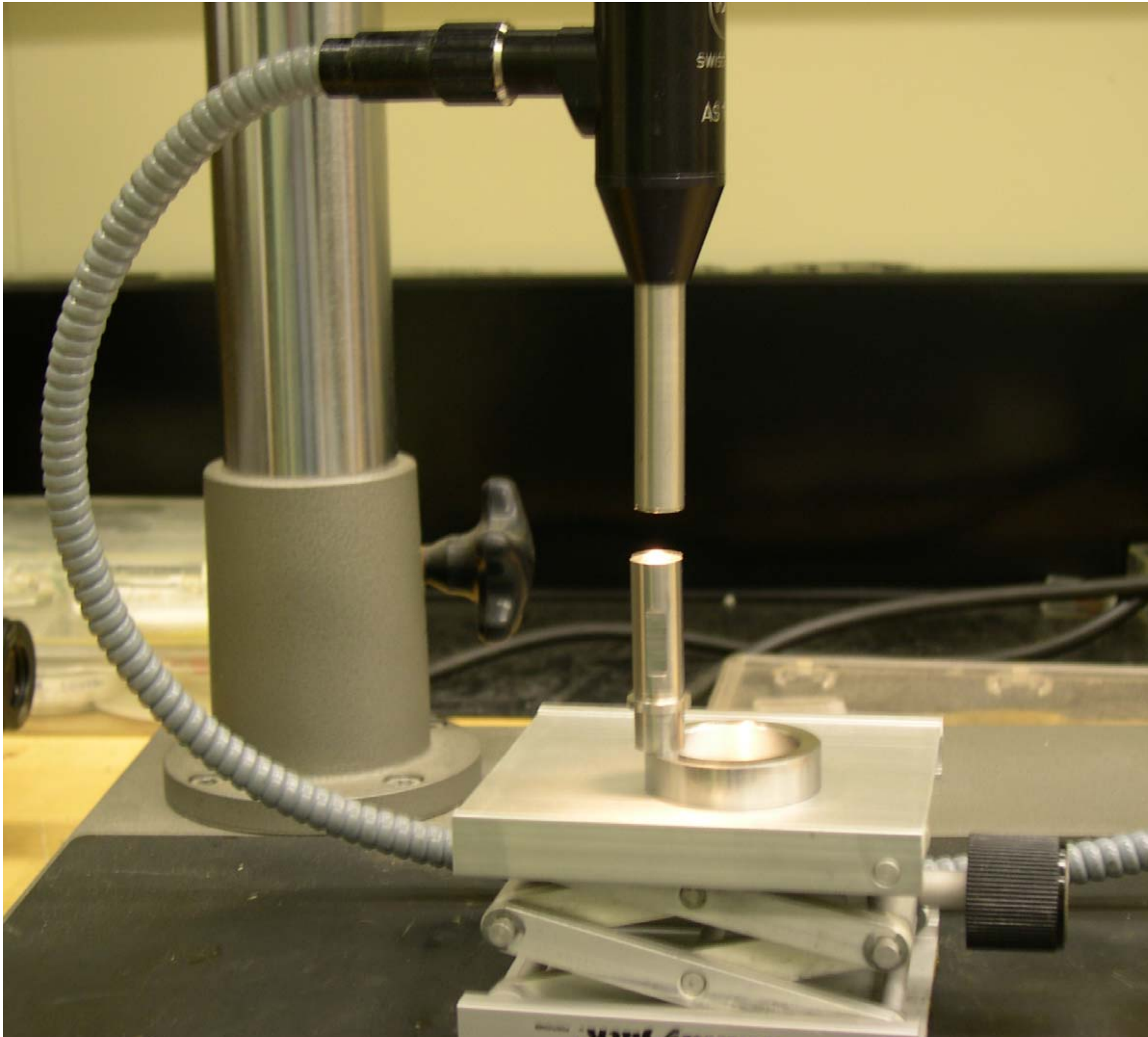


Weights - Outboard of normal position

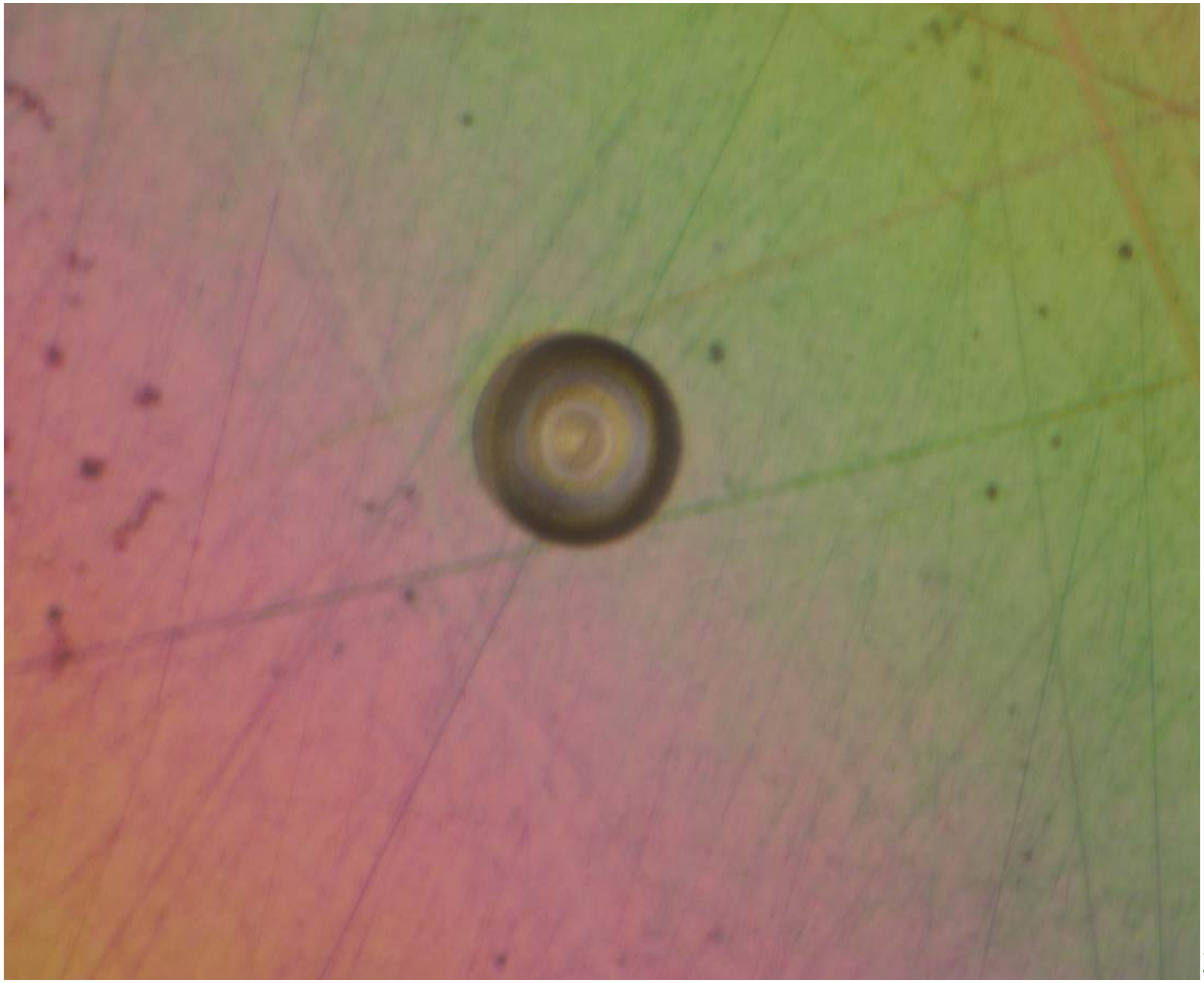
Mircroscope - Long working distance, 30X to 100X

Dimples - Better on pin, only one or a few needed

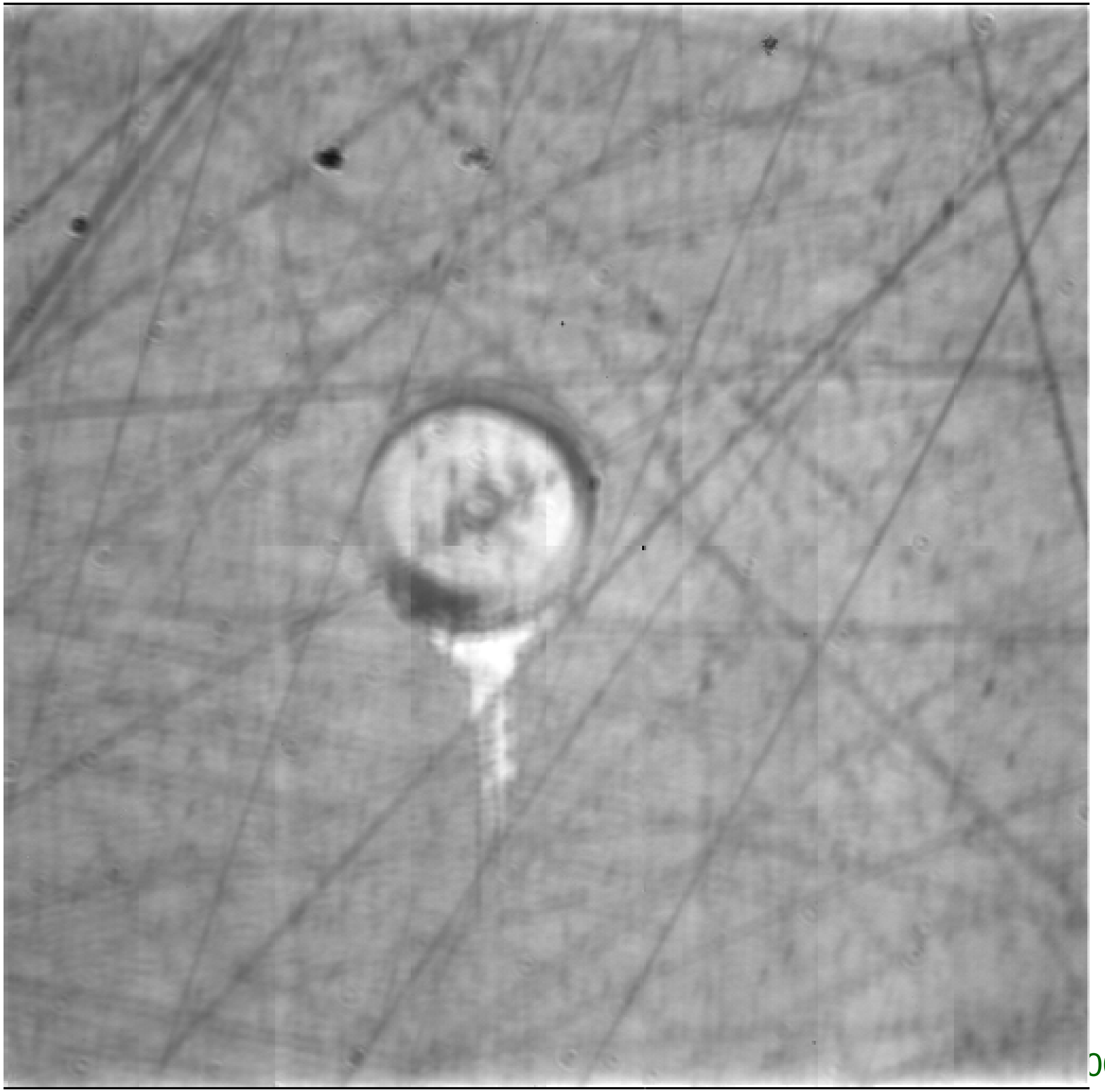
Pin Material - Sapphire, Glass, Fused Silica, Plexiglass



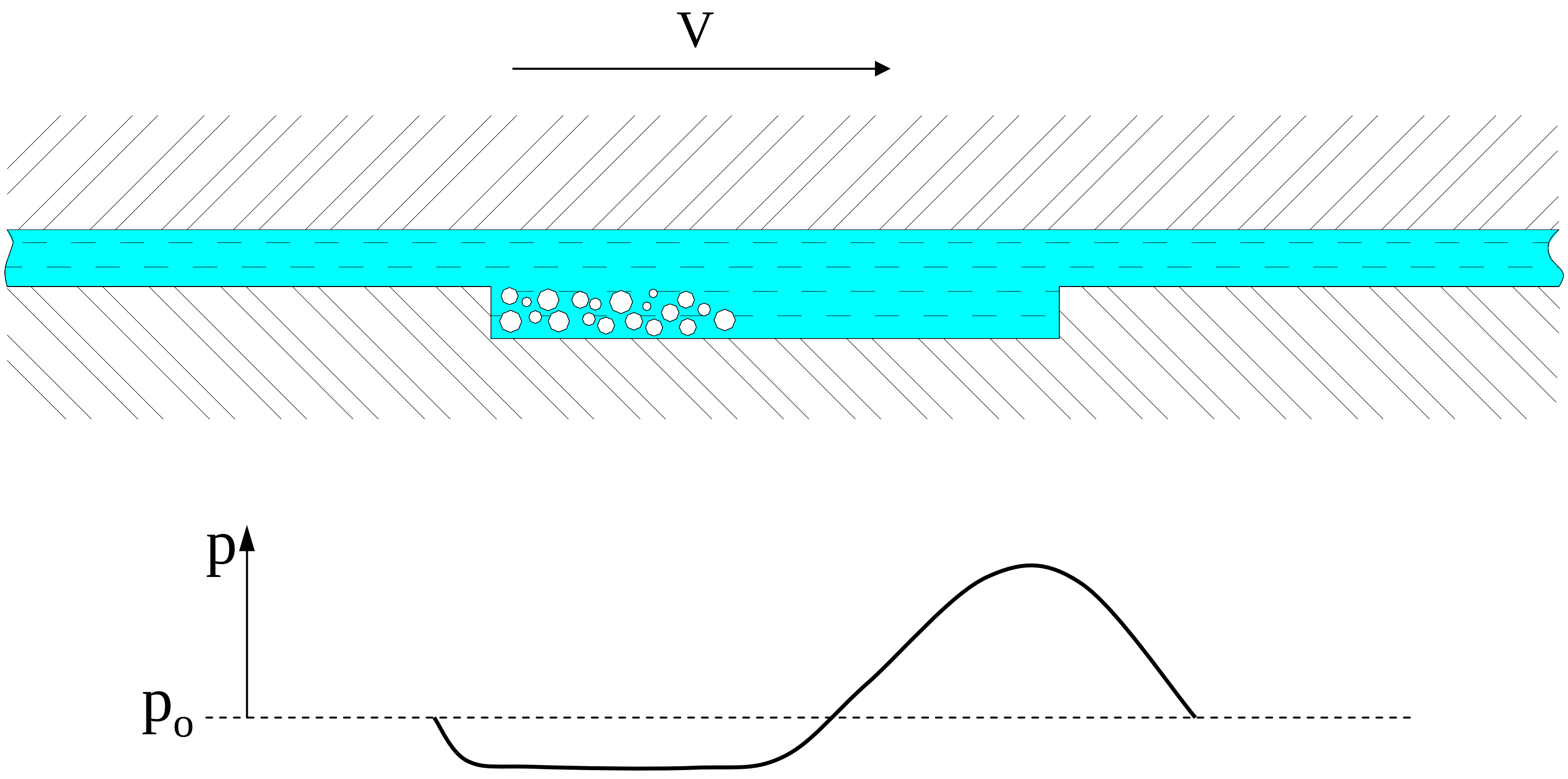
Optical Microscope Image of Dimple Through Sapphire Ball With Parallel Flats



0.3 mm/s siding speed; cavitation gas in dimple and trail of gas



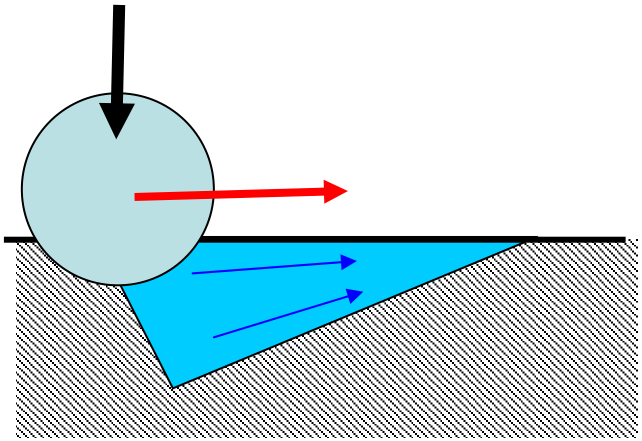
Effect of Cavitation on Pressure at a Dimple



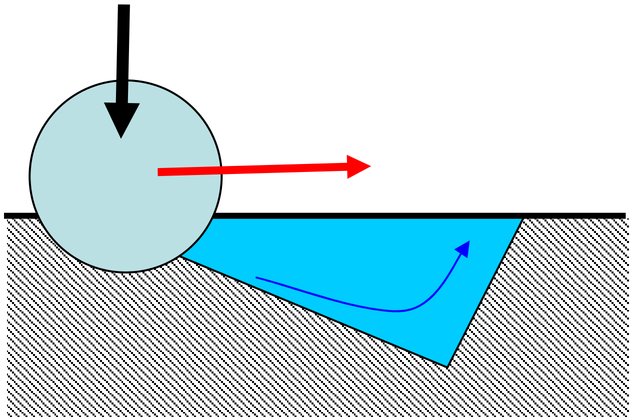
Regime II: High load high speed regime, EHL

- When the apparent contact pressure exceeds 180 MPa, friction increases!
- But about EHL theory?
- EHL has much higher contact pressures
- Let us examine what EHL models will tell us about surface textures
- Prof. Jane Wang of Northwestern University and Dr. Dong Zhu of Eaton Corporation have developed a model on surface roughness

Create an artificial wedge using elasto-plasto-deformation to push the liquid under boundary lubrication conditions



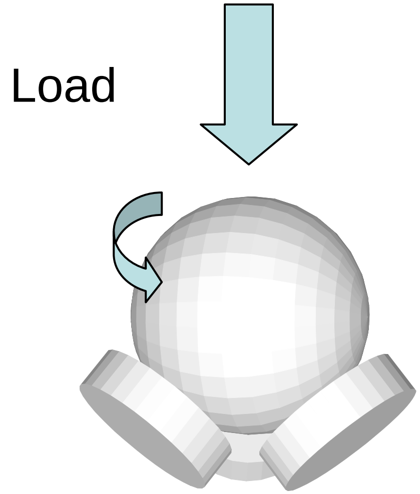
Create hydrodynamic lift



Forced fluid pressure

➢Objective: To investigate the surface texture effect at high contact pressures

➢Tester: ball on three flat



Materials: 52100 steel ball
52100 steel flats
Brass flats

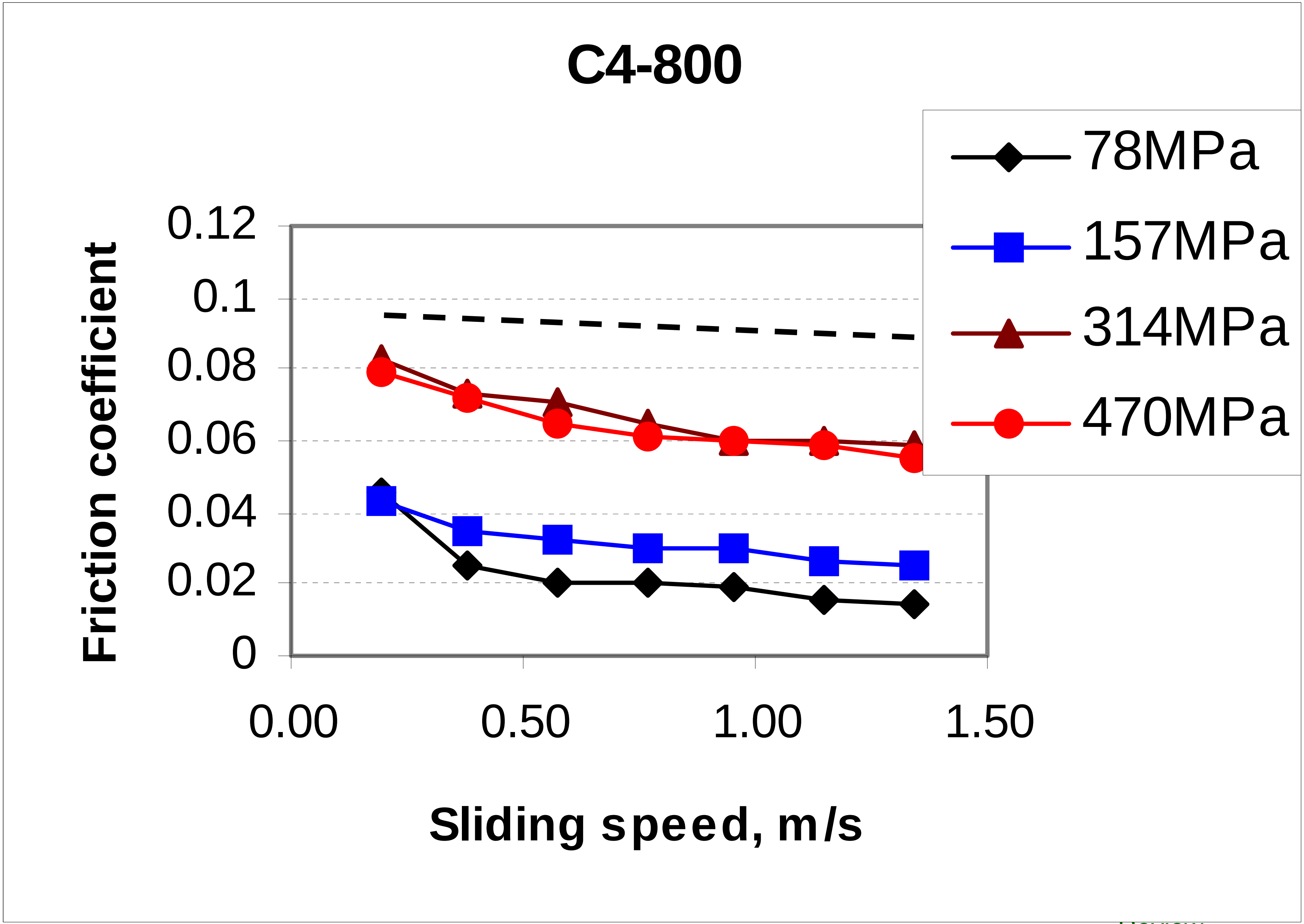
Rotating speed: 500 rpm – 5000 rpm
(0.19 m/s – 1.9 m/s)

Load:	5 - 20 Kg
Apparent Contact P_{mean}:	716 – 1136 MPa
Apparent max. contact P_{max}:	1074 – 1704 MPa

Merit Review

Major friction reduction mechanisms

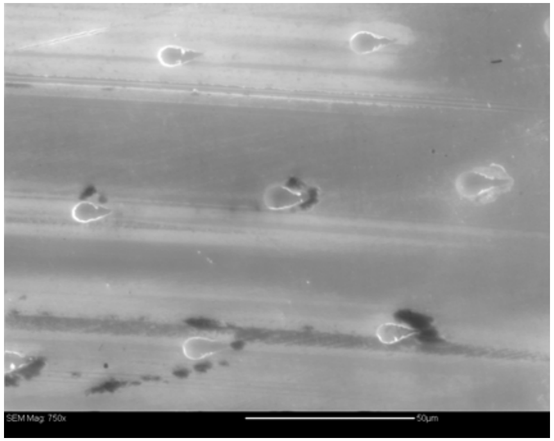
Load \ Speed	Low	Medium	High
Low			Regime I: hydrodynamic lift; reverse flow
Medium		Regime II: cavitation, elastohydrodynamic; squeeze flow	Regime II: cavitation, elastohydrodynamic; squeeze flow
High	Regime III: hydrostatic lift force; leakage rate vs sealing pressures; elastic plastic deformation rates	Regime III: hydrostatic lift force; leakage rate vs sealing pressures; elastic plastic deformation rates	



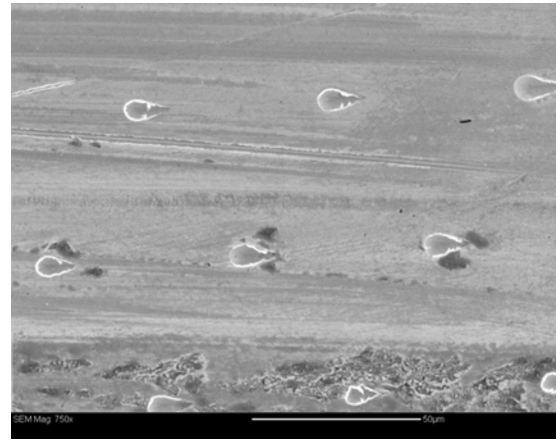
C4-800
Friction coefficient
0.12
0.1
0.08
0.06
0.04
0.02
0
0.00
0.50
1.00
1.50
Sliding speed, m/s
78MPa
157MPa
314MPa
470MPa

Review

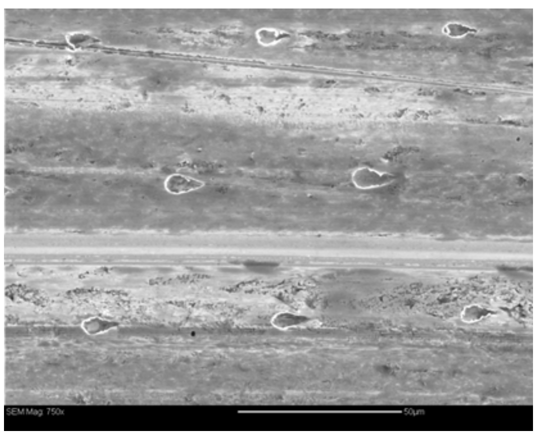
C2-400-2, Target area ratio=3.5%



78MPa



157MPa



314MPa

470MPa

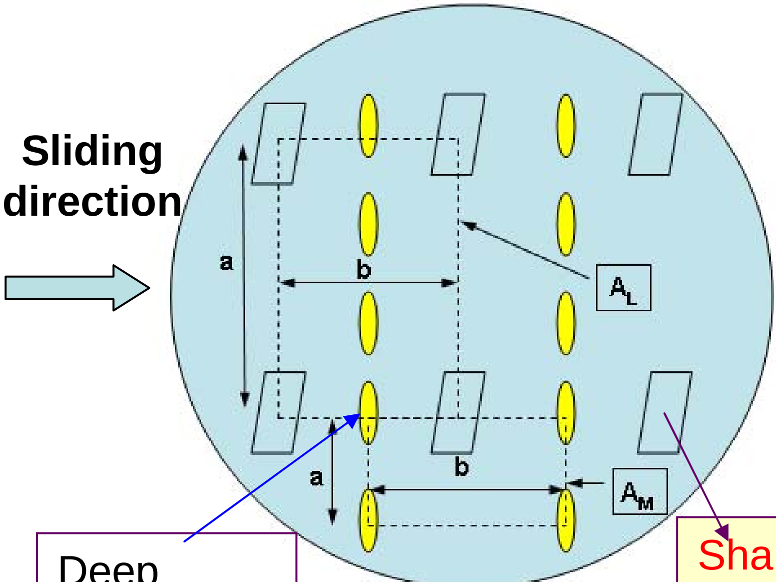
Worn surface becomes a little rough even at lowest pressure, and rough level increases with increasing the pressure.

How can this technology be implemented?

- Need coatings and lubricant chemistry to protect the texture features and to further enhance the friction reduction ability
- If the contact is varies over a range of speed and load, the contact has to morph according to the operating conditions to achieve significant friction reduction over the range
- To do this, we need “multi-scale” surface texture design, i.e. different textures appear under different operating conditions

Texture design I: individual features with different properties

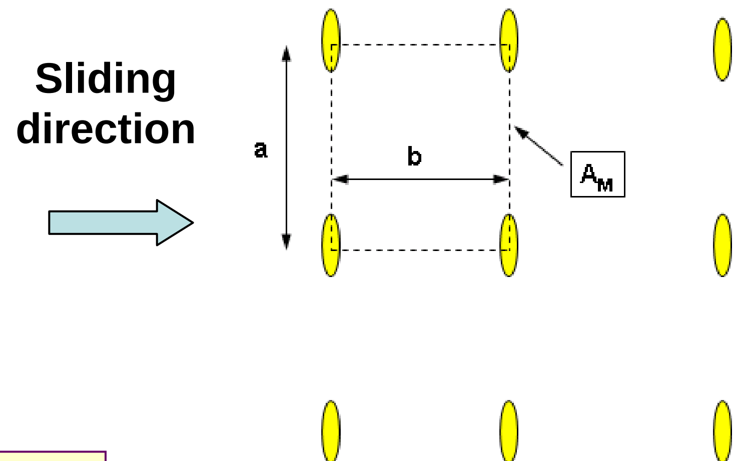
- Pattern 1



Deep ellipse for hi load, L speed

Shallow large dimples for hi S, L load

- Pattern 2



Multiscale (parallelogram)
Pitch: 400×100,40×100 μm
Area ratio: 10%

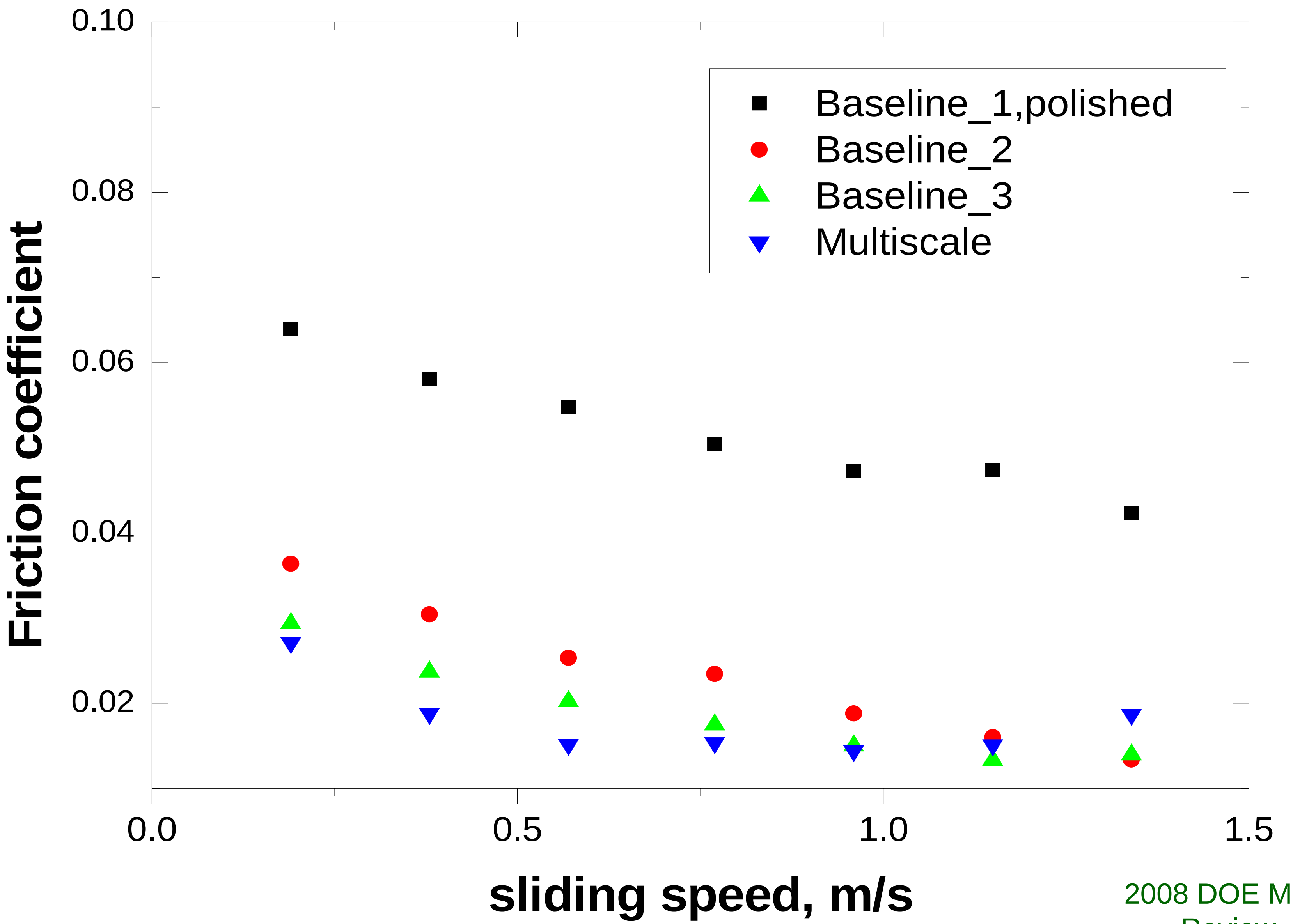
Ellipse
Pitch: 40×100 μm
Area ratio: 7%

Test conditions: load and speed

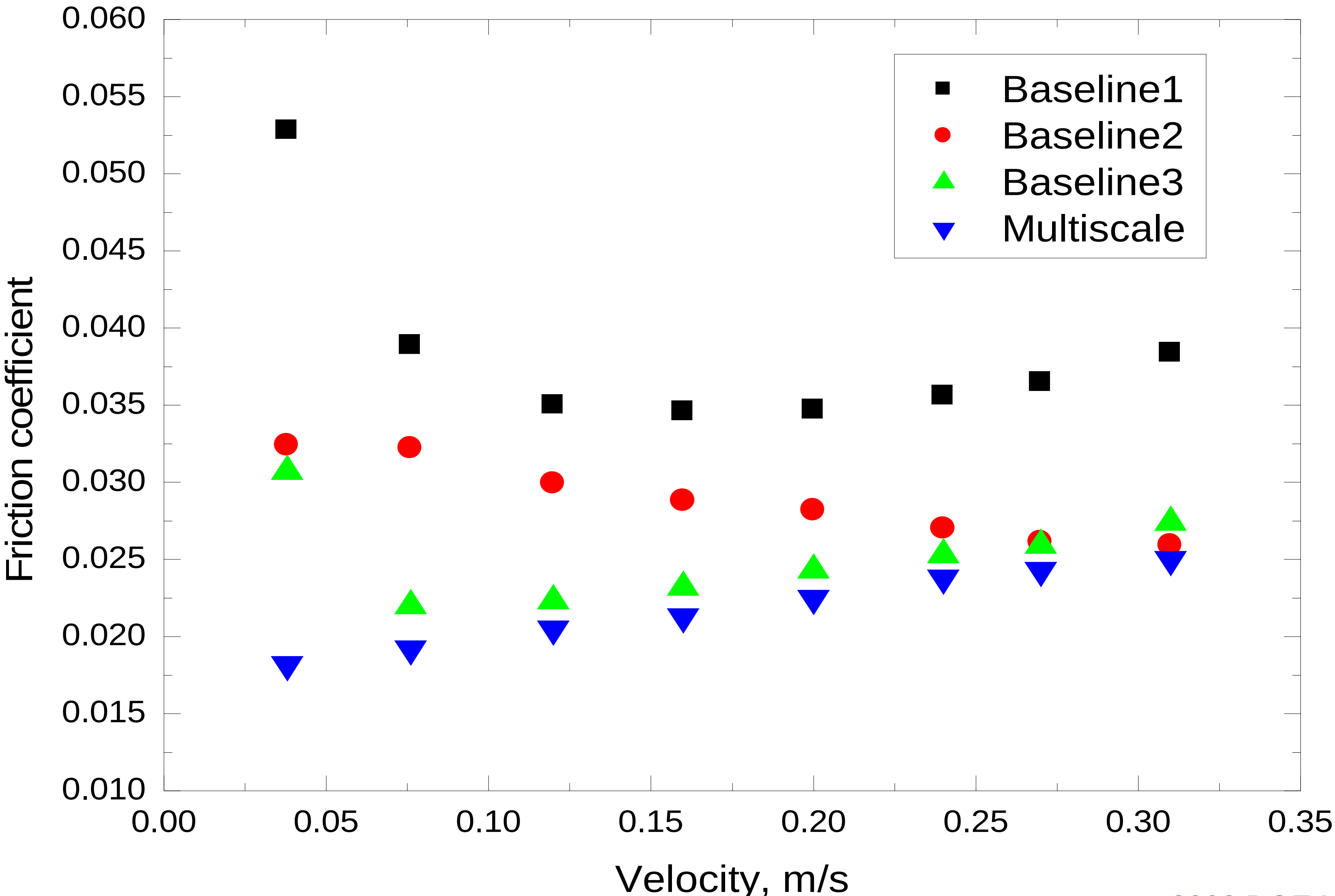
Four-ball wear tester	
Load:	
10 Kg	(157 MPa)
20 Kg	(314 MPa)
30 Kg	(470 MPa)
Speed:	3500 rpm (1.34 m/s)
	3000 rpm (1.15 m/s)
	2500 rpm (0.96 m/s)
	2000 rpm (0.77 m/s)
	1500 rpm (0.57 m/s)
	1000 rpm (0.38 m/s)
	500 rpm (0.19 m/s)

Pin-on-disk wear tester		
Load:		
5 N	(MPa)	
15 N	(MPa)	
25 N	(MPa)	
Speed:	18 rpm	(0.038 m/s)
	36 rpm	(0.076 m/s)
	57 rpm	(0.123 m/s)
	76 rpm	(0.160 m/s)
	96 rpm	(0.202 m/s)
	115 rpm	(0.241 m/s)
	129 rpm	(0.276 m/s)
	150 rpm	(0.314 m/s)

Comparison of all the samples, **157MPa**



Comparison of friction using P-o-d, 15N



This year’s milestones

- Develop thin film coatings on textured samples
- Develop compatible surface chemical coatings to 1) protect the thin film; 2) further reduce friction and pumping losses
- Discussed with industrial partners to test this technology on selected components

Next year goals

- Conduct component tests by industrial partners on textured samples
- Revise textures if necessary to achieve frictional losses
- Continue to pair thin films and chemical bonded films to optimize them for various applications
- Develop a design guideline for the integrated surface technology to promote accelerated commercialization

Conclusion

- Surface texturing has been shown to be able to control interfacial properties
- Detailed example in friction reduction in engine components has been shown
- Other change in materials properties using surface texturing is just beginning
- This technology to increase energy efficiency is important world-wide in the context of global energy supply and demand
- International cooperative research effort is underway to promote mutual savings in energy

IA-AMT

Implementing Agreement For A Programme Of Research And Development On Advanced Materials For Transportation Applications

Mr. Rogelio Sullivan, US DOE, Chairman

A Brief History

- The IEA IA-AMT began in 1985 by the US Department of Energy, US Army, NIST, ORNL to promote the use of advanced materials in transportation technology. The activity focuses on jointly developing materials technologies vital to fuel economy and energy efficiency in transportation
- It also establishes test methods & standards across the national boundaries so that advanced materials can be made available quickly for everyone to achieve energy efficiency goals
- Countries and individual organization, companies can participate in this international technical undertaking.

www.iea-ia-amt.org

Recent energy situation has prompted….

- 2005 G-8 summit at Gleneagles invited presidents from 5 countries were invited to attend as a part of the effort to coordinate efforts in energy & trade (Brazil, China, India, Mexico, & South Africa). The President of IEA was also invited to attend the meeting
- The communique calls for increased involvements by more developing countries to form partnerships in IEA activities to deal with the energy issues
- IEA AMT has been responding to invite China, Brazil, Mexico to join its activities

G8

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

G8 Goals

“We will act with resolve and urgency to meet our shared multiple objectives of reducing greenhouse gas emissions, improving the global environment, enhancing energy security and cutting air pollution in conjunction with our vigorous efforts to reduce poverty“ [Gleneagles]

“We will move forward with timely implementation of the Gleneagles Plan of Action. We have instructed our relevant ministers to continue the Dialogue on Climate Change, Clean Energy and Sustainable Development and report its outcomes to the G8 Summit in 2008” [St. Petersburg]

IEA Response

QuickTime™ and a
TIFF (Uncompressed) decompresso
are needed to see this picture.

- **Advise on alternative energy scenarios and strategies**
- **Transform the way we use energy**
  - Energy indicators
  - Buildings
  - Appliances
  - Surface transport
  - Industry
- **Powering a clean energy future**
  - Cleaner fossil fuels
  - Carbon capture and storage
  - Integration renewables electricity grids
- **Promoting networks for R&D**

Membership

- Current signatory countries: US, Germany, Belgium, Sweden, Canada, UK, China
- Australia, Finland, and Japan have agreed to join AMT
- Poland, Mexico have applied to join
- Invitations to send observers have been issued to Singapore, Israel, S Korea
- Both Israel and Korea have attended the Executive Committee meetings

Implementing Agreement on Advanced Materials (AMT)

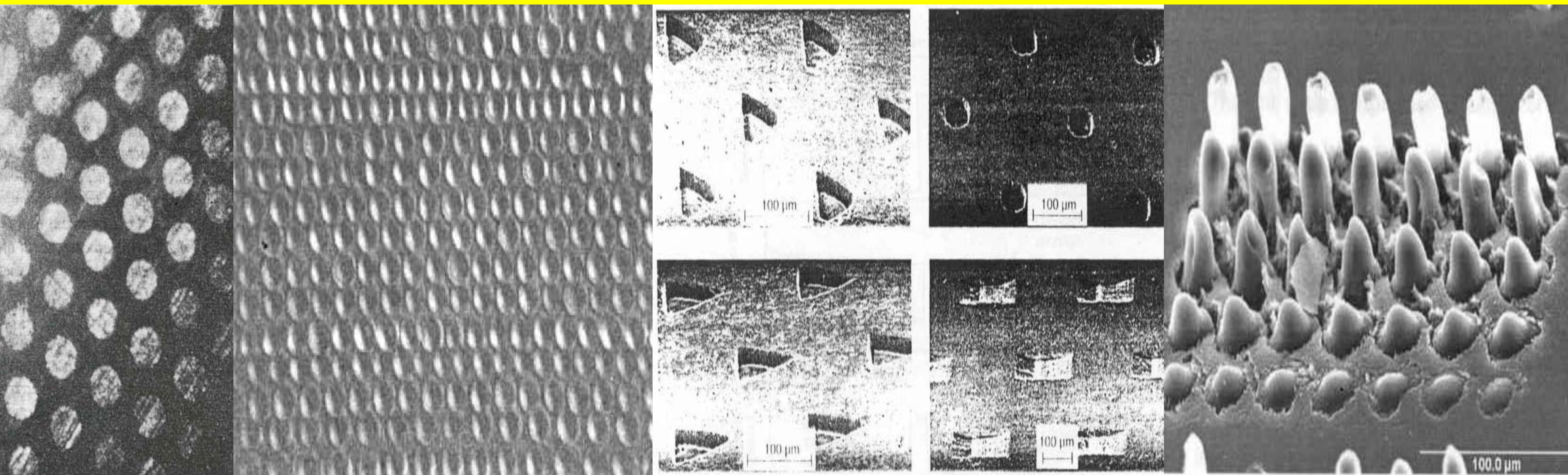
AMT focuses on advanced materials critical to the development of energy efficient, environmental friendly technologies by:

- *Exchange of materials*
- *Develop test methods to characterize new materials*
- *Develop test methods to evaluate performance of these materials*
- *International joint demonstration of new materials technology*

Current annexes and planned technical annexes

- Annex IV – Integrated surface technology for friction control
- Annex V – Magnesium alloy corrosion protection
- Annex VI – Carbon composites for weight reduction
- Annex VII – Nanomaterials, nanostructured materials for weight-reduction, higher strength, longer durability, lower cost, higher performance
- Annex VIII – Advanced coatings for harsh environments such as combustion chambers, liners, rings for wear resistance, friction control, and controlled heat transfer characteristics

Annex IV: an integrated surface technology to control friction



•Chairman: Stephen M. Hsu

•George Washington University

•Washington DC, USA

Objectives of annex 4

- Develop surface texture patterns to control friction of engine components
- Develop synergistic combination of thin films, coatings, with appropriate chemistries to further achieve friction reduction under engine component operating conditions
- International joint technology demonstration
- Project Outcome: Design guidelines of surface engineering for engine components

Annex V Magnesium alloy corrosion protection

Mg Alloys in automotive and truck applications: current status and new directions

- **Wenyue Zheng, Ph.D**
- **Group Leader – Materials Performance**
- **CANMET Materials Technology Laboratory,**
- **Natural Resources Canada (NRCan)**
- **568 Booth St., Ottawa, Canada**
- **Wenyue@nrcan.gc.ca**

Corrosion: a technical barrier for Mg application

<u>Modes of Mg corrosion in automotive environment:</u>

-General corrosion: alloy chemistry, impurities…
-Galvanic corrosion: dissimilar metals
-Stress corrosion/corrosion fatigue: stress/environment synergy

University of Sunderland

Low Cost Carbon Fibre for Vehicle Weight Reduction

Alan Wheatley
University of Sunderland

amap

Nanomaterials technical plan as a new IEA annex

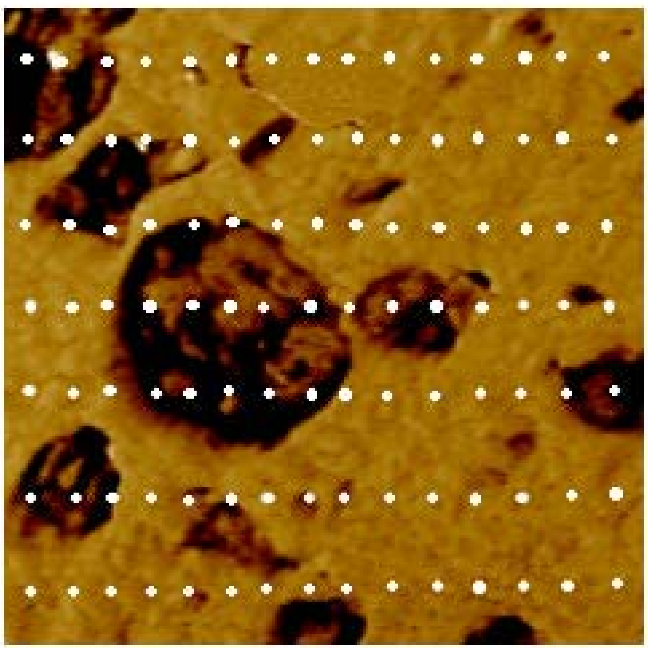
- Leaders:
- Stephen Hsu (GWU USA)
- and Tom Malis (NRC Canada)

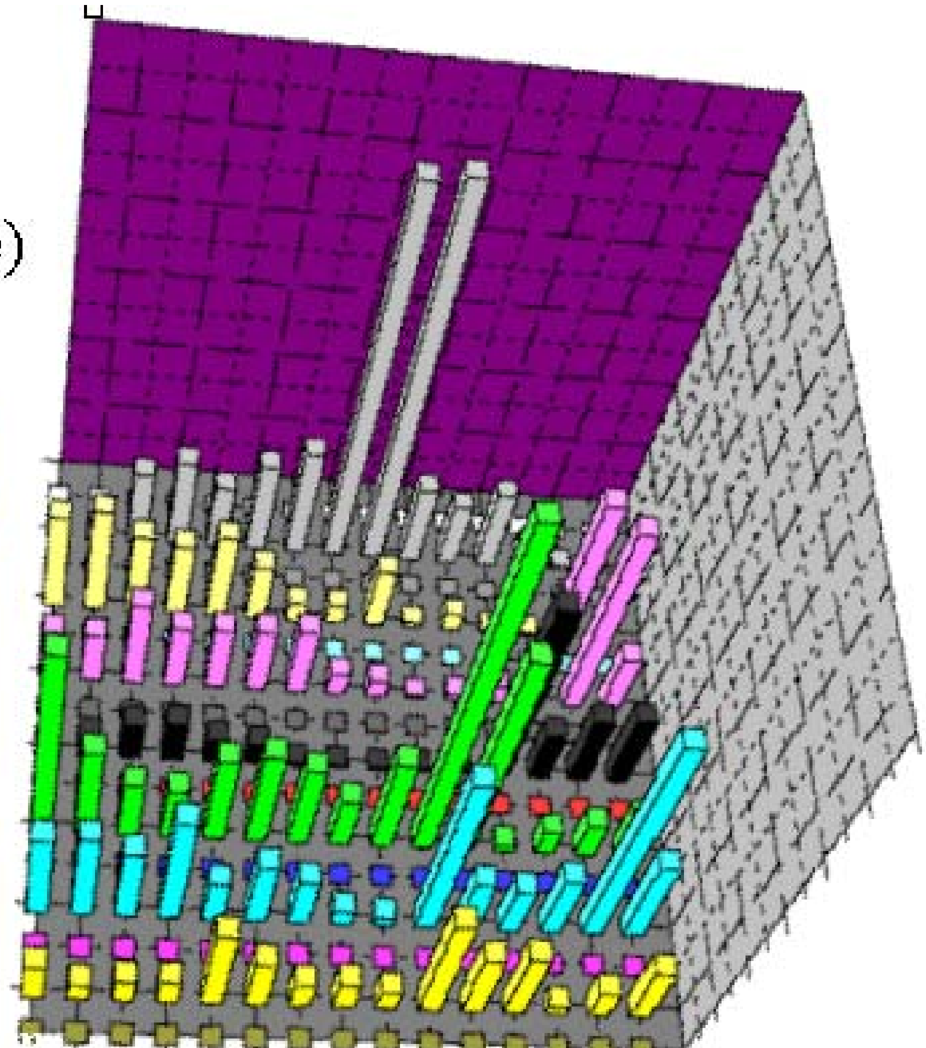
Problem definition

- Clay particle dispersed polymer blends exhibit strong mechanical properties and can be injection molded for metal substitution
- The mechanical strength depends on the degree of dispersion of the nanoparticles within the polymer matrix
- Macro mechanical property testing found variations among batches
- How to measure/predict/monitor the quality of such materials?

Modulus Mapping on TPO: 15x7

Modulus Mapping of
TPO (4 μm phase image)





Conclusions

- World energy demand and supply is at an historical tight level
- Developing countries are consuming much higher petroleum to fuel their industrial development
- IEA provides an international forum to exchange technical information and promote joint technologies that will reduce oil consumptions world wide
- Leveraging each other's effort in energy efficiency technology and practice will save oil consumption together

Presentations:

- “The Influence of Surface texturing on friction and adhesion: from nm to mm,” Plenary Lecture, Ecotrib 2007, Ljubjana, Slovenia, June 13-15, 2007.
- “Surface texturing of Ecomaterials,” Keynote Lecture, the 8th International Eco-materials Processing and Design Conference, Kitakyushu, Japan, Jan 11-13, 2007.
- “Design of surface textures for heavily loaded contacts,” S. M. Hsu, STLE Annual meeting, Calgary, Alberta, Canada, May 8-11, 2006.
- “Surface texture and interface properties,” John Crane Packing Co., Morton Grove, Chicago, IL, May 31, 2006.