An Integrated Surface Technology for Optimum Performance

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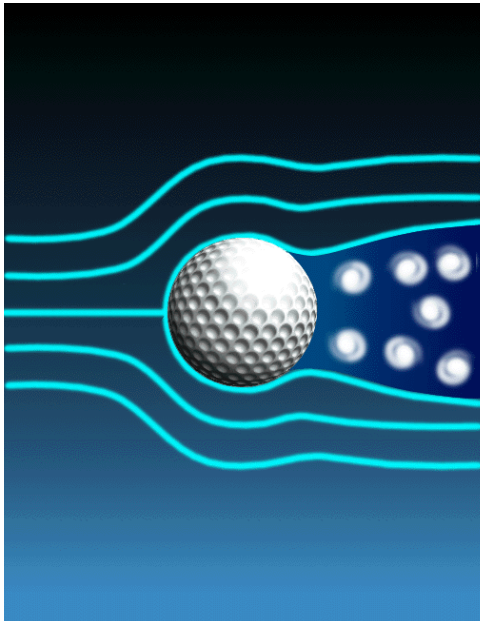
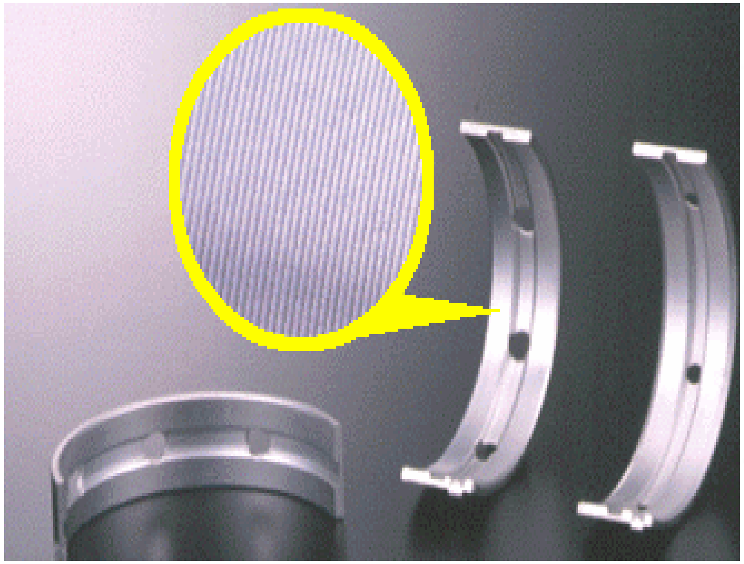
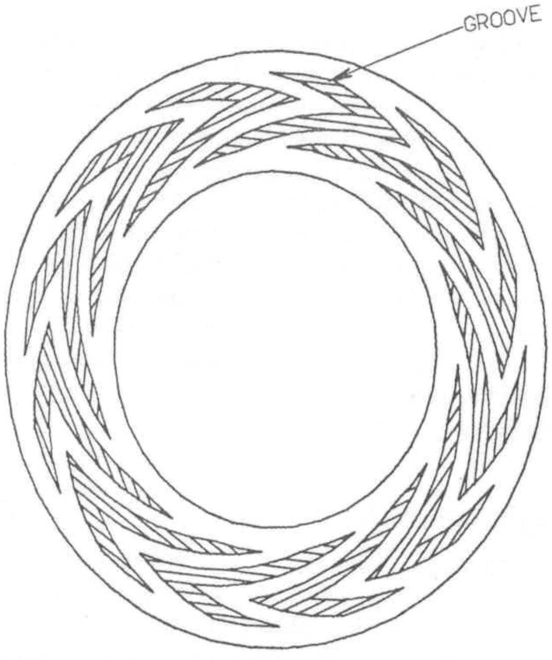


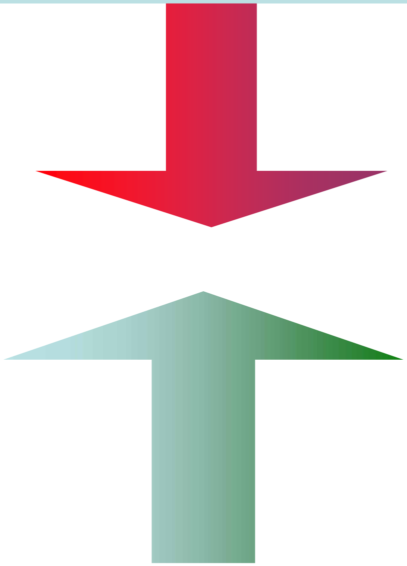




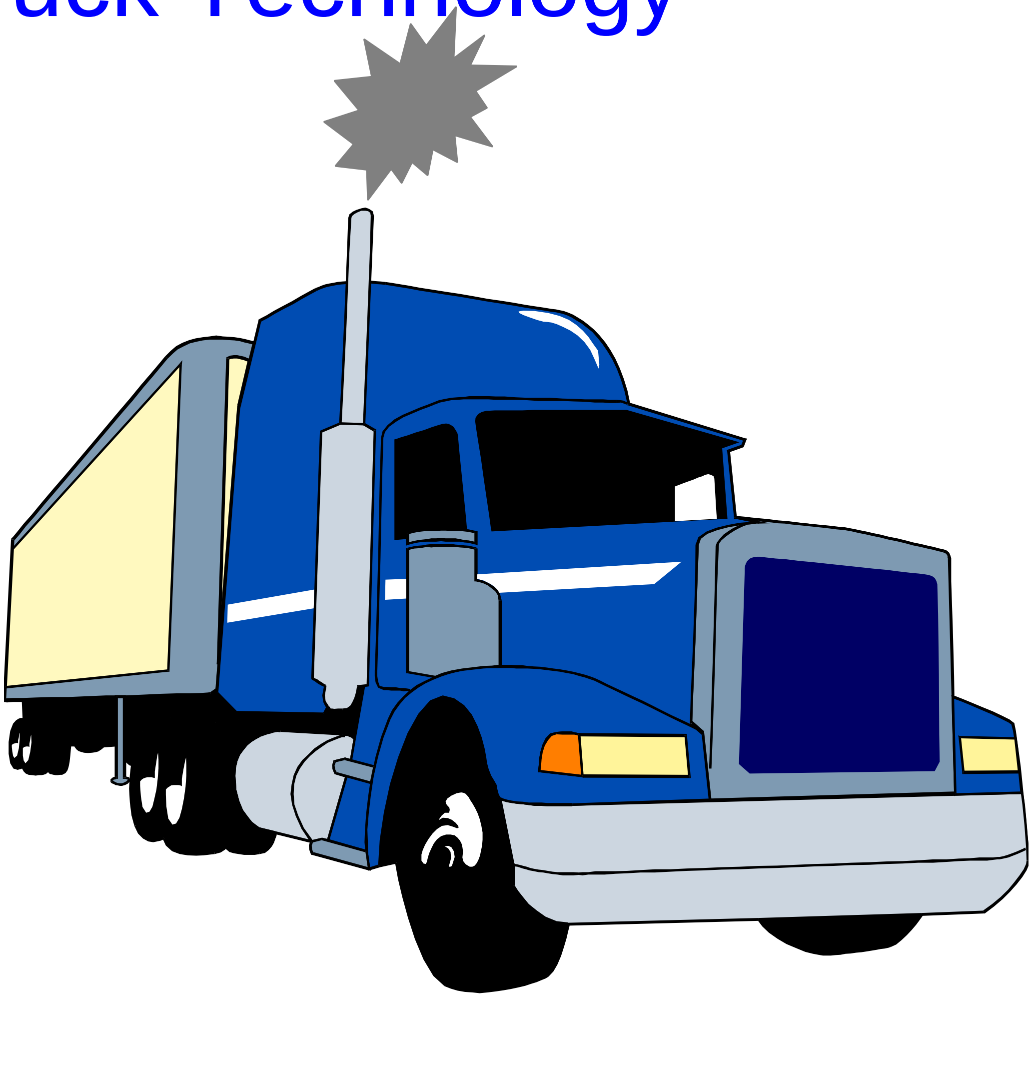
Motivations

Heavy-Duty Truck Technology

- Fuel Economy



- Emissions
  - Hydrocarbons
  - NOx
  - Nanoparticles



Implications for Engine Technology and Materials Technology

- Friction reduction a priority
  - Heavy duty diesel engine highly loaded
  - High operating temperatures
  - Friction reduction for trucks is difficult
  - Largest fuel economy gains have been in aerodynamics, viscosity reduction, weight reduction
- Durability of critical engine components
  - Directly affects service intervals/down-time
  - Fuel injectors wear is a serious concern
  - Current lubrication technology will not be able to provide significant improvement to fuel economy or durability

Alternative approach??

New Opportunity

- New technology advances in
  - Surface texturing
  - Quasi-crystalline films
  - Diamond-like carbon films
  - Multi-layer nm sandwich
  - Nanomaterials (nanostructured thin films)
  - Radically new lubricant chemistry (nanoparticles, self-assembled molecules)

Potential exists for an optimized combination of surface textures, thin films, and new chemistries to create a new surface technology that controls friction for fuel economy and durability in engines

Surface Texturing

- A physical way to change the contact interface by designing specific features into the surface to induce or enhance the following:
  - Wear particle trapping (eliminate abrasion)
  - Lubricant reservoir (high temperature, high load)
  - Hydrodynamic fluid lift under high speed low load
  - Micro-plasto hydrostatic lubrication

Positive & negative features

Dimples, grooves, ellipse

Geometric patterns: hexagonal, square, triangular

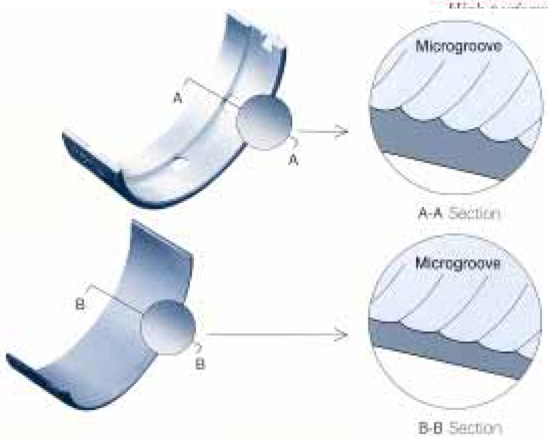
TAIHO, 1995

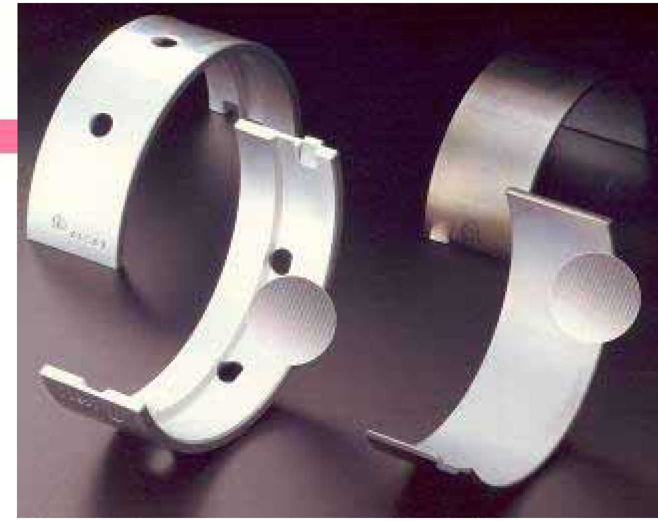
エンジン用軸受
Engine Bearing

マイクログルーブベアリング

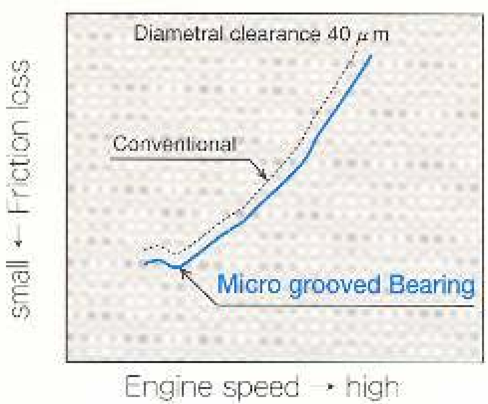
Micro grooved Bearing

軸受性能を大幅に向上させた高機能エンジン軸受
High-performance engine bearing with dramatically improved bearing performance



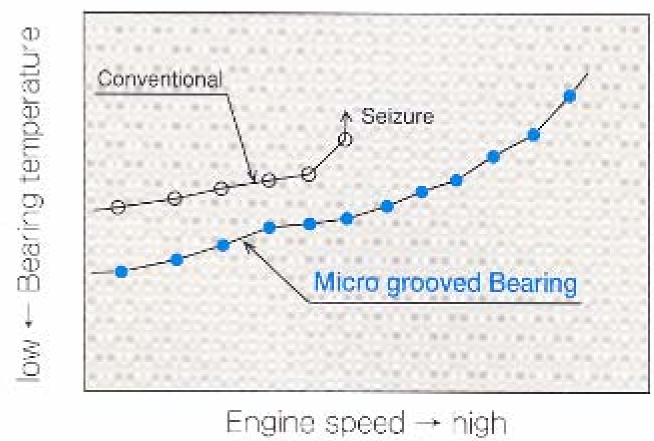


1. Frictional property



Test machine
A-type engine

3. Seizure resistance



Evaluation condition
Crankshaft bearing of gasoline engine

So Why This Has Not Caught On?

- Benefits demonstrated at high speed, low load region for dimpled surface, primarily in seals applications
- High speed low load regime is not the most important technological area in most engine applications
- Cost of texturing vs benefits, careful surface finishing can yield significant benefits (not clear what is the max. benefits from sophisticated texturing which is largely unexplored)
- Lack of theory and understanding on how to design these features and how these features will impact friction and durability under what set of conditions

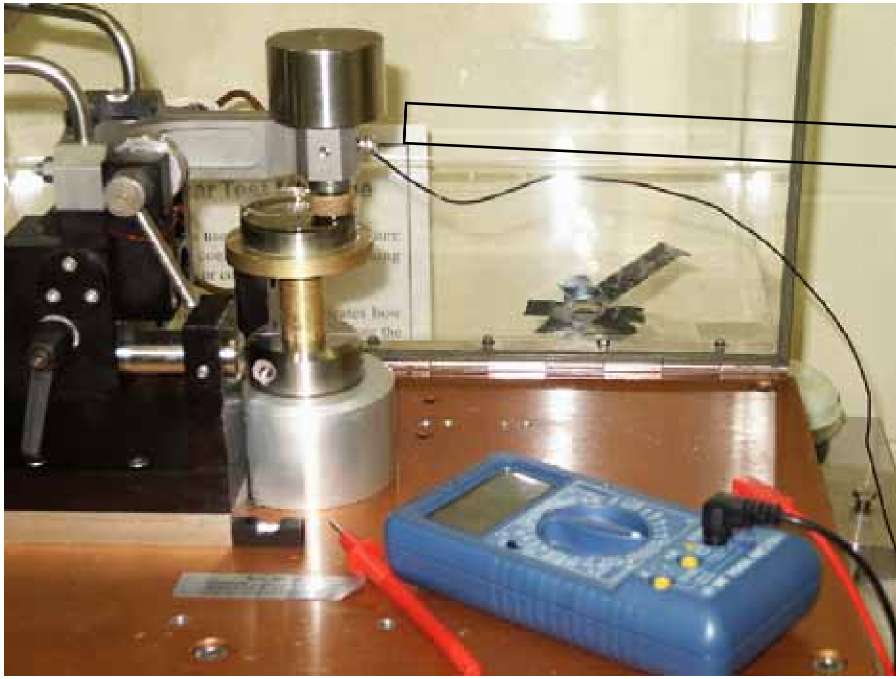
Region I: High-speed, low-load conditions

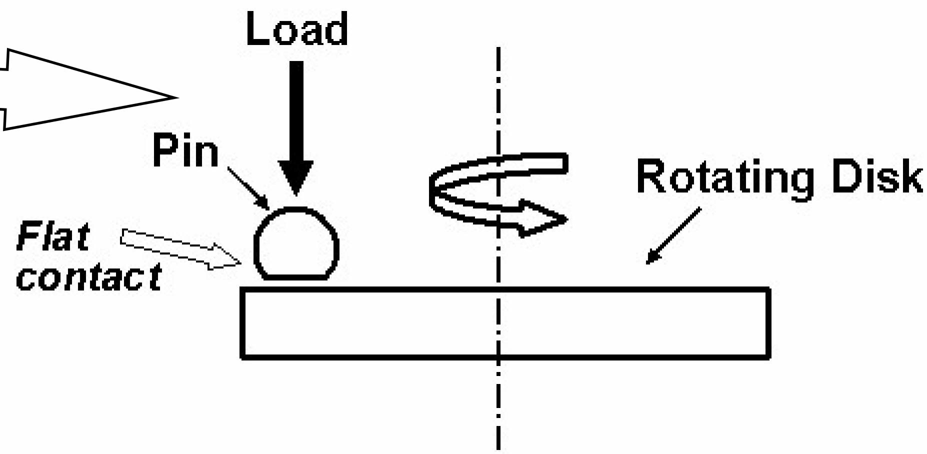
Steel on steel

- 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

- The shift from mixed lubrication regime to hydrodynamic

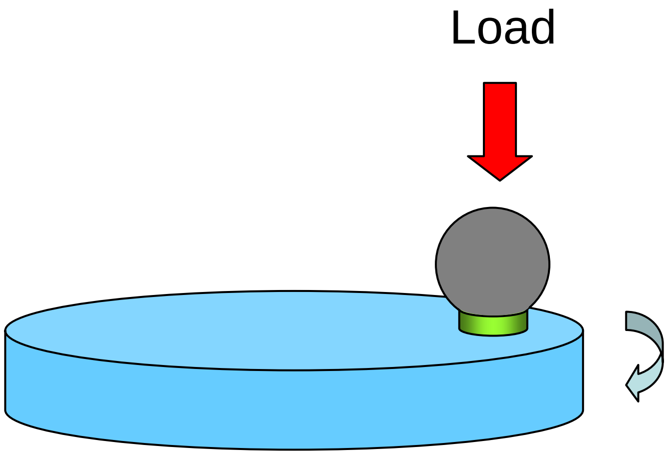
Experimental Procedure





Flat pin
Pin-on-disk fric. machine

Modified Flat-on-Disk Test Conditions



Material: steel/steel

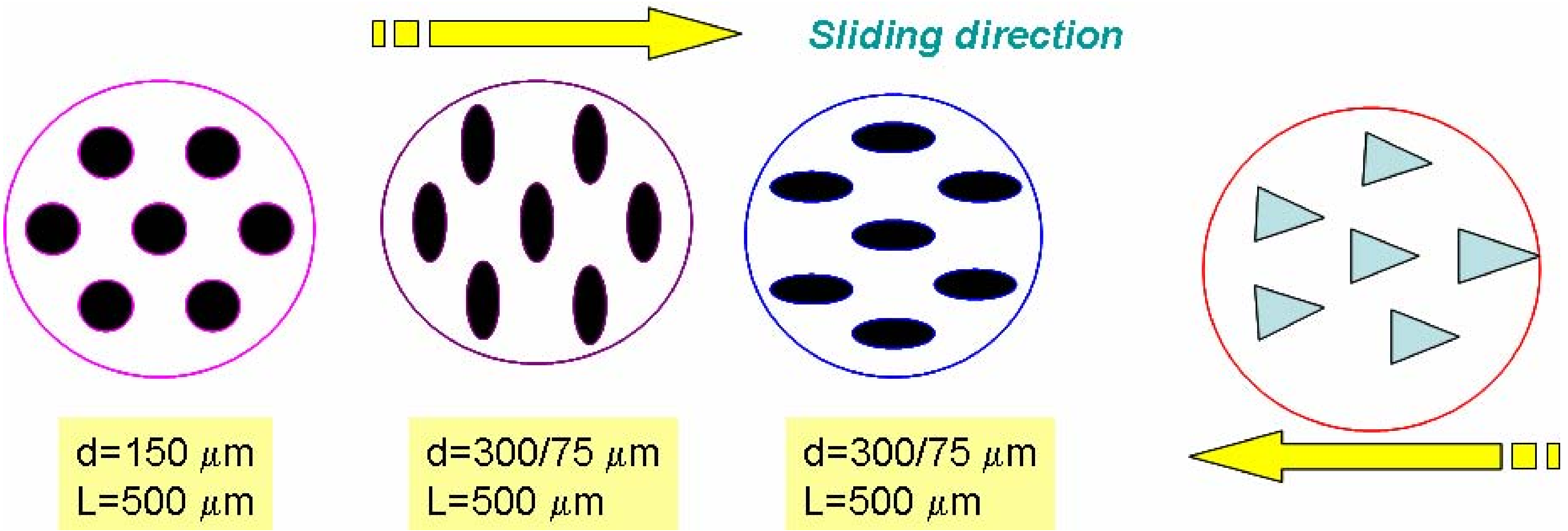
Diameter of small disk: 6.35 mm

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

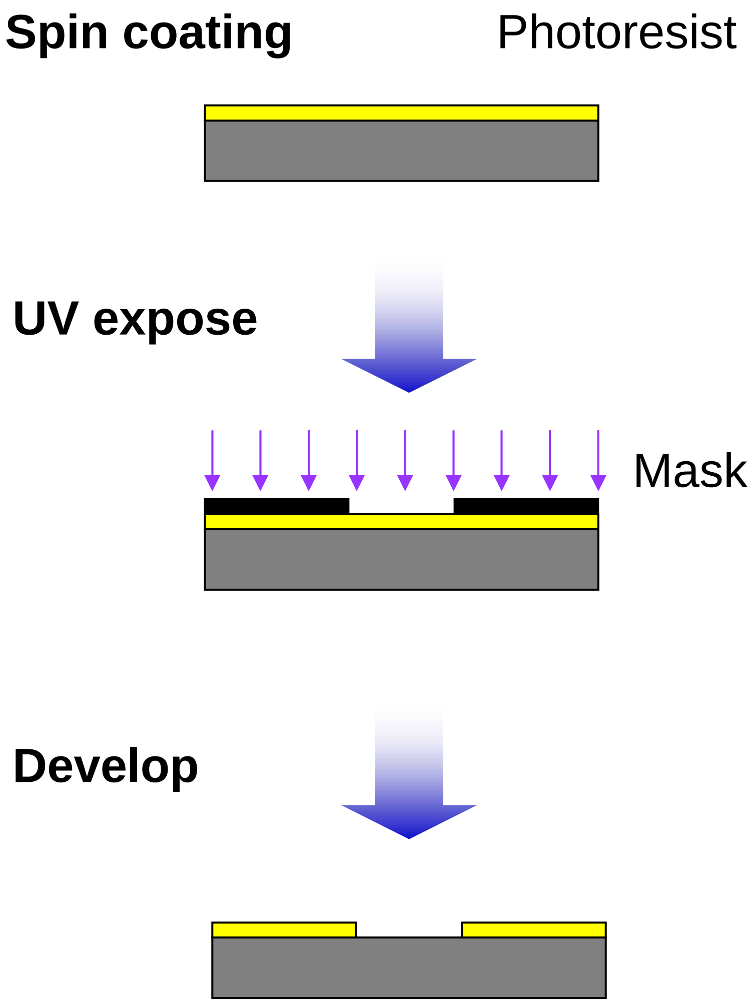
Lubricant: purified parafin oil
(Saybolt number 125/135)

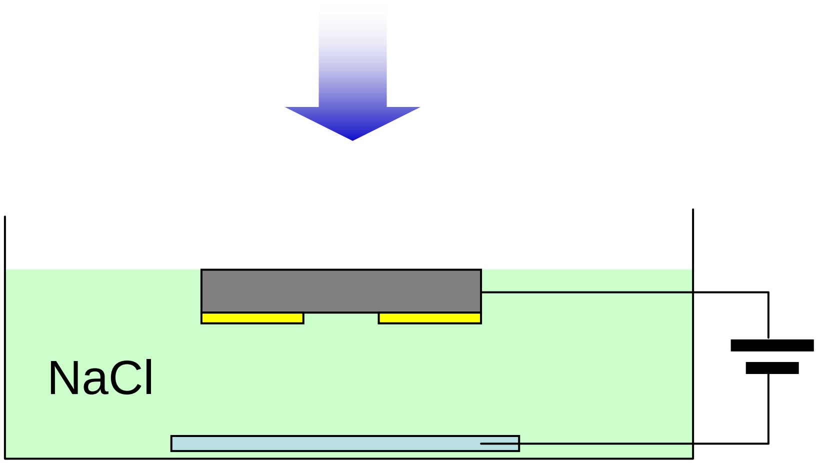
Temperature: room temperature

NIST study: The effect of shape, distribution with same number, same area density, different shape and distribution at low loads and high speeds

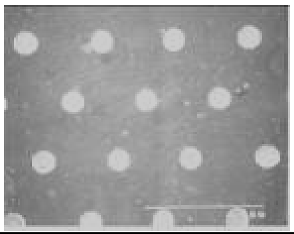
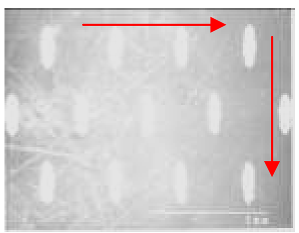
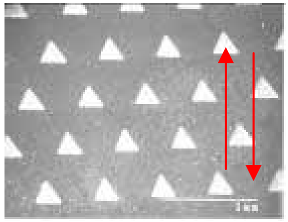


Microlithograph and Electrochemical Etching



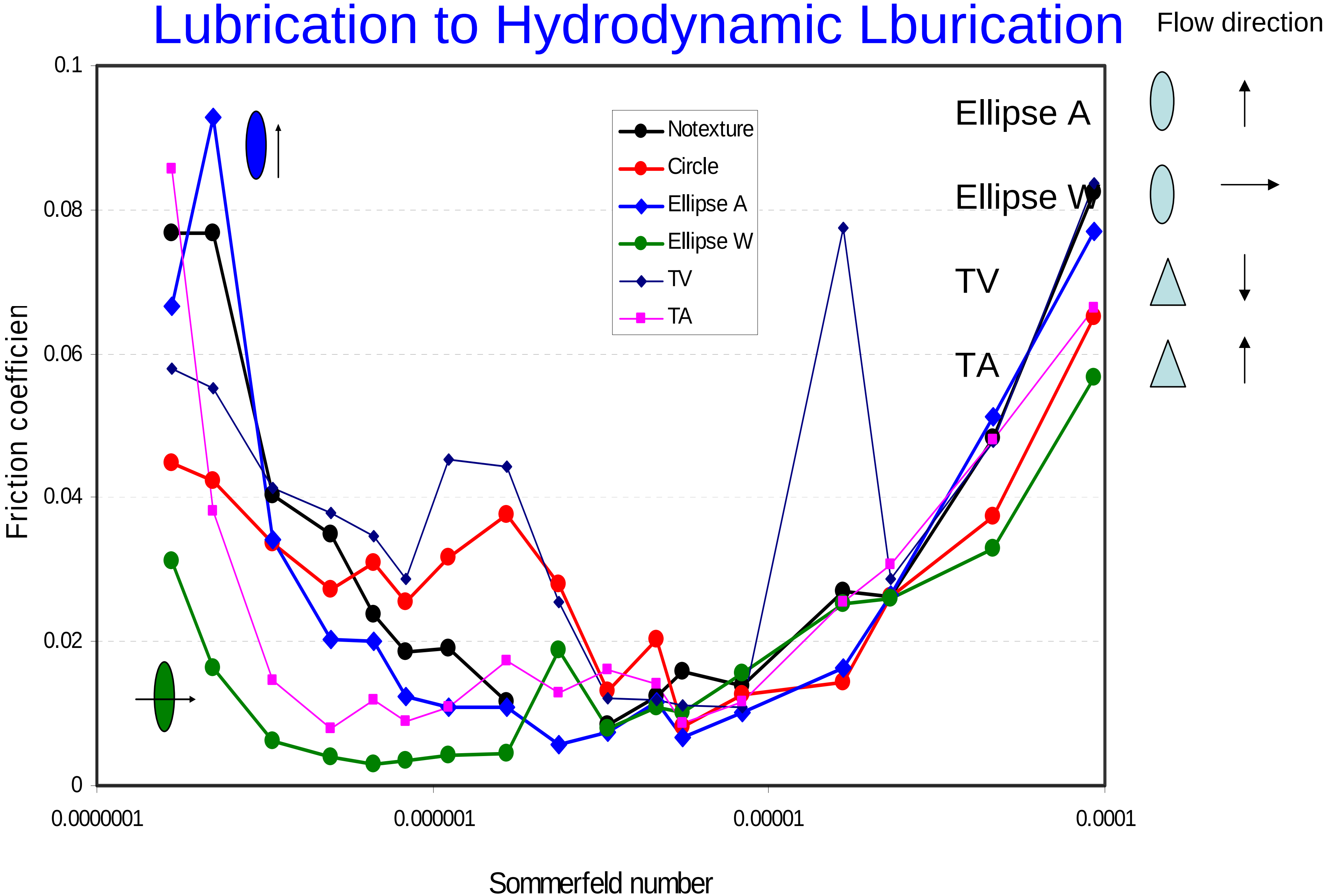


Features of Surface Texture

	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

Effect Of Geometry on Transition from Mixed Lubrication to Hydrodynamic Lburication

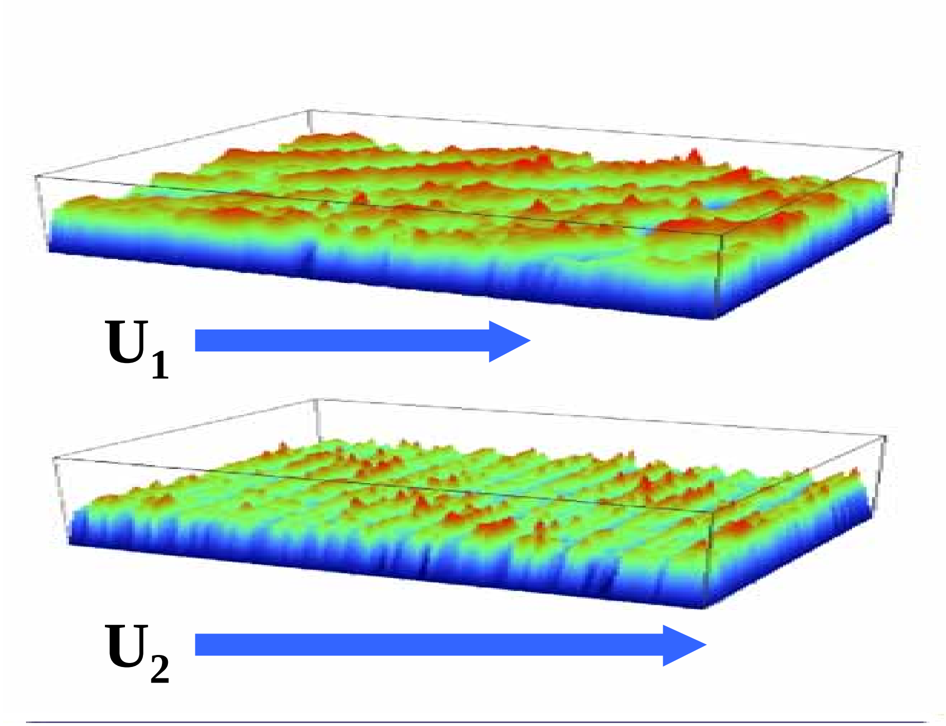


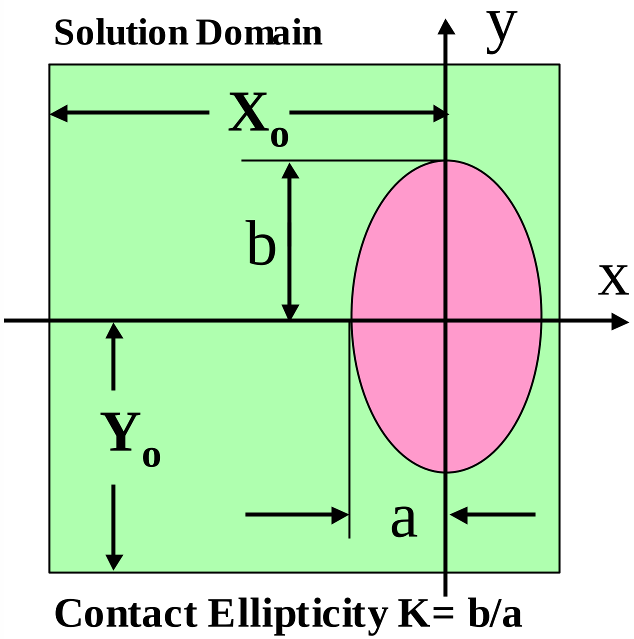
What does the theory say?

- Work with Eaton and Northwestern University to explore models to check the results
- Computer simulation model developed over the past 10 years on surface roughness based on pure fluid flow phenomena
- This is their model in collaboration with us

A Transient Mixed EHL Model

Zhu and Hu's mixed lubrication model (1999-2001) can be used as a design tool to predict the contact and lubrication characteristics and optimize the component surface finish, performance and life. It can also serve as a base of **"Virtual Texturing".**





Basic Equations

Reynolds Equation

$$\frac{\partial}{\partial x}\left(\frac{\rho}{12\eta^{*}}h^{3}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho}{12\eta^{*}}h^{3}\frac{\partial p}{\partial y}\right)=U\frac{\partial(\rho h)}{\partial x}+\frac{\partial(\rho h)}{\partial t}$$

Film Thickness Equation

$$h=h_0(t)+B_x x^2+B_y y^2+V(x,y,t)+\delta_1(x,y,t)+\delta_2(x,y,t)$$

Elasticity Equation

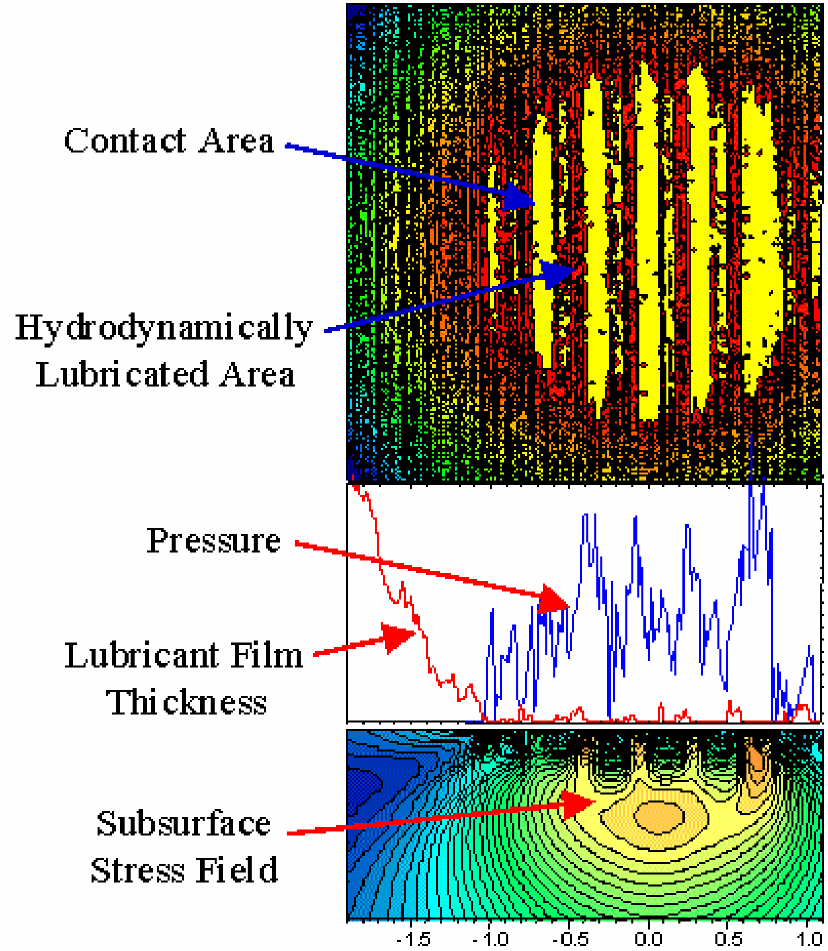
$$V(x,y,t)=\frac{2}{\pi E'}\iint_{\Omega}\frac{p(\xi,\varsigma)+p_c(\xi,\varsigma)}{\sqrt{(x-\xi)^2+(y-\varsigma)^2}}d\xi d\varsigma$$

Friction in Mixed Lubrication

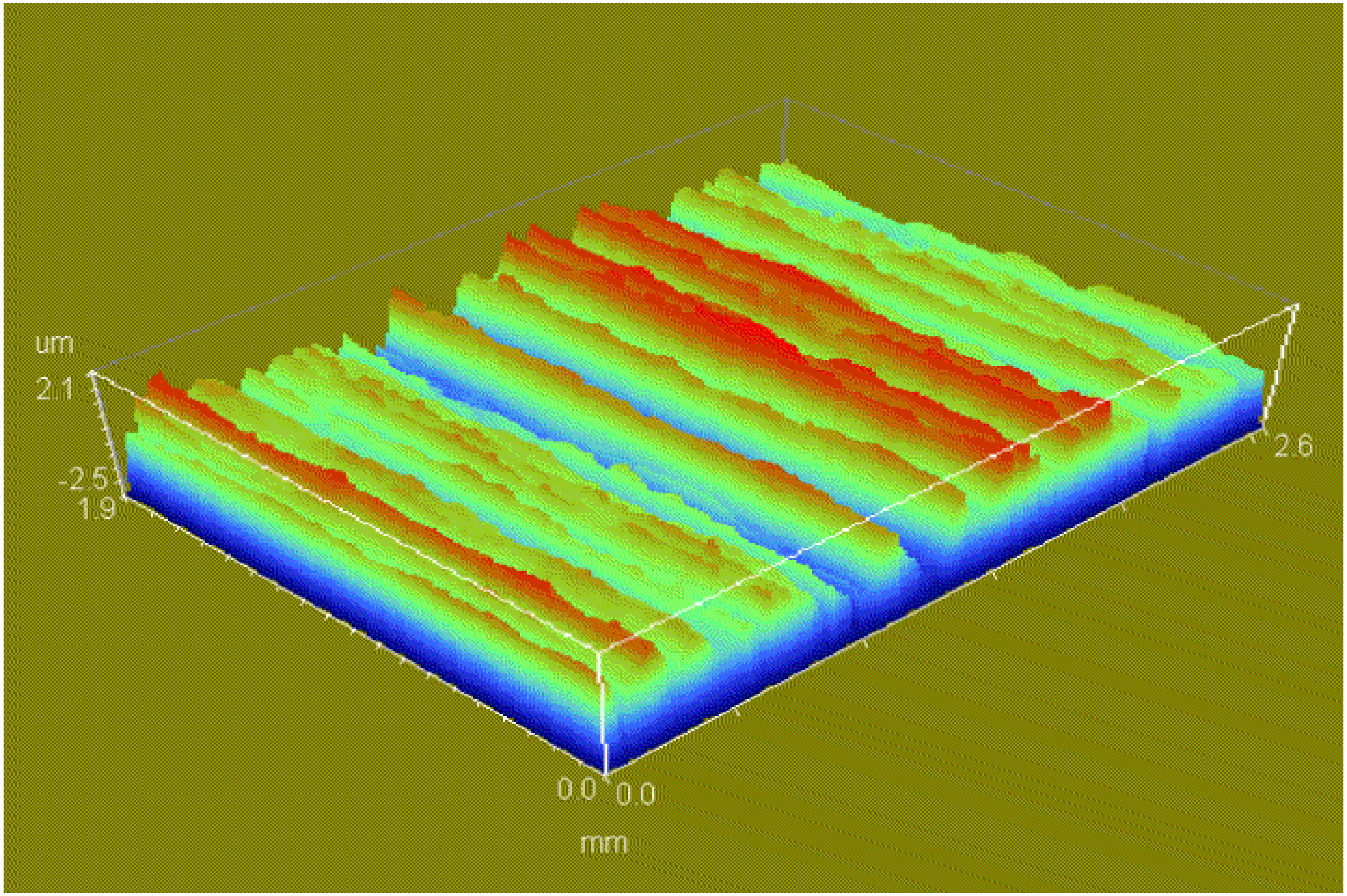
In hydrodynamic areas:
using Bair & Winer's non-Newtonian elastic-viscous fluid model:

$$\dot{\gamma} = \frac{\tau}{G_x} - \frac{\tau_L}{\eta} \ln\left(1 - \frac{\tau}{\tau_L}\right)$$

In contact areas: using an experimentally estimated boundary lubrication coefficient of friction (Typically 0.08 ~ 0.12).

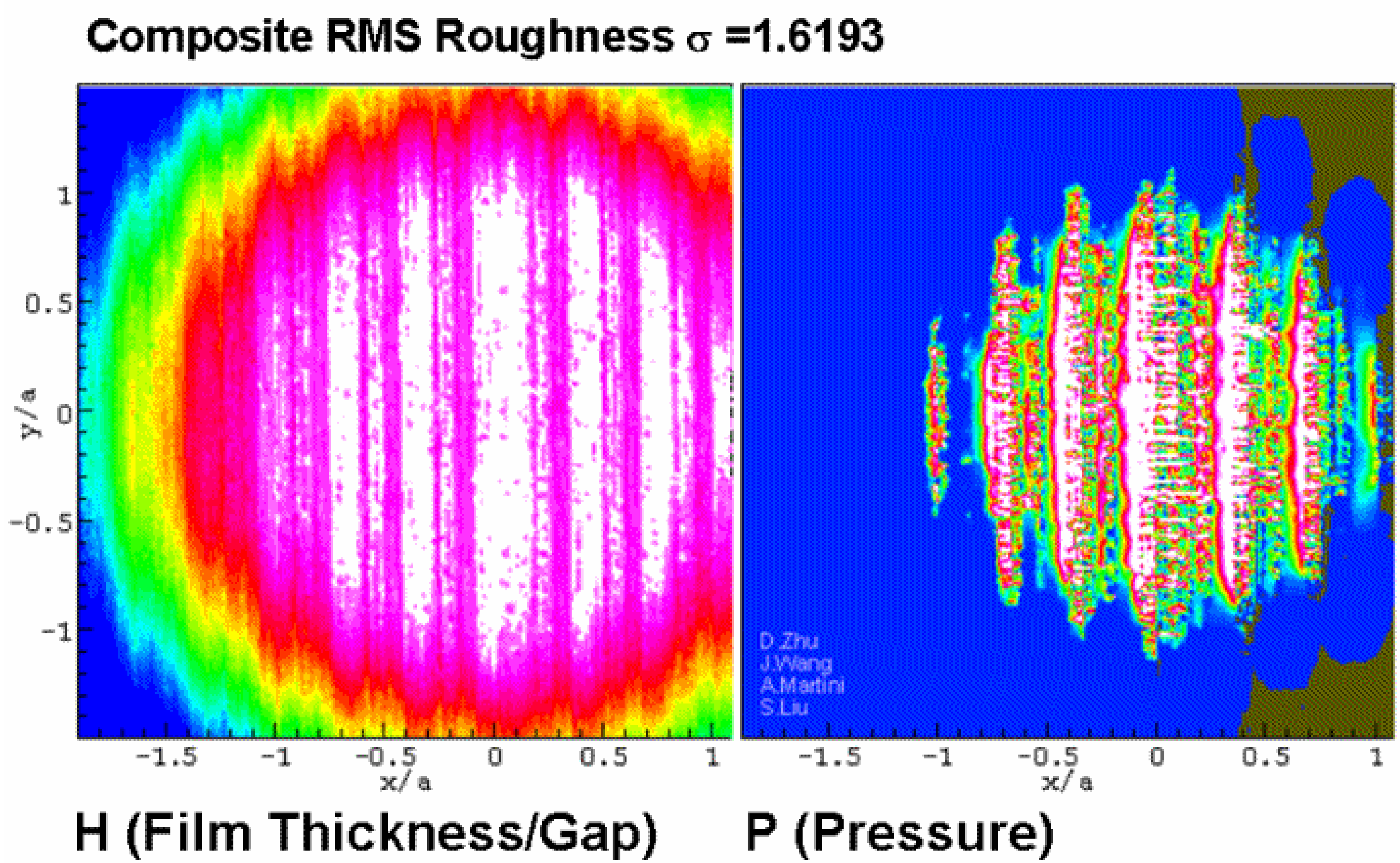


Ground Surface



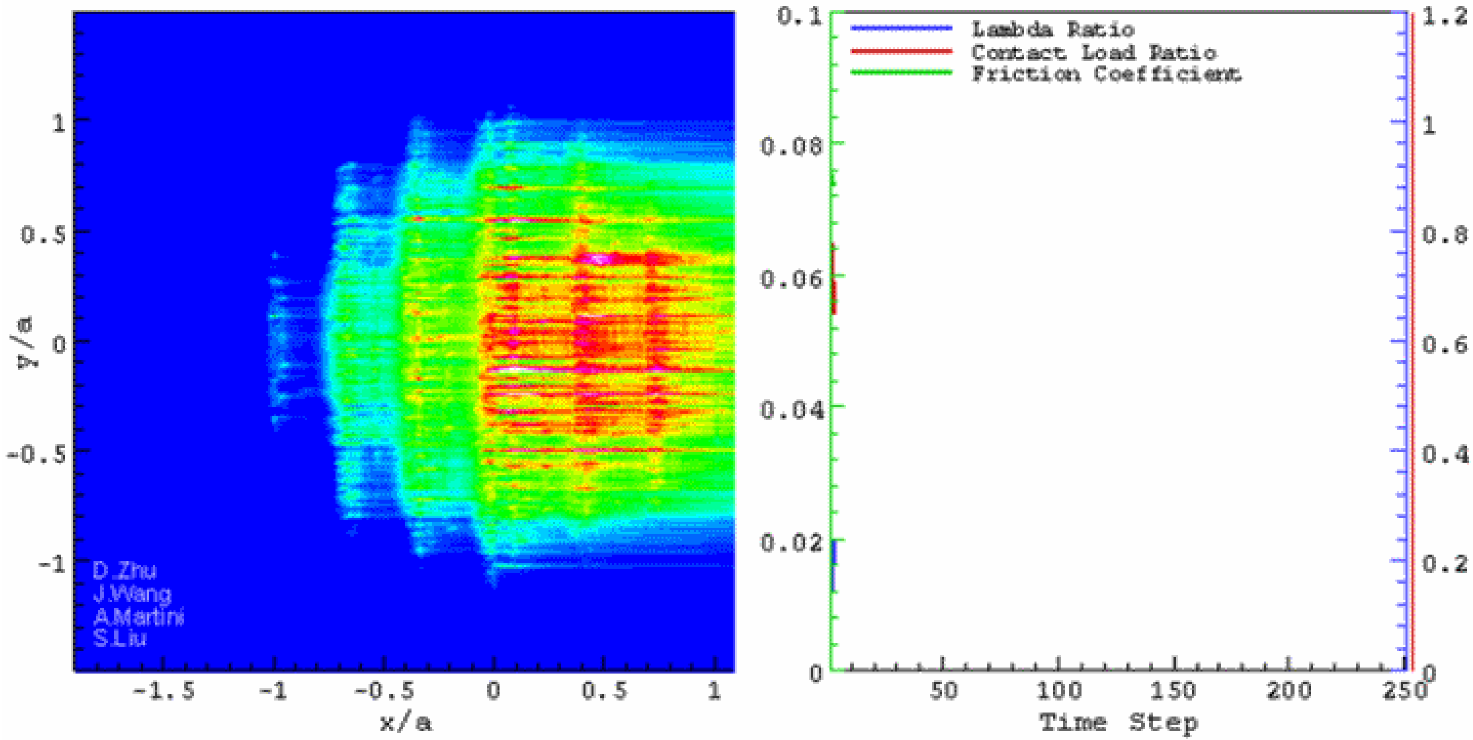
Ra= 0.9288 μm, Rq= 1.1400 μ m, Rz= 12.620 μ m

Solution for Ground Surfaces

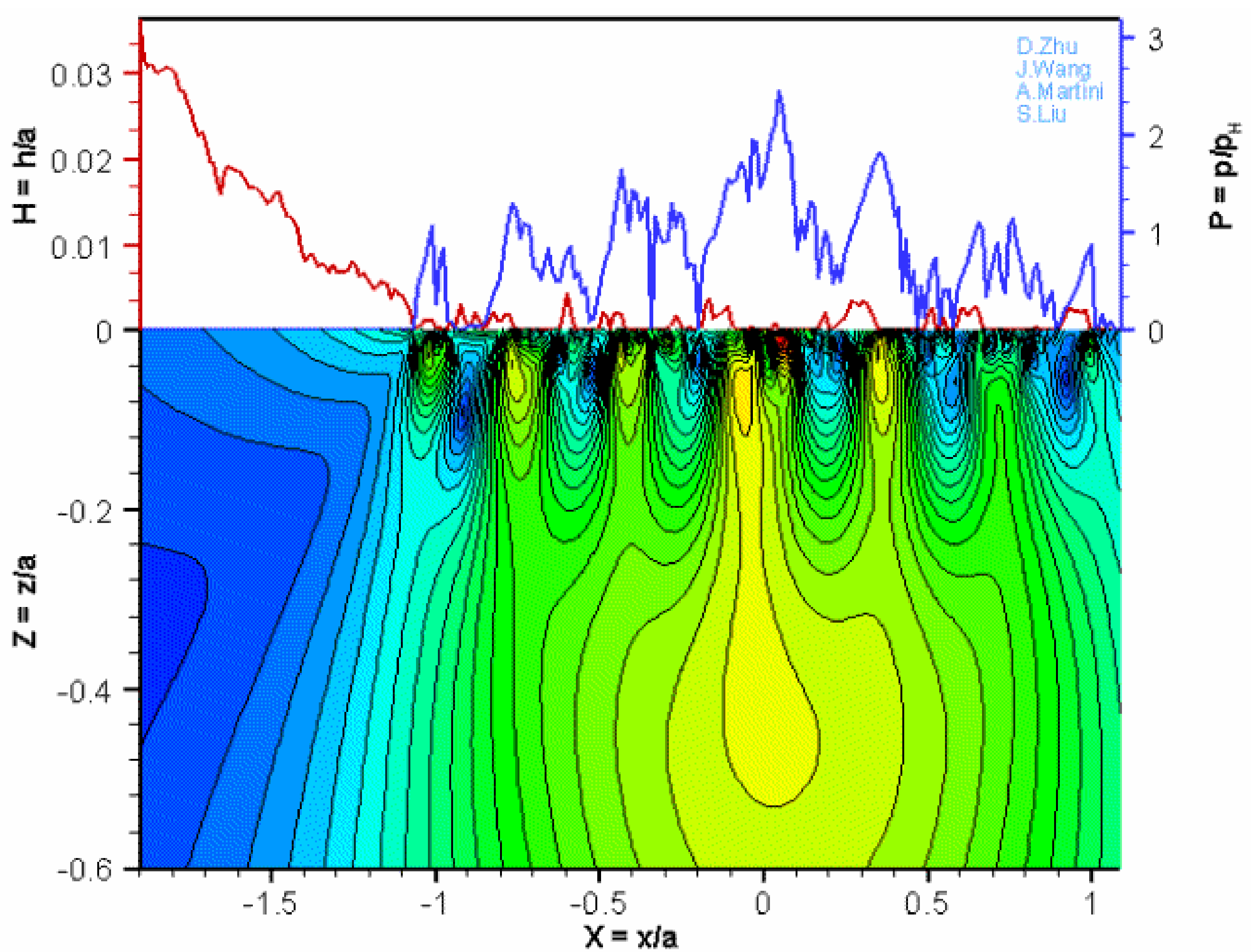


Solution for Ground Surfaces

Composite RMS Roughness σ =1.6193

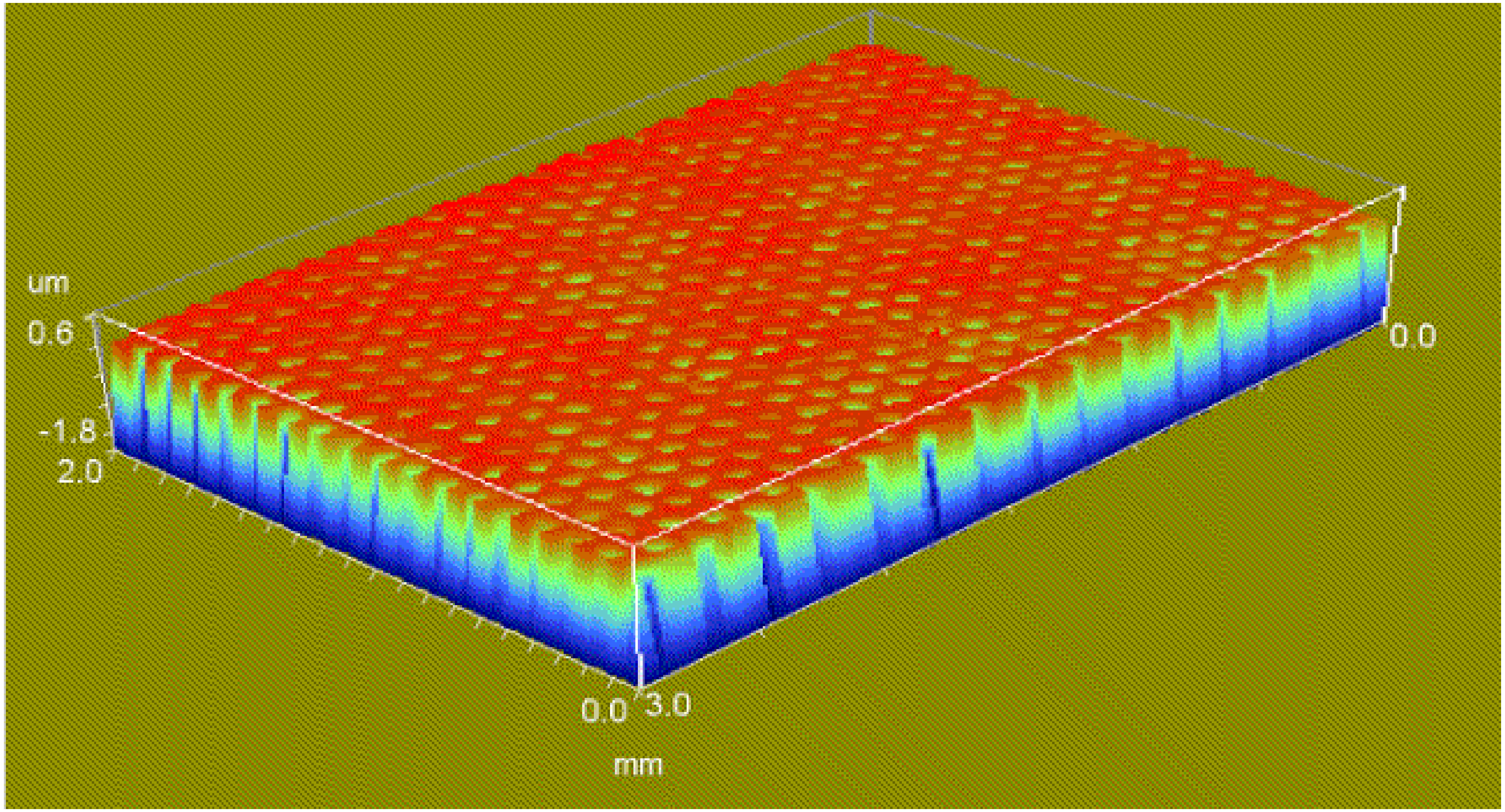


T (Flash Temperature)



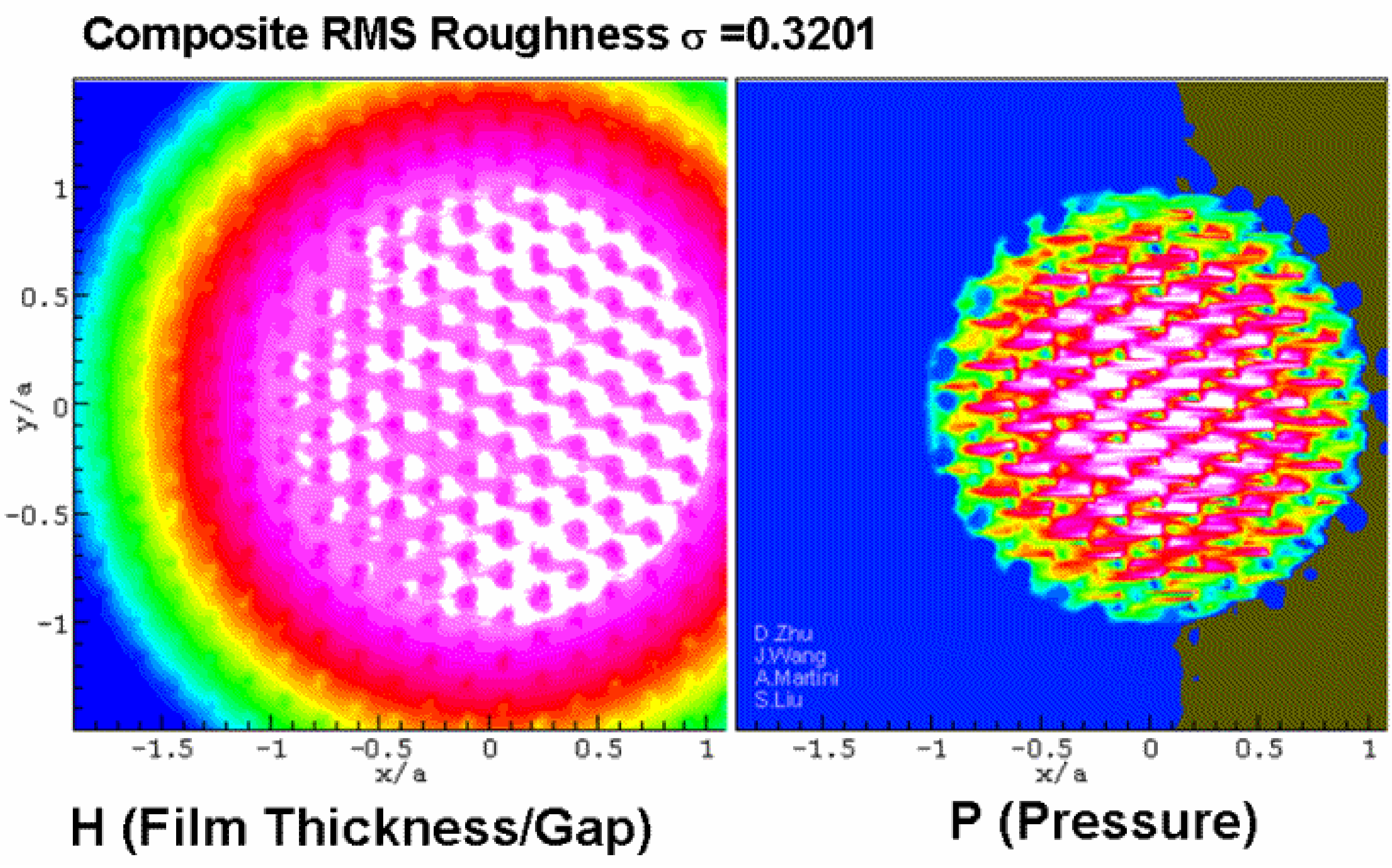
D.Zhu
J.Wang
A.Martini
S.Liu
H = h/a
P = p/p_H
Z = z/a
X = x/a
0.03
0.02
0.01
0
-0.2
-0.4
-0.6
3
2
1
-1.5
-1
-0.5
0.5

Dimpled Surface

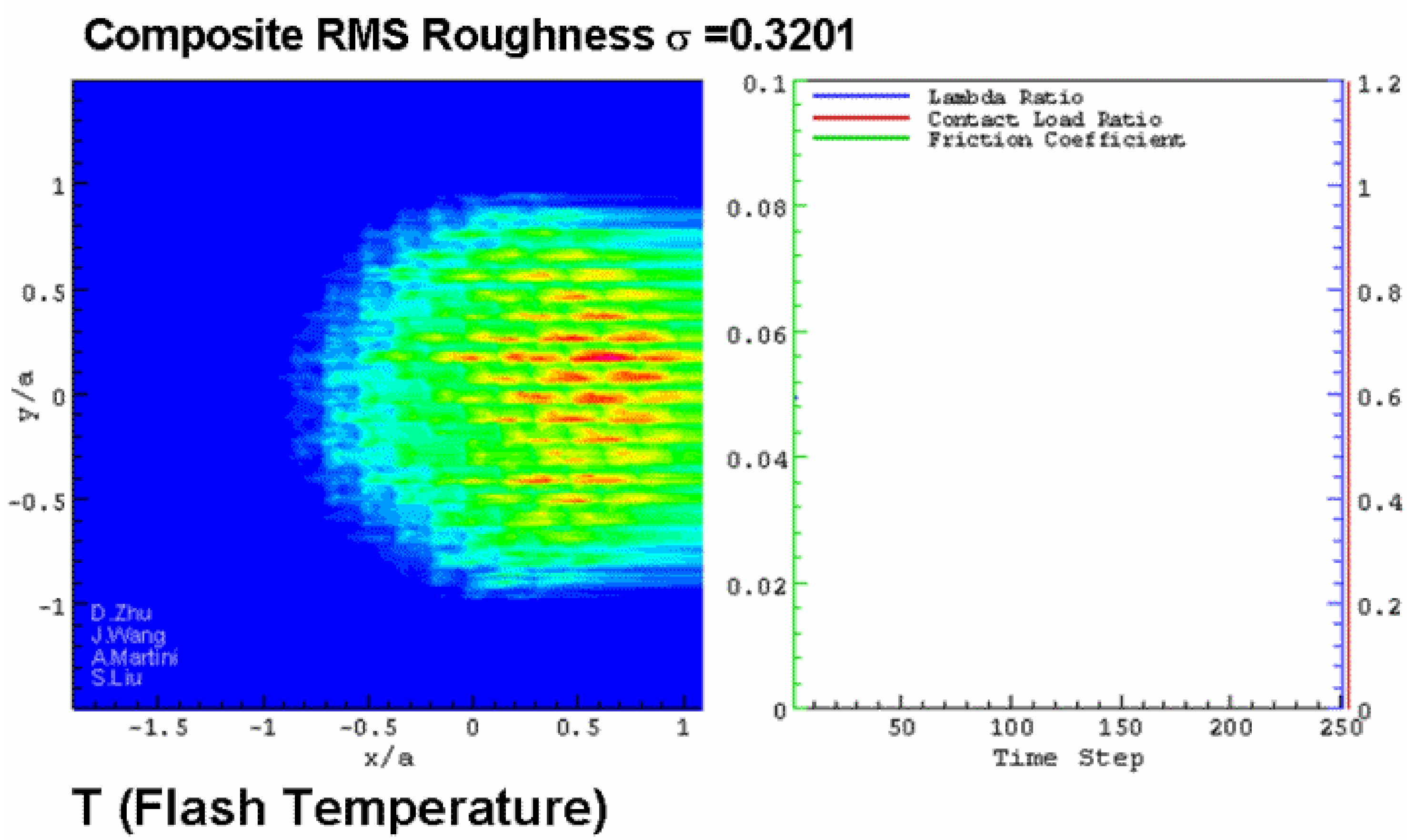


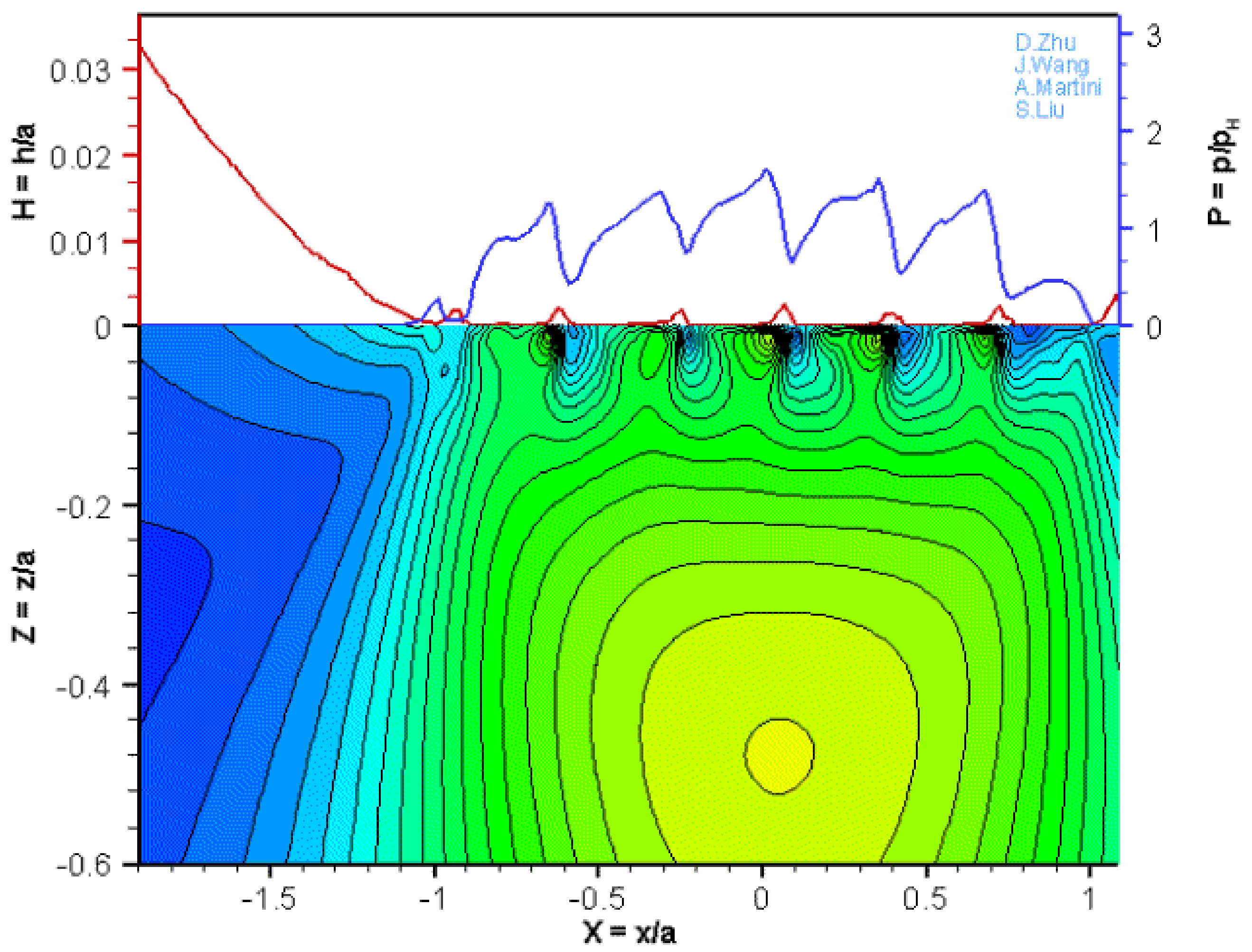
Ra= 0.1987 μm, Rq= 0.304 μ m, Rz= 10.04 μ m

Solution for Dimpled Surfaces



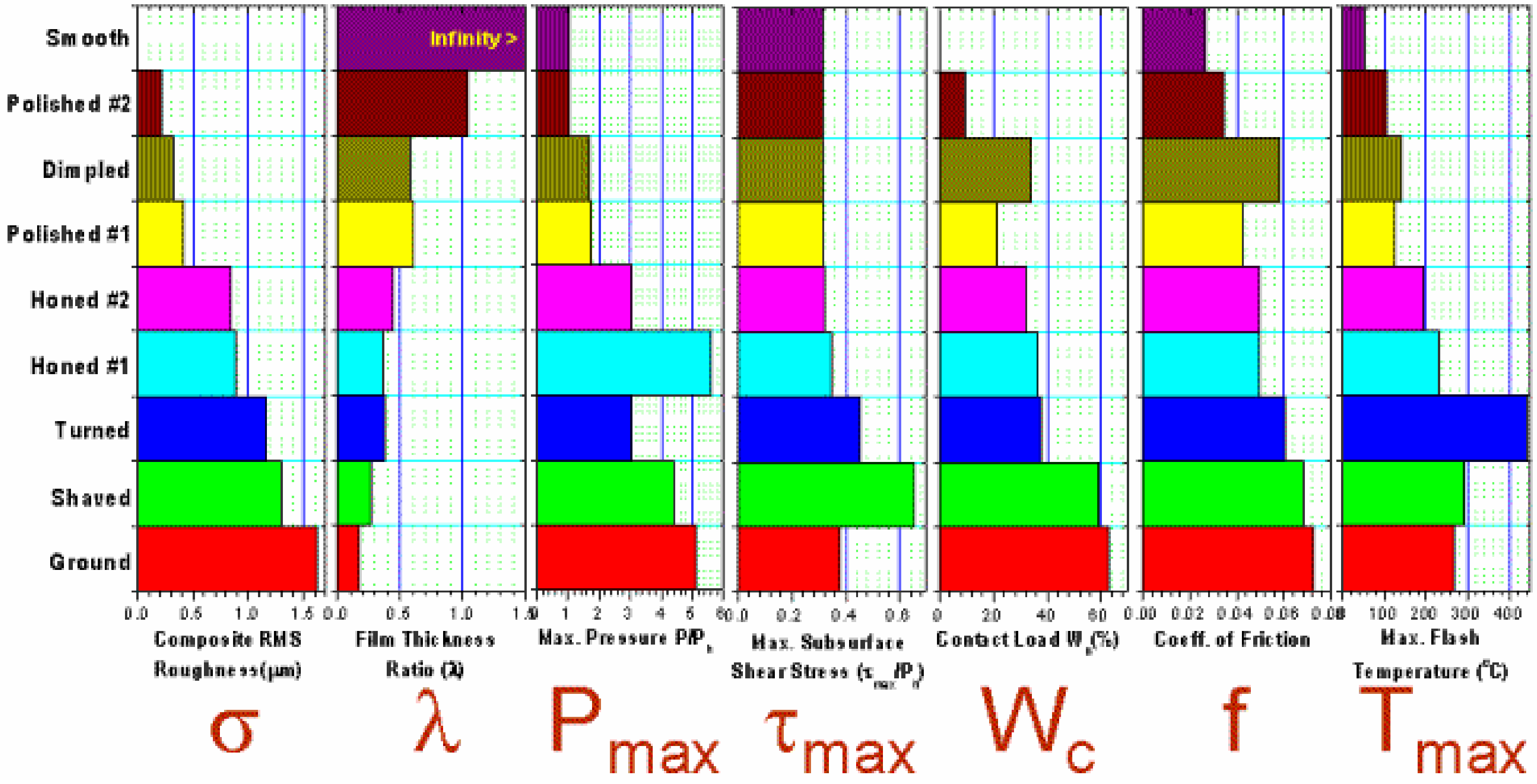
Solution for Dimpled Surfaces





D.Zhu
J.Wang
A.Martini
S.Liu
0.03
0.02
0.01
0
H = h/a
3
2
1
0
P = p/p_H
-0.2
-0.4
-0.6
Z = z/a
-1.5
-1
-0.5
0
0.5
1
X = x/a

Summary of Comparison



The model suggests

- Benefits from low contact pressure
- Simulations at GPa range suggest dimples increase friction
- This agrees with our experimental results

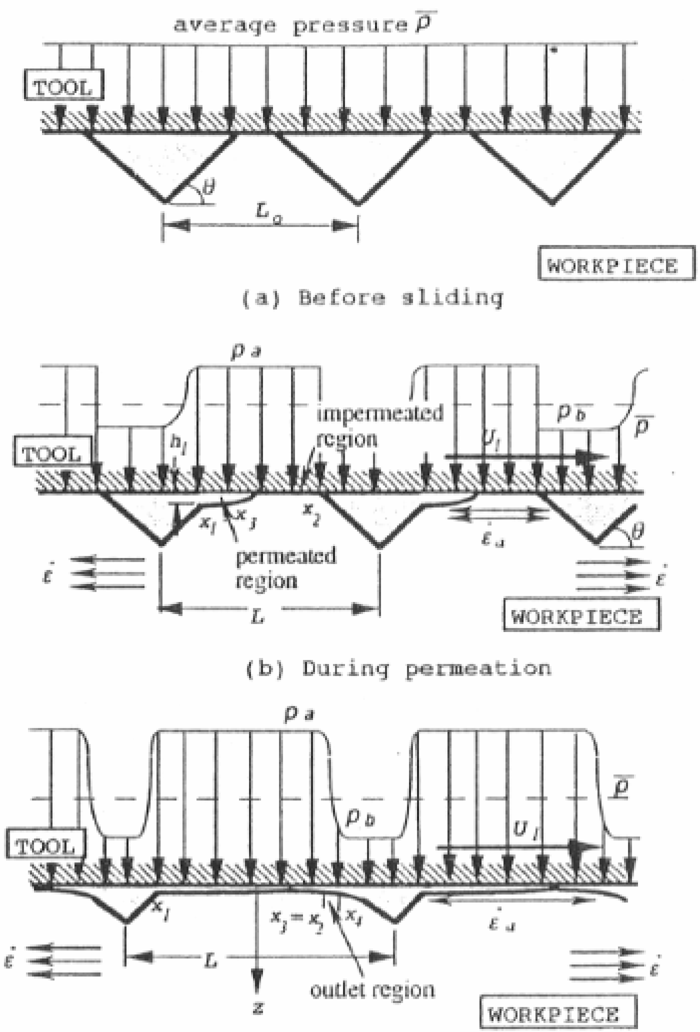
Surface texturing

- Energy saving needs to be in high load, slow to medium speed range
- How to design surface features to generate micro-hydrodynamic pressure where none exists under heavily loaded contacts?

Region II. High load, low speed regime

- Current pin-on-disk apparatus is limited to applied loads
- Gears, transmissions, cams operate at much higher loads
- Develop a way to make measurements on ball-on-three flats geometry in a four ball wear machine

Hydro-elasto-lubrication



(a) Before sliding

(b) During permeation

(c) After permeation

High pressure

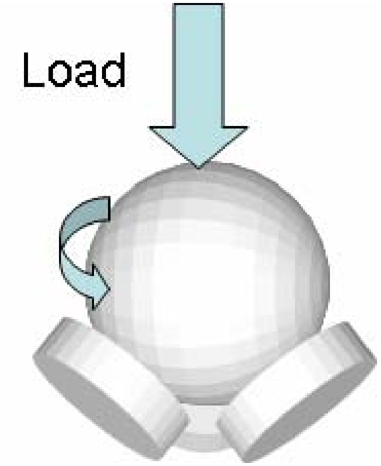
Deformation

Squeeze

Lubrication

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

Tester: Ball on Three Flat

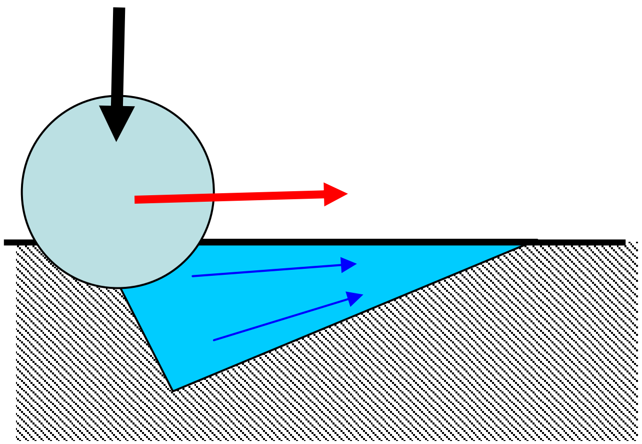


Materials: 52100 steel ball
52100 steel flats
Brass flats

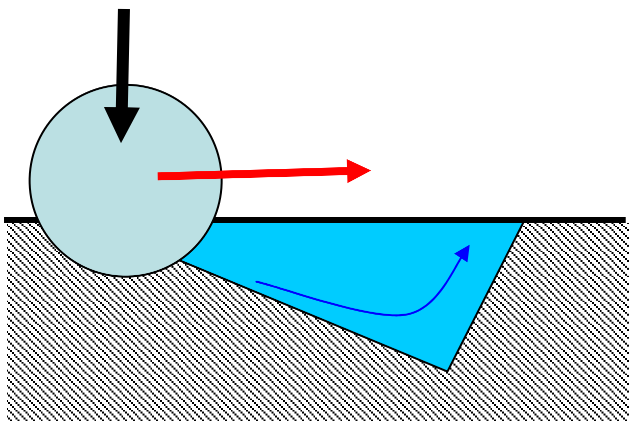
Rotating speed: 500 rpm – 5000 rpm
(0.19 m/s – 1.9 m/s)

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

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



Create hydrodynamic lift

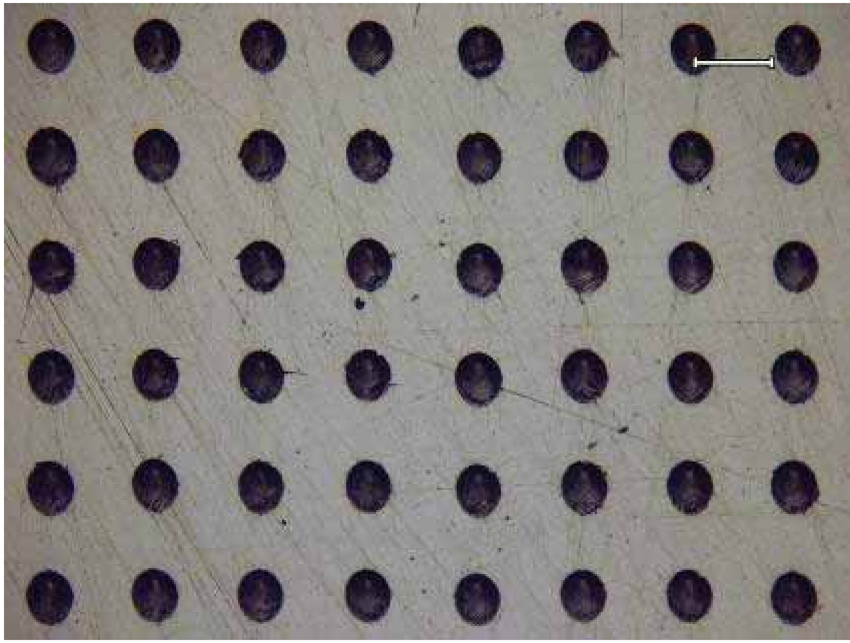


Forced fluid pressure

New Texture Design

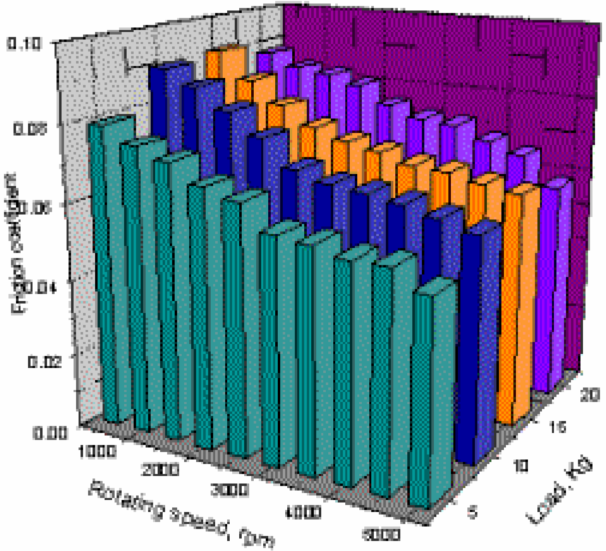
Load: 5, 10 Kg (maxima pressure 500MPa)
Speed: 600 rpm, others: room temperature.

Diameter: 40-60, Pitch: 100 μm, Depth: 8 μm

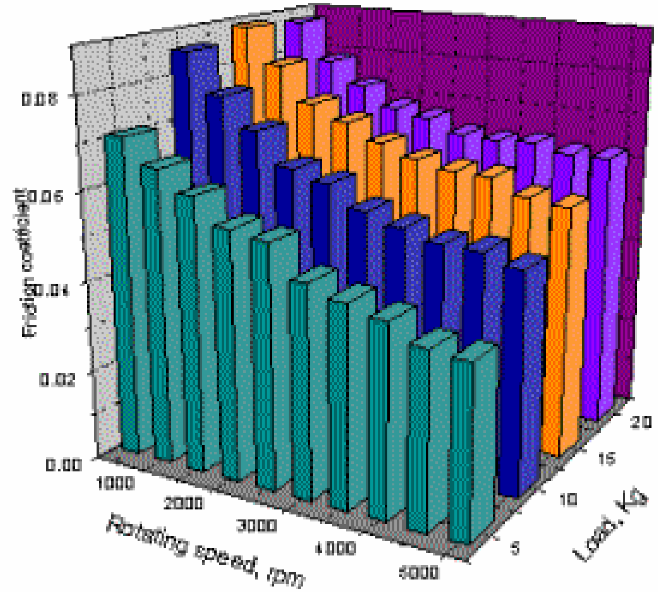


Sloped bottom to artificially generate hydrodynamic pressure

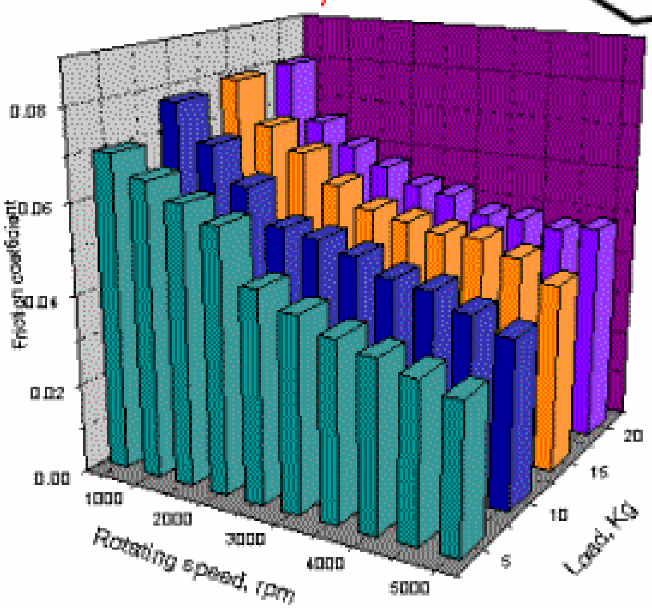
Etched circle dimples, $\phi 40 \mu m$ depth 5-6 μm, density 30%



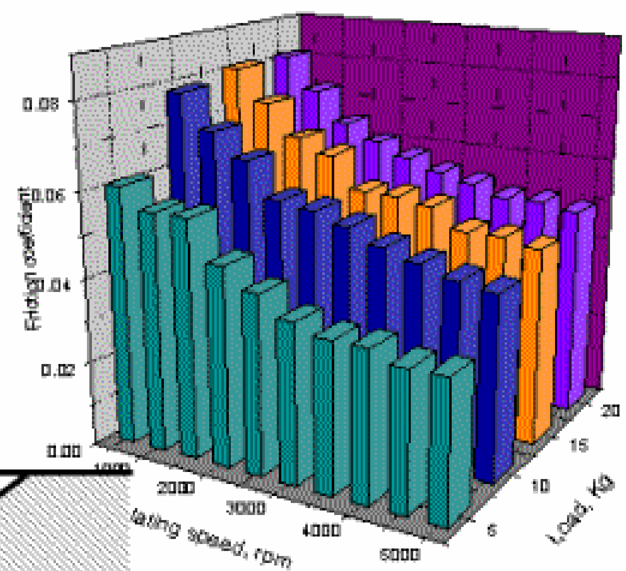
untextured

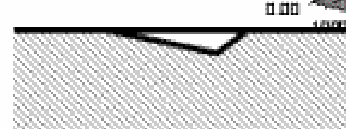


Tilted indent, direction 1



Tilted indent, direction 2





Summary

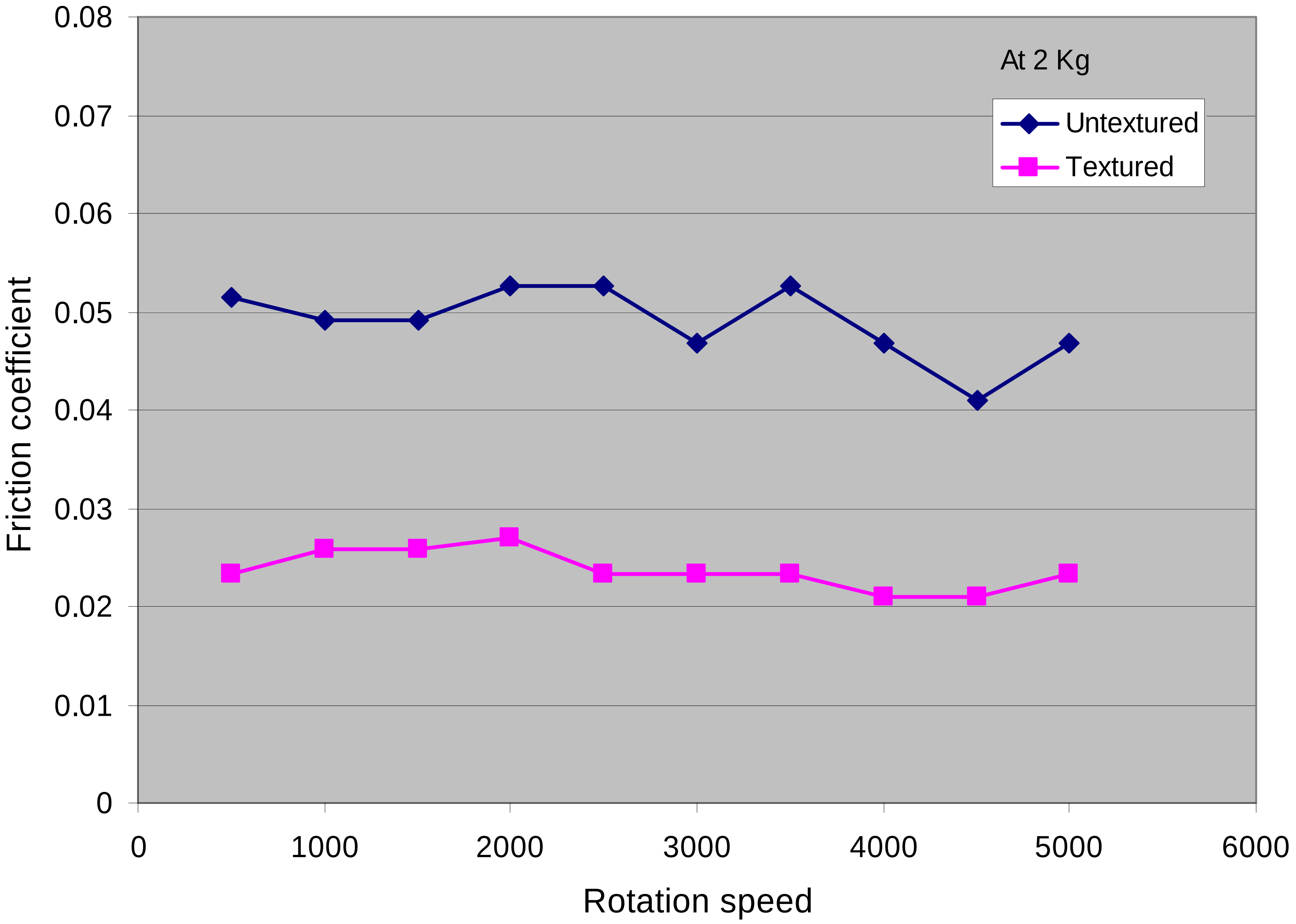
- The dimples with artificial wedge shows friction reduction under high contact pressure up to 20 kg load on a four ball contact
- The number of features, feature depth, bearing ratio l/d are important
- What is the optimum point under high load?

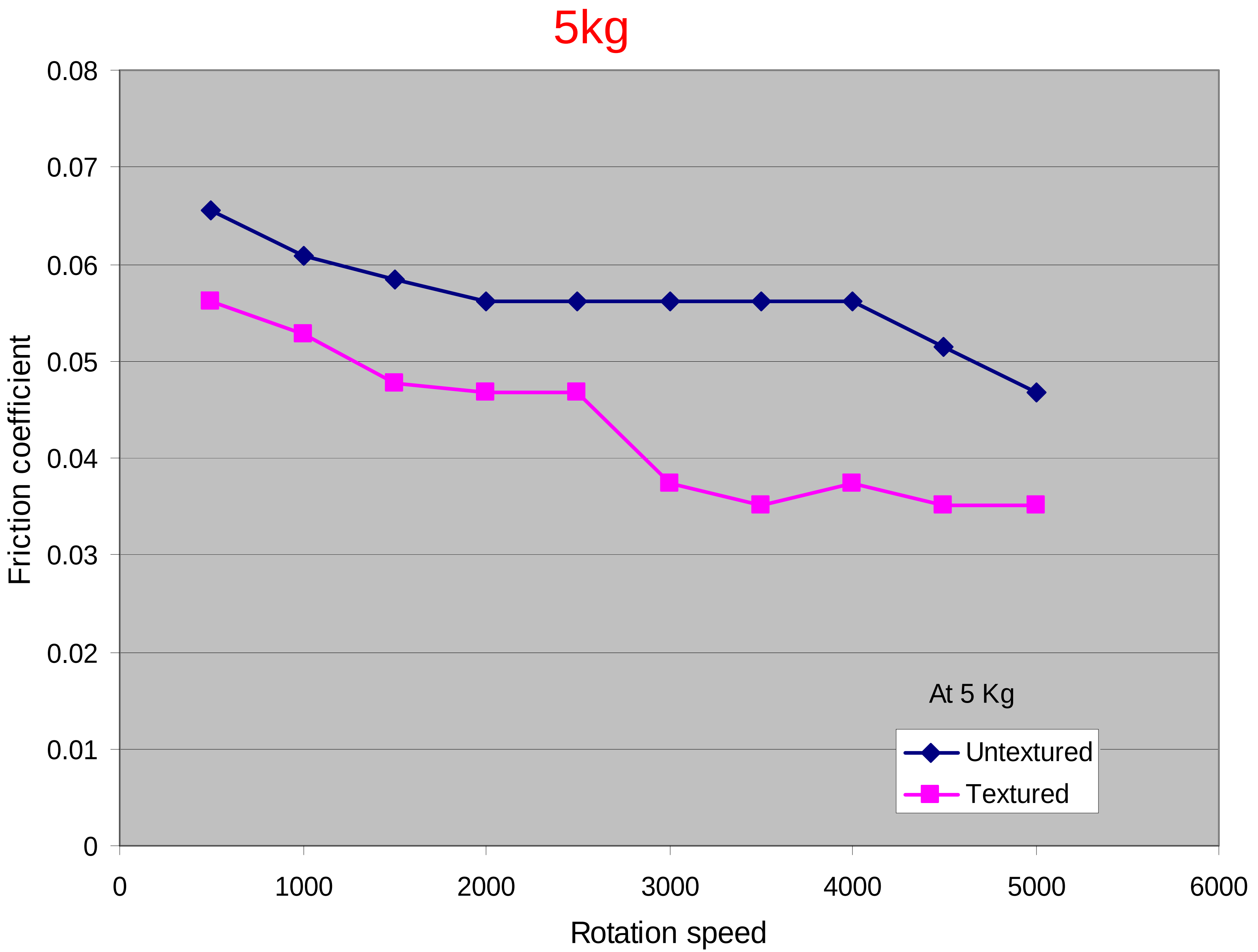
Optimization of This New Principle

- Size variation
- Pitch variation
- Shape control
- Slope control
- Deformation control

A new texturing technique has been developed

2 kg load, steel on copper





5kg
Friction coefficient
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1000
2000
3000
4000
5000
6000
Rotation speed
At 5 Kg
Untextured
Textured

Conclusions

- Surface texture size and shape have a significant effect on friction and wear
- Orientation of surface features have a marked effect
- Detailed mechanisms of friction reduction is not fully understood
- Edge effect (stress intensity increase), leakage rate (loss of fluid pressure), depth of features to yield stresses are important

Conclusion

- First demonstration of GPa texture result
- Showing slight improvement in friction according to conventional texturing theory
- The number of features and the size of the feature need reconsideration
- Radically new design produced significant friction reduction at GPa contact pressure
- Need NEW theoretical models to explain this success