The Integrated Tribological Surface – Cross-Disciplinary Research Challenges

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Note: Opinions expressed are those of the author only
Overview – need, opportunities, challenges

• The societal need: friction reduction=energy conservation
  – 30-40% of fuel for transportation goes to overcoming piston ring and gear friction
  – Design, weight-reduction, materials substitutions are reaching their limits

• The opportunity: the surface is “coming out of the closet”, taking its proper role
  – recent advances in many fields hold much promise, especially in mechanics, materials and related areas; as yet they are mostly in the research stage

• The challenges: much basic and applied research is needed
  – integration and cross-disciplinary efforts are a must at all scales, macro- to micro- to nano-. 
The Emergence of the Surface

• David Tabor: “God created materials, the Devil made the surface”.

• Until recently the surface was difficult to study and to engineer properly – one mostly worked with what one could get from the manufacturing process

• Contact mechanics and surface science and engineering have made major strides since 1990. Coatings, surface analysis, modeling, and modification are now commonplace

• Surface topography – texture – remains a last frontier. It is the focus of some current efforts and shows promise of reducing friction in many cases by 10-30%

• Integration of efforts in the many fields is needed (interaction, connection, collaboration!) (interação, conexão, colaboração!)
The Case for Engineered Surface Texture

• Dimples and texture work in nature for fluid flow over a surface – shark skin, lotus leaf
• Also used in sports – golf ball
• Growing literature on tribological benefits
  – Suh – wear particle traps
  – Etsion et al – seals and piston rings: improved performance, leakage, friction, breakdown load
  – Kato et al – water lubricated Si-ceramic seal and thrust bearings: improved performance in specific ranges
  – Bay et al – oil pockets in cold drawing of metal
Sharks have used **surface texture** to lower friction for > 200 M years. Parallel placoid riblets guide fluid flow and prevent sideway turbulence across skin. Riblets do not grow with fish. Sharks typically swim 5-20 km/h, max ~ 40. Riblets may help in glides after spurs
0.5 mm

(Gray’s paradox, 1936: dolphins aren’t strong enough to swim as they do, surface properties must be unusual. Led to belief that biomimetics would give best solutions to everything)

Fig. 3.2. Shark skin surface. (a) Directionality of the riblet groove pattern in the shark *Isurus oxyrinchus*. (b) Scale surface of the shark *Sphyraena lewini*. (c) Scale surface of the shark *Etmopterus spinax.*


Fig. 3 Above: Longitudinal and cross-flow on a ribbed surface; below: drag reduction performance of various rib geometries

Bechert et al, Naturwissenschaft. 2000, 87, 157
Symbol of Purity
The Lotus Leaf

“The white lotus, born in the water and grown in the water, rises beyond the water and remains unsoiled by the water” (ancient Indian Buddhist text)
Golf Balls and Dimples

- Since 1618 “featheries” balls used, goose feathers stuffed inside cowhide pouch, seams inside
- 1848 – smooth gutta percha balls introduced; did not fly as well as “featheries”; after 1880 they were given texture to fly equally as well
- Dimples (in rows) introduced in 1905 (standard 336 in US, 330 in UK); round ones are standard, hexagonal ones may be better
Drag force drops at high speed, soccer ball doesn’t slow as much as goalie expects

\[ F_D = \frac{C_D \rho A v^2}{2} \]

But \( C_D \) depends on \( v \), drops suddenly when airflow changes from smooth and laminar to turbulent. Laminar separates early = vortices = drag; turbulent separates late = less drag.

Reynolds number at drop depends on surface Roughness. For dimpled golf ball \( R \approx 2 \times 10^4 \); For smoother soccer ball \( R \approx 4 \times 10^5 \)

(Tribological Reynolds numbers are smaller)
Comparisons can only go so far

- Examples from nature involving moving, contacting, textured surfaces do not seem to exist
- Examples from sports equipment seem to be rare – the golf club example is one of the few

The Case for Engineered Surface Texture

• Significant benefits have been reported:
  – For mechanical seals a 30% reduction in friction, reduced leakage, and 2-10X increase in breakdown load
  – Similar friction reductions for automotive piston rings, planar thrust bearings, and some tools
  – Strieber curve generally moves left and down: transitions between hydrodynamic and mixed lubrication and on to boundary lubrication move to lower speeds and/or greater loads
Under the right conditions dimples move Striebeck curve left and the top down

(or: viscosity x velocity x width/ load)
The Case against Engineered Surface Texture

- Sometimes designer texture works the other way – it results in greater friction and lower breakdown loads; it currently seems somewhat unpredictable what will happen and why

- And: good, reliable lab experiments at higher contact loads are difficult to do (flat on flat often required, sufficiently large to engage a number of texture units at any one time. Direct in situ observation is very difficult
Early work, MIT 89

304 SS pin and disk
3mm pin
Texture made by tip
Of Rc indenter

i = indents, 66 um deep,
Spacing 0.5 mm, 27%
Area coverage

P and wt parallel
And transverse
Grooves, 500 um
Spacing, 36 um
Deep, area 45%

Ct = transverse
Grooves, 
255um spacing, 
20 um deep.
Area 72%
15 N load, 10 mm/s
2.1 MPa, So +
0.5 x 10^(-7),
b.l. region,
μ = 0.09 on smooth,
0.12 on dimples,
0.135 on grooves

2 N load, 0.28
MPa, So ~
3.7 x 10^(-7)
μ = 0.01 on
smooth, 0.125
on wide
grooves,
0.085 close gr.
0.135 indents

Pure mineral oil lubricant
Post mortem of a few simple experiments with groove texture

- The groove texture used was detrimental to friction, it pushed the transition from hydrodynamic to mixed friction to lower loads
- Why?
- Maybe:
  - Too much area devoted to texture (45-72%), contact pressure on remaining surface becomes too high
  - Edges of texture begin to act as roughness
  - Grooves may conduct oil away from contact
  - Pin was too small (3 mm) for contact to “average” over sufficient texture to build up pressure
  - Wear particles were not a major issue in these tests
Much recent work with pulsed-laser dimpled surfaces

Disk #3 - standard

Disk #4 - high dimple density

Disk #5 - standard unlapped

Disk #1 - lower dimple depth

Argonne National Lab

- $W_c$: critical load
- $W_{c_0}$: critical load of untextured specimen at 800 rpm
- $W_c/W_{c_0}$: critical load ratio

SiC/SiC
Rotational speed $n$: 1200rpm
Lubricant: Purified water
Supply rate: 60ml/min
DIMPLE – a small hollow or dent, permanent or evanescent, formed in the surface of some plump part of the human body, esp. in the cheeks in the act of smiling and regarded as a pleasing feature

“Three letters in her hand and three thousand dimples in her cheek and chin”

“That dimpled chin wherein delight did dwell” (Gascoigne, 1587)

“And smiling eddies dimpled on the main…”

“The garden pool’s dark surface… breaks into dimples small and bright” (Wadsworth)
What if you wanted dimples but weren't born with them? Do you have any alternatives? Way back in 1896, our inventor thought he had the right tool for the job, the Dimple Drill! This dimple producing device has a rounded tip made of either ivory, marble or India rubber. To produce the dimple, simply press the Dimple Drill's tip on the desired dimple lacking area and turn the knob, rotating the dull tip on your face, like a drill. The inventor says it may also be used to nurture and maintain already existing dimples. Does it work? As a wise Sage must have said at some time... "getting a dimple is not as simple as a pimple".

Dimple Drill
US Patent 560,351* / Issued 1896
Dimples – Type II

(Dimples to the Rescue)
Dimples – Type III
Circles

Diameter: 150 $\mu$m
Distance: 500 $\mu$m
Area ratio: 7%
Depth: 8 $\mu$m
Ellipses

Diameter: 300/75 μm
Distance: 500 μm
Area ratio: 7%
Depth: 8 μm
Total dimple length perpendicular to sliding controls,
Greater length, lower friction, lower Strubeck curve transitions
Results vs. Proposed Mechanisms

- Cavitation
- Inertial effects (Reynolds No. too large to ignore
- Lubricant supply from dimple provides reactant for trubochemical events, or coolant, or lubrication to tops of contacting asperities
- Lift from mini wedges in dimples
- Traps for wear particles
Effect of cavitation at single engineered (positive) asperity, negative asperities (dimples) expected to behave similarly. Hamilton, Walowit, Allen, J. Basic Engr. 1966, 177

Role of cavities in metal cold rolling and drawing.
Le, Sutcliffe, J. Trib. 125, 2003, 384
Inertia contributions do provide a net lift, depending on Dimple dimensions and local Reynolds number

Arghir et al, J. Tribology 125, 2003, 309-318
What does this have to do with Advanced Materials and Mechanics, besides being new Tribology?

• Traditional Reynolds Equation lubrication is being challenged
• Traditional thinking of the surface as “the end of something, the start of nothing” needs to be challenged as well; rather it should be like a “skin” with separate functions, properties, information and sensing capabilities
• Primary leadership has to come from materials and mechanics communities but with input from many other fields
Dimpled Surface

Ra = 0.1987 µm, Rq = 0.304 µm, Rz = 10.04 µm
Solution for Dimpled Surfaces

Composite RMS Roughness $\sigma = 0.3201 \mu m$

$H$ (Film Thickness/Gap) \quad P$ (Pressure)$
The traditional view of boundary lubrication films

A – physisorption; b – chemisorption; c – reaction film (Godfrey)
Challenged, for example, by developments in

- Fluid-surface interactions
- Fluids in micro- and nanoscale confined spaces and channels
- Controllable molecular morphologies
- Molecular assembly and mechanics
- Smart surface materials, on-off microstructural features
Real world lubricant: Tricresylphosphate. As the temperature increases above 200K, TCP fragments upon impact on the substrate. It forms a lubricious reaction film on iron whenever oxygen is present.
Polymers Near Surfaces

Single-component Systems

Interface Friction Coefficient: $\zeta_p(M) = M \zeta_m(1 + f \{M/M_e\})$

Surface Relaxation Time: $\tau_s(M) = \tau_m(\Theta \{v_s; M; \xi/kT\} + g \{M\})$

(Archer, Cornell)
Broadband Dielectric Spectroscopy

**Motivation:** Fundamental understanding of relaxation dynamics of adsorbed chain molecules is required for designing tethered lubricants for small systems (MEMS & NEMS).

**Model System:** *cis-polyisoprene chains in controlled porous glass*

**Chain Dynamics:** *are studied using Dielectric Relaxation Spectroscopy*

The pore diameter is set to be \( \sim 2R_G \). Therefore, the confinement effect is mainly due to the surface adsorption effect, while the geometric effect can be neglected.
Stimuli-responsive amphiphilic Y-shaped brush with dissimilar arms attached to a single grafting point (right): switching of surface nanostructures upon treatment with selective solvents (left).

(Tsukruk)
Lahann et al
Science 299,03, 371
Otsuka et al, MRS Bull Feb 02, 91
**Background**

- Novel alkyl monolayers on silicon as coatings for MEMS/NEMS devices.
- Molecular tribology in liquid environments.

**Uniqueness**

- First experimental and molecular simulation studies are performed to study the molecular tribology of alkyl monolayers on silicon.
- First simulation studies of how surface (from hydrophobic to hydrophilic) and solvent (from polar to non-polar) properties affect nano-scale friction.
- Simulations are performed in a geometry where confined fluids are in contact with bulk fluids, closer to SFA experiments and MEMS/NEMS devices.

**Impact**

- Fundamental understanding of molecular tribology in liquid environments.
- Novel coatings for MEMS/NEMS devices.
- More realistic simulations with the new simulation geometry.

**Results**

**MD Simulations**

Graph showing friction coefficient for water, methanol, and n-decane as a function of monolayer composition (0%, 50%, 100% -OH %).

**AFM Experiments**

Graph showing friction force as a function of total load for different surfaces (SiO2/Si, H-Si, C10-COOH/Si, C10-COOCH3/Si, C11-CH3/Si).
AFM Micrograph \( \{L \times W \times H\} = \{3\, \mu m \times 3\, \mu m \times 50\, \text{nm}\}; \quad \Delta_q = 47\, \text{nm}; \quad \Delta_t = 0.3\, \mu m \)

AFM Micrograph \( \{L \times W \times H\} = \{8\, \mu m \times 8\, \mu m \times 1\, \mu m\}; \quad \Delta_q = 0.23\, \mu m; \quad \Delta_t = 1.1\, \mu m \)

Nanotribological molecular coatings

Fabrication of a new generation of “superelastic” nanocomposite nanotribological coatings compatible with MEMS =>

Monomolecular nanocomposite polymer layers (<10 nm) with 2D network of interconnected nanodomains from functionalized block-copolymers grafted to silicon via reactive interface

Concept:

Bare silicon surface of MEMS

Surface functionalization

Reactive silicon surface via functionalized self-assembled monolayer

(Tsukruk, IO State)

Robust nanocomposite elastic layer with nanodomain net structure (top: 1x1µm AFM image)
Surface Roughness and Slippage at Fluid/Solid Interfaces

7 vol% PS20M ($M_w = 20 \times 10^6$, $Pl$: 1.15) in Diethyl Phthalate

6 vol% PS8.4M ($M_w = 8.42 \times 10^6$, $Pl$: 1.15) in Diethyl Phthalate

Surfaces with rms roughness of order $1/2 R_g$ virtually eliminate slip.
Water Lubrication

Yingxi (Elaine) Zhu
Steve Granick
University of Illinois at Urbana-Champaign
Support - NSF Tribology Program
Ordering of Liquid

by the adjoining surface

Criteria:
- molecules smaller than the crystalline lattice size
- structure of confined liquid film should equilibrate on the time scale

misalignment of surface lattice frustrated water?
Friction force map proposed by Luengo, Israelachvili, Granick (WEAR 200, 1996, 328)

Fig. 6: Proposed friction map of friction force plotted against sliding velocity

Takes account of limiting shear stress response of confined films (L=load; D=film thickness, De=Debrah number = 1 where applied shear rate exceeds natural relaxation time of boundary layer film
Nanotube water
Stays more fluid
Has lower freezing pt.
(Koleshnikov ANL Nanotechweb 6/25/04)
There are useful effects and phenomena at nanoscale

- Nanostructures are strong (Hall-Petch) and may provide rapid diffusion paths (nitriding at low T)
- Self-assembly may provide composite nanostructured films with built-in texture
- Specific attachment sites for additive molecules
- Switchable surfaces
- Smart-film surface layers, superelasticity, on-off surface features
- Liquid/surface molecular match
- Lotus effect
- Monolayer liquids are different; liquid-solid nanoscale composite alloys for tribology?
The major challenge may be:

• to take the nanoscale effects and use them to develop the optimal surface/liquid-solid interface for the microscopic and macroscopic behaviors of tribological surfaces

• Requires cross-disciplinary efforts, mechanics and materials to lead –

• *interaction, connection, collaboration!* - *interação, conexão, colaboração!*
Conclusions

• Texture seems to work
• Technological and societal benefits could be substantial
• Need to understand mechanism(s)
• Advanced in many nanoscale fields can be of use in developing the integrated tribological surface
• It is just beginning
What now?

We need bold, innovative cross-disciplinary thinking “outside the envelope”
Benefits will accrue in many other fields