

# Nanomaterials in Tribology

## A Tutorial

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STLE/ASME International Joint Tribology Conference  
October 20-22, 2008, Miami, Florida, USA



# Acknowledgements

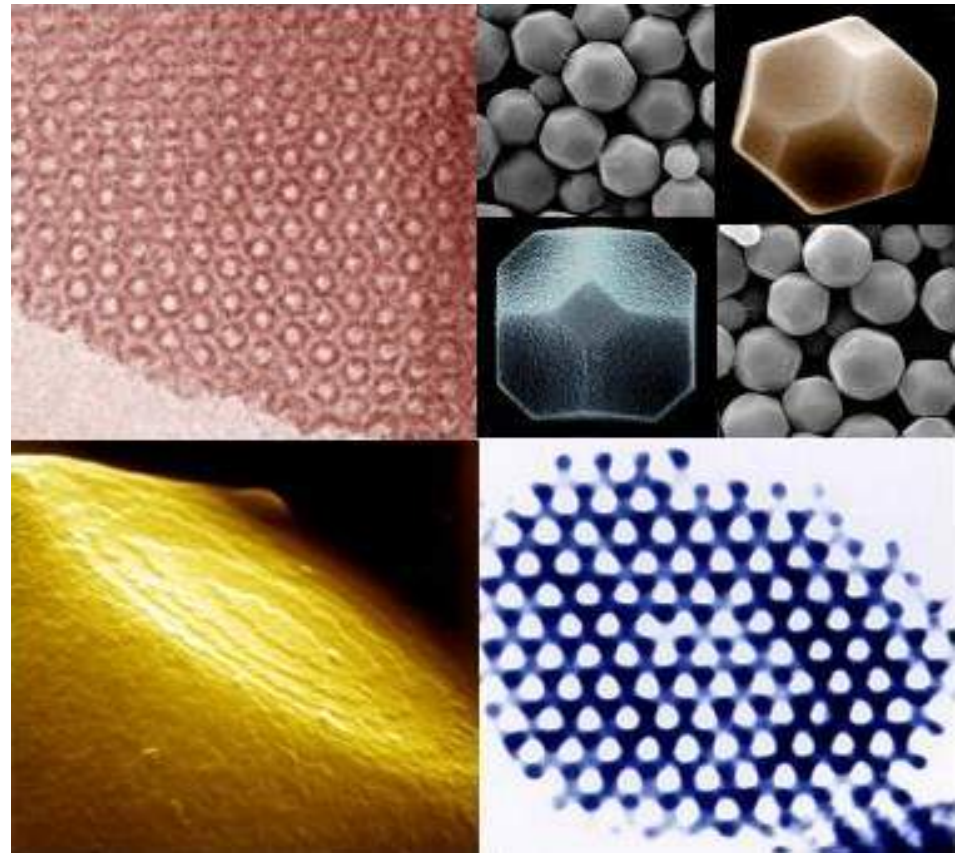
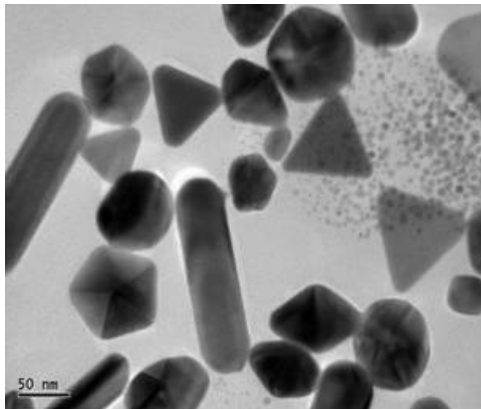
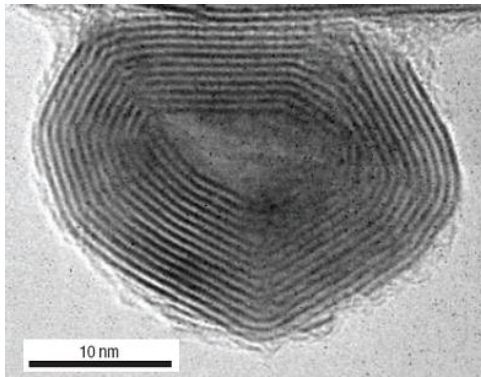
Dr. Subrata Kundu, TAMU



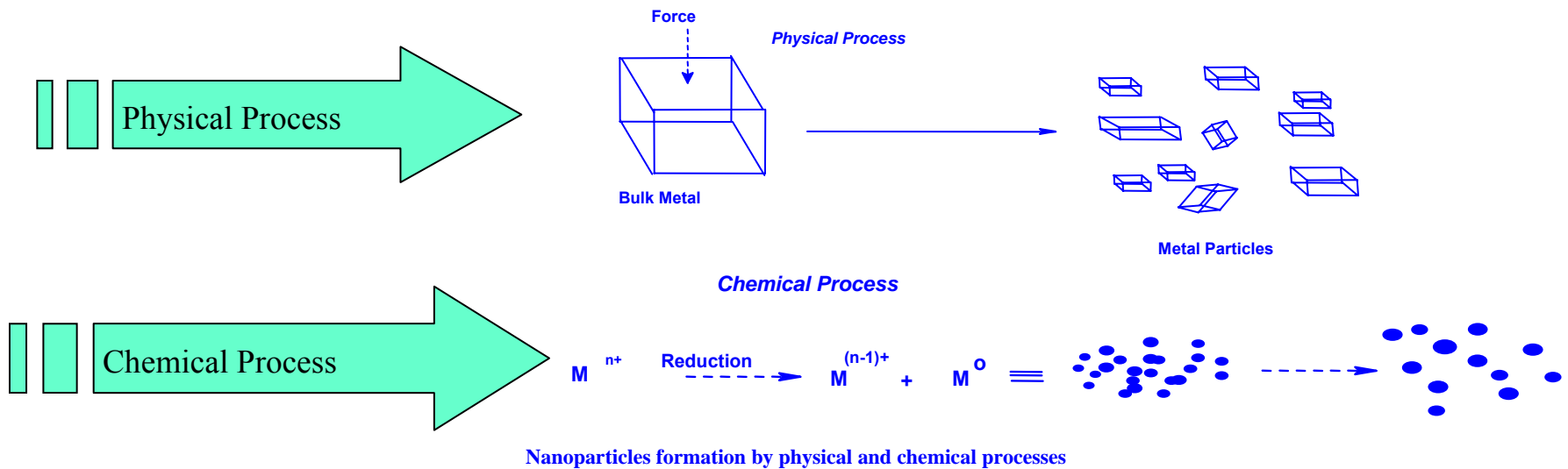
# Outline

- Brief Introduction to Nanomaterials
- Nanomaterials in tribology
  - as friction modifier
  - for anti-wear
- Future trend

# Nanomaterials are made into various forms



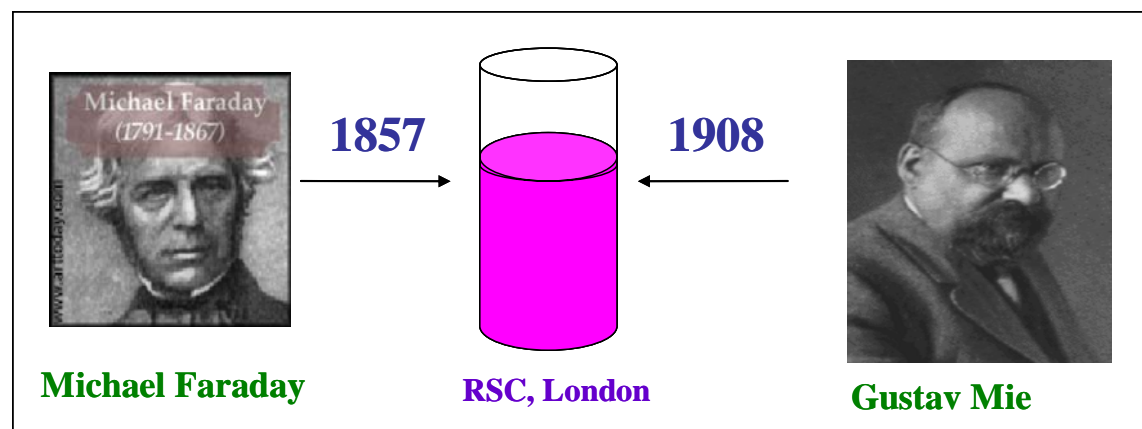
# Methods of synthesis



High surface to volume ratio

Top-down vs. bottom-up method

# Synthesis methods



M. Faraday (1857) 1<sup>st</sup> prepared colloidal gold using phosphorous in CS<sub>2</sub> and the pink color solution is still stable and kept in RSC, UK

- Vapor transport
- Wet chemical method
- Photoactivation (UV-light)
- $\gamma$ -Radiolysis technique
- Laser pulse technique
- Sonochemical method

*Kundu et al., New J Chem. 2003, 27, 656. & J.*

*Phys. Chem. B. 2005, 109, 13166.*

*M. Faraday, Philos. Trans. 1857, 147, 145.*

*G. Frens, Nature 1973, 241, 20.*

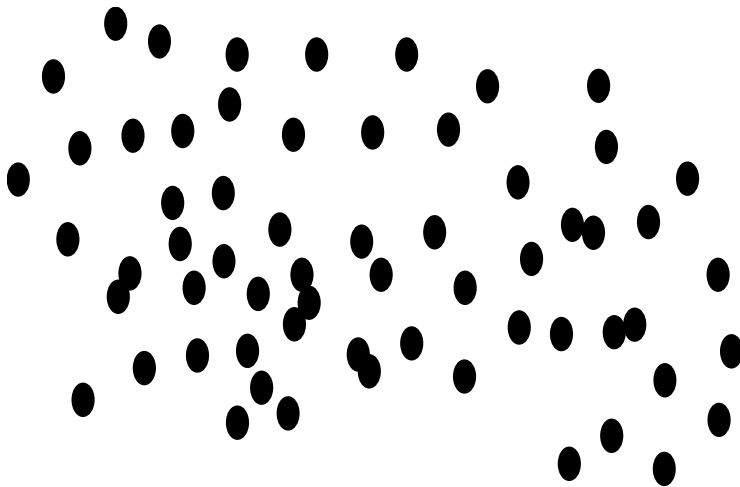
*West et al., PNAS., 2003, 100, 13549. 6*

Step-1

**Nucleation**

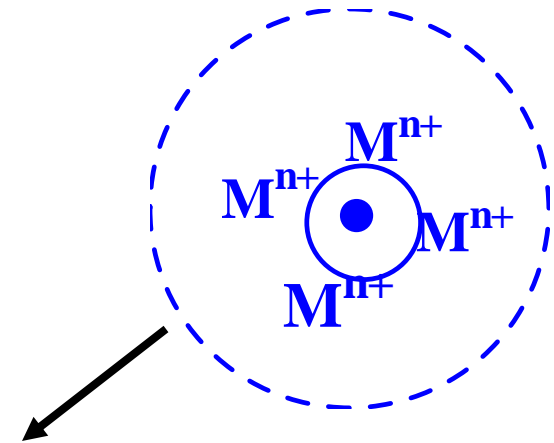


Metal Ion  $\xrightarrow{\text{Reduction}}$  Metal (0)

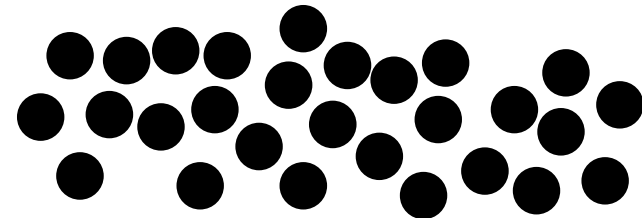


Step-2

**Growth**

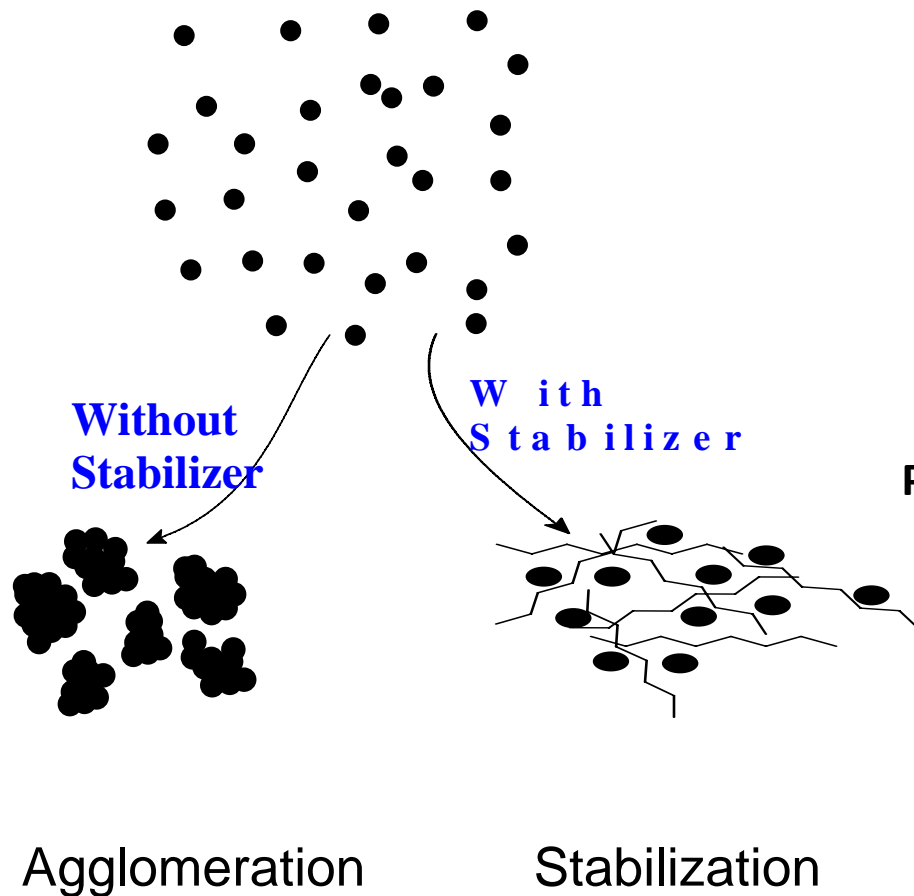


**Reduction**

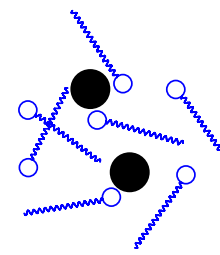


# Step-3

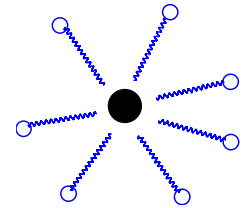
## Stabilization



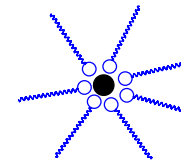
Stabilizer:



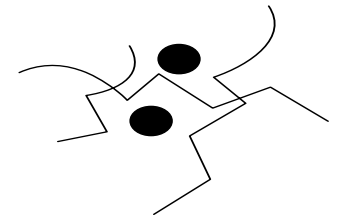
Surfactants



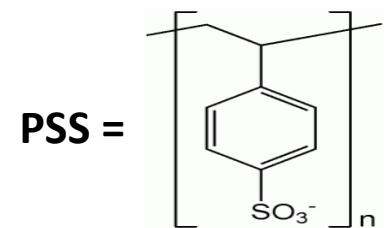
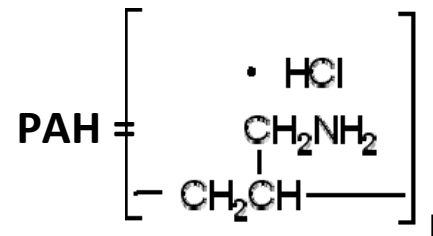
Micelle



Reverse Micelle

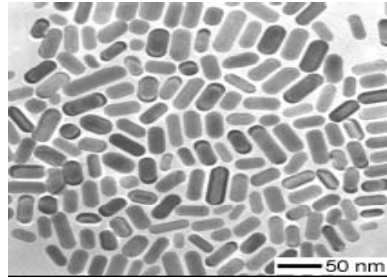


Polymers

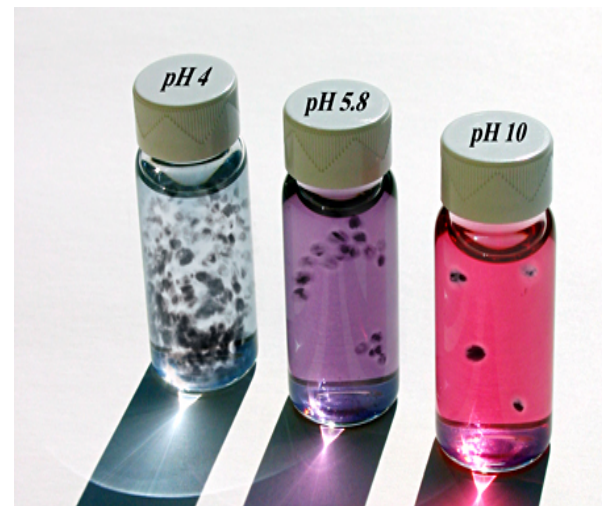
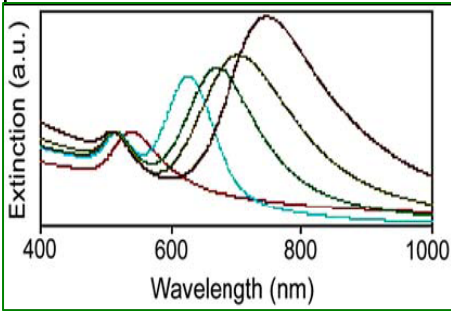
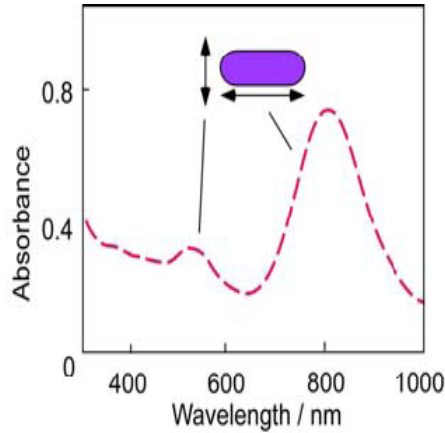
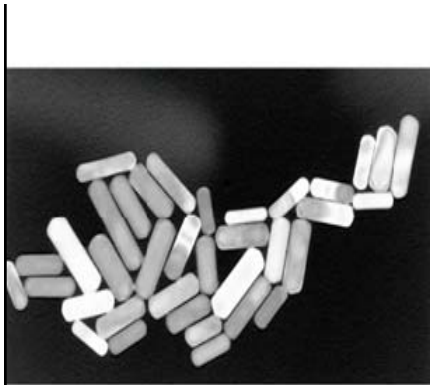
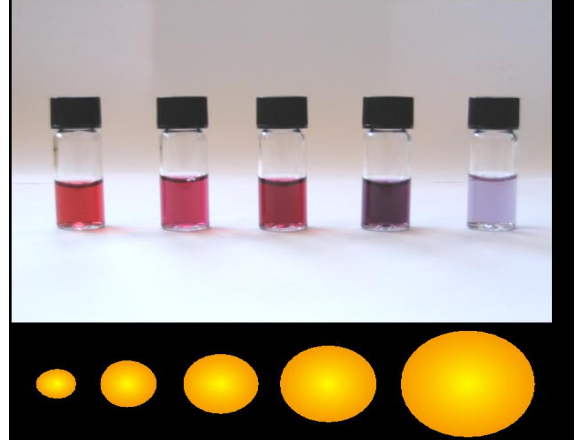


Thiol : Brust et al., Chem. Comm., 1994, 801.  
 Dendrimer : Esumi et al., Langmuir, 2000, 16, 2604.  
 Surfactants: Kundu et al., J. Am. Chem. Soc., 2005, 127, 17600.

# Gold nanorods



Particles absorb at different wavelengths depending on the size of particles



*El-Sayed (GT), Murphy (USC), Mirkin (NWU), Yang (UCB), Kundu & Liang (TAMU)*

# Tribomaterials



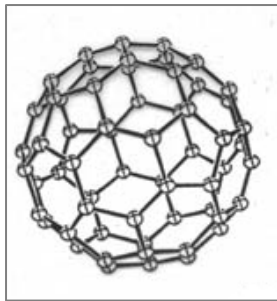
Nanoparticulates  
Thin films/layers  
Nanocomposites

Friction reduction

Anti-wear

Lubricant additives

# Crystal structures of materials



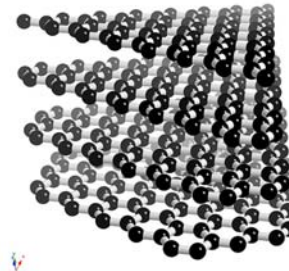
Buckyball



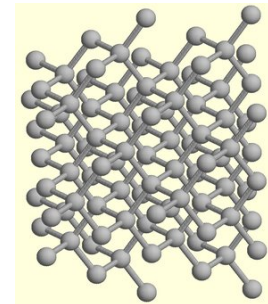
SWNT



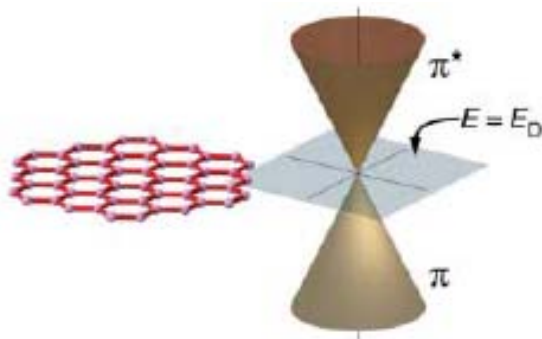
MWNT



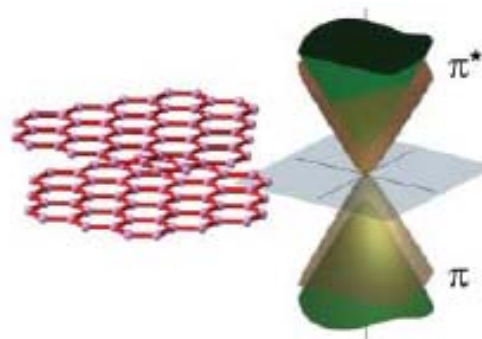
graphite



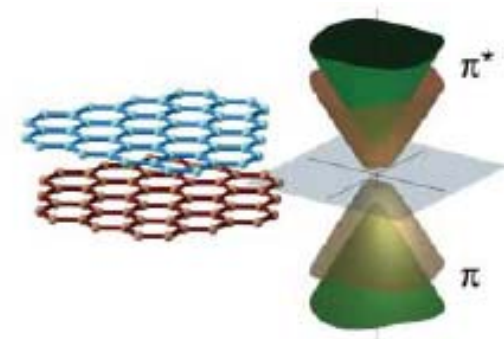
diamond



Single Layer Graphene

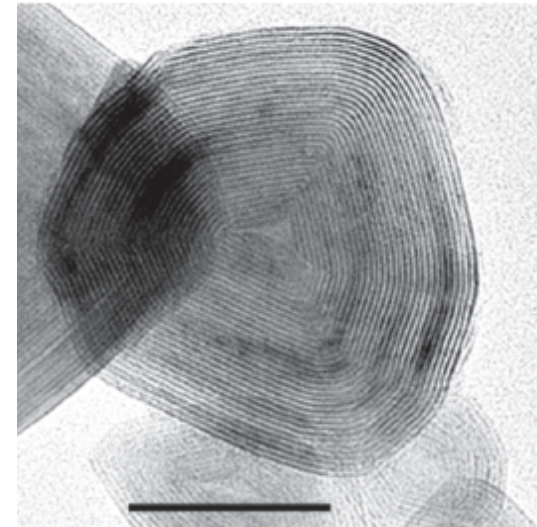
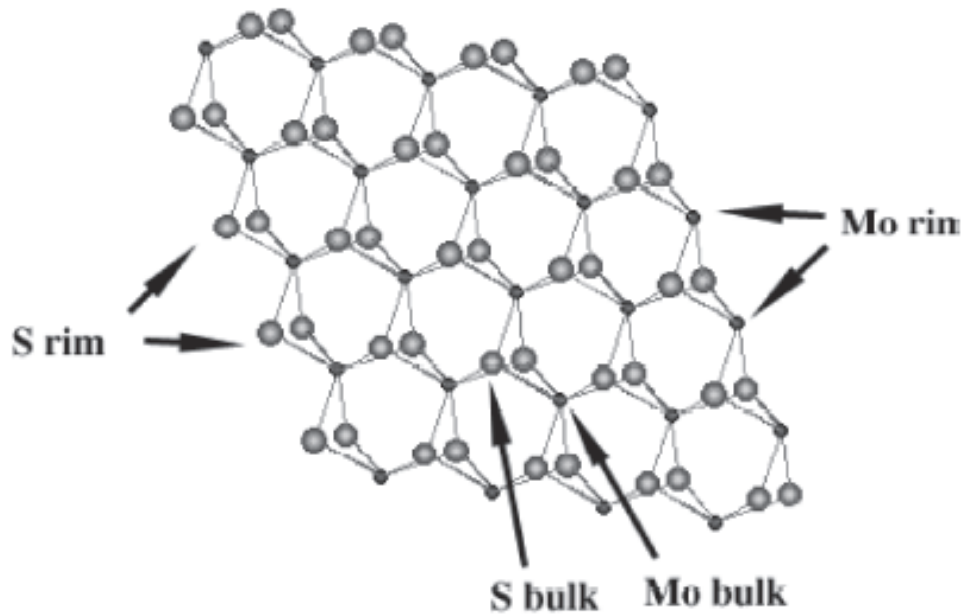


Symmetric Double Layer Graphene

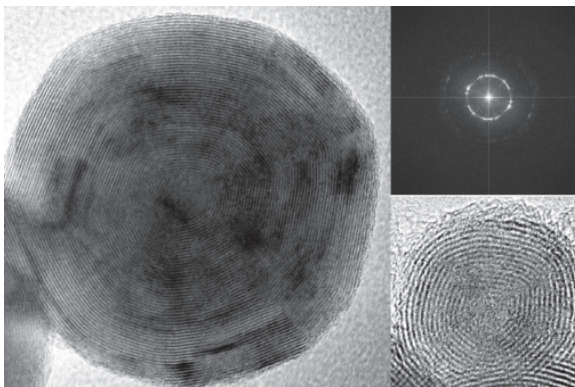


Asymmetric Double Layer Graphene

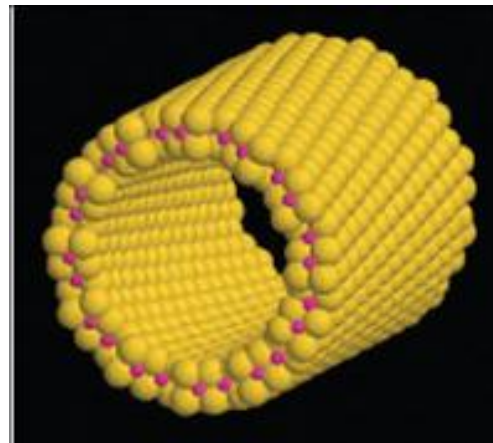
# Layered structures for lubrication



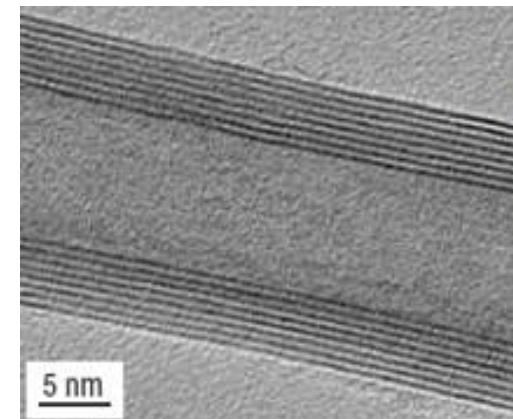
MoS<sub>2</sub>



TiS<sub>2</sub>

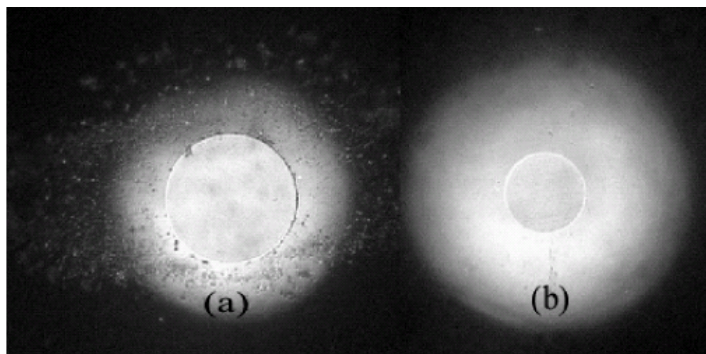
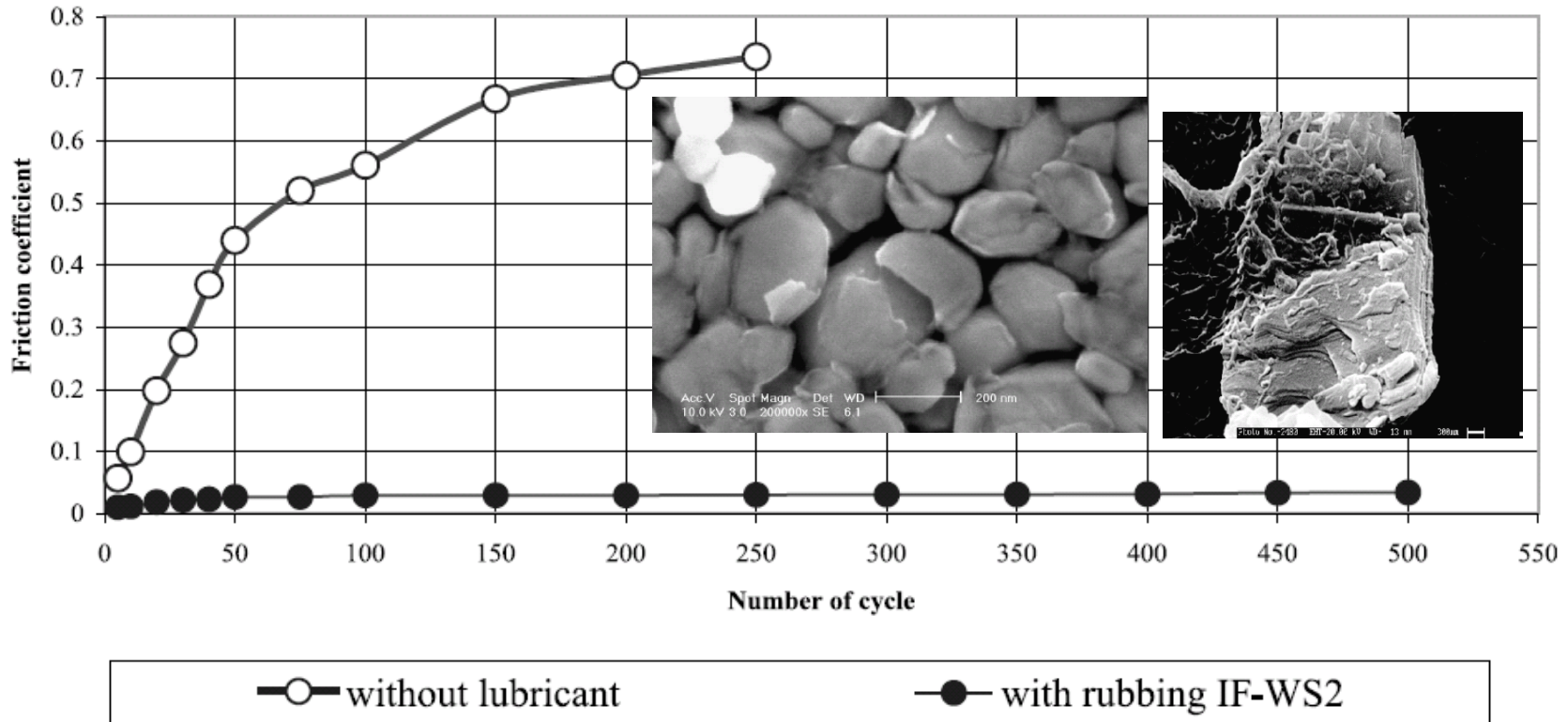


WS<sub>2</sub>



<b>Materials</b>	<b>E (TPa)</b>	<b>Tensile Strength (GPa)</b>	<b>Elongation at Break (%)</b>
SWNT	1 to 5	13-53	16
MWNT	0.8-0.9	150	
BN	1.2		
GaN	0.25-0.5		
WS <sub>2</sub>	0.15	170	12
Stainless Steel	~0.2	~0.65-1	15-50
Kevlar	~0.15	~3.5	~2

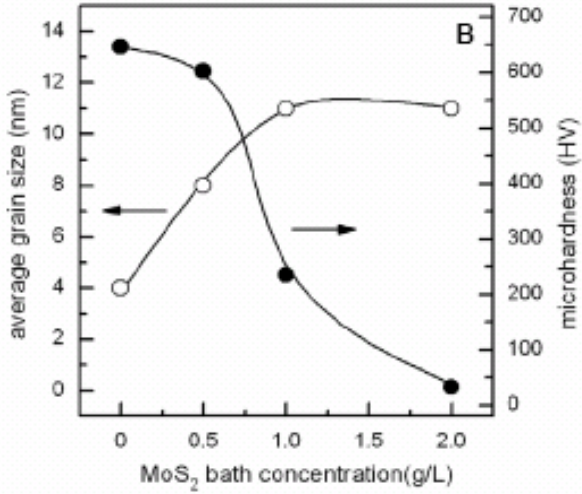
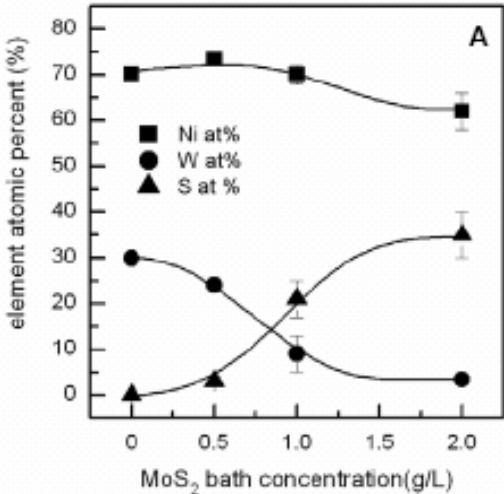
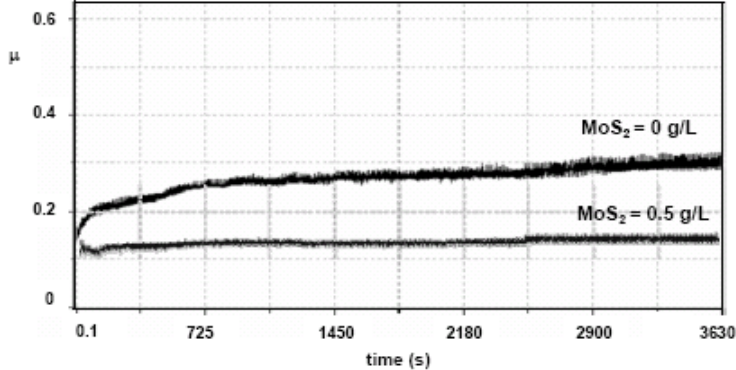
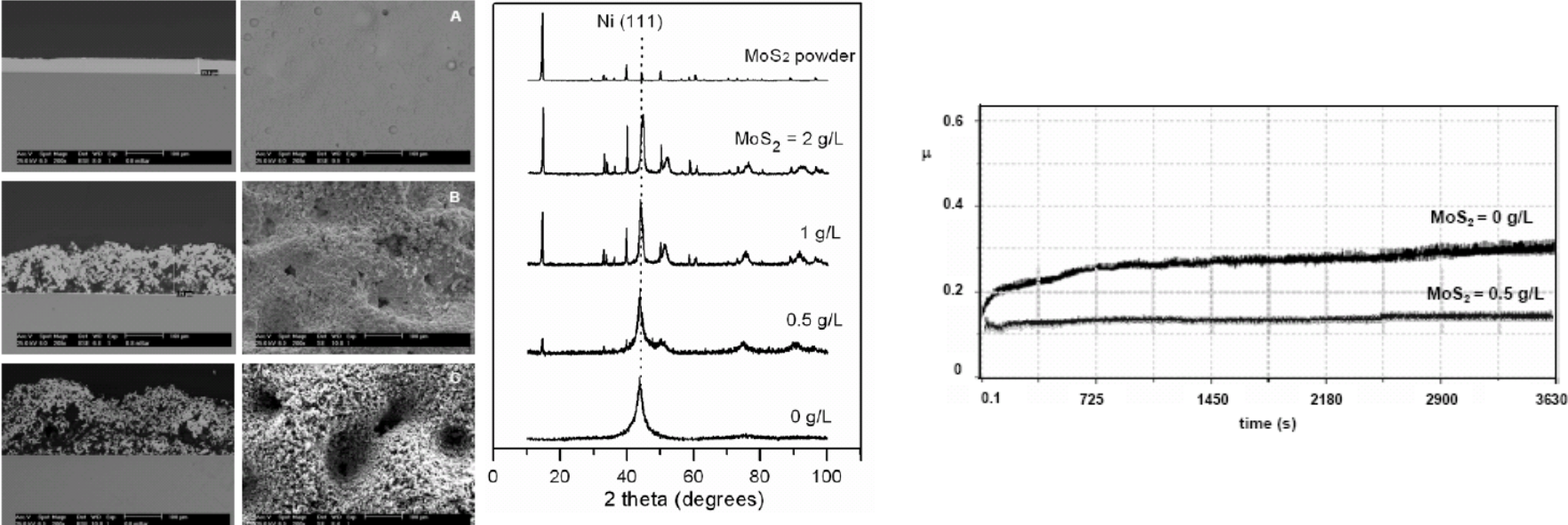
# As a solid lubricant for self-lubricating



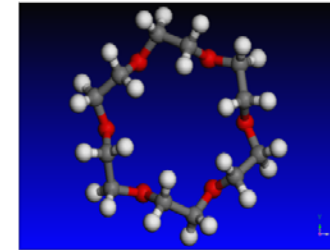
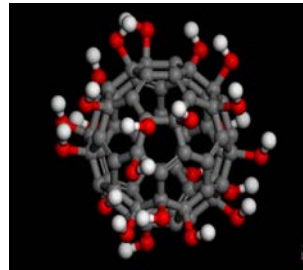
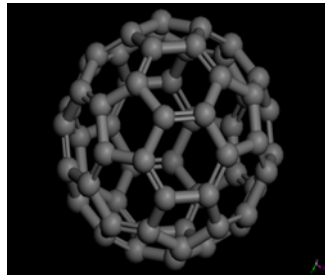
A  $\text{Si}_3\text{N}_4$  ball against  $\text{Al}_2\text{O}_3$  flat.  
(a) Without film; (b) with NPs.

*Rapoport, Nanosci. & Nanotech., 2004. 14*

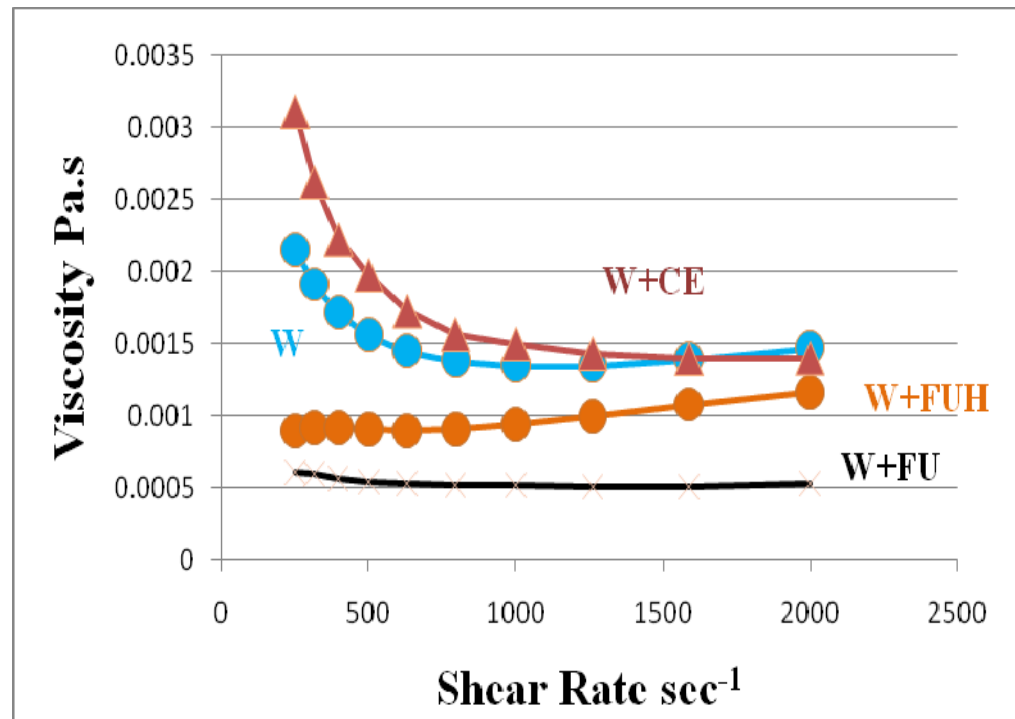
# As a thinfilm



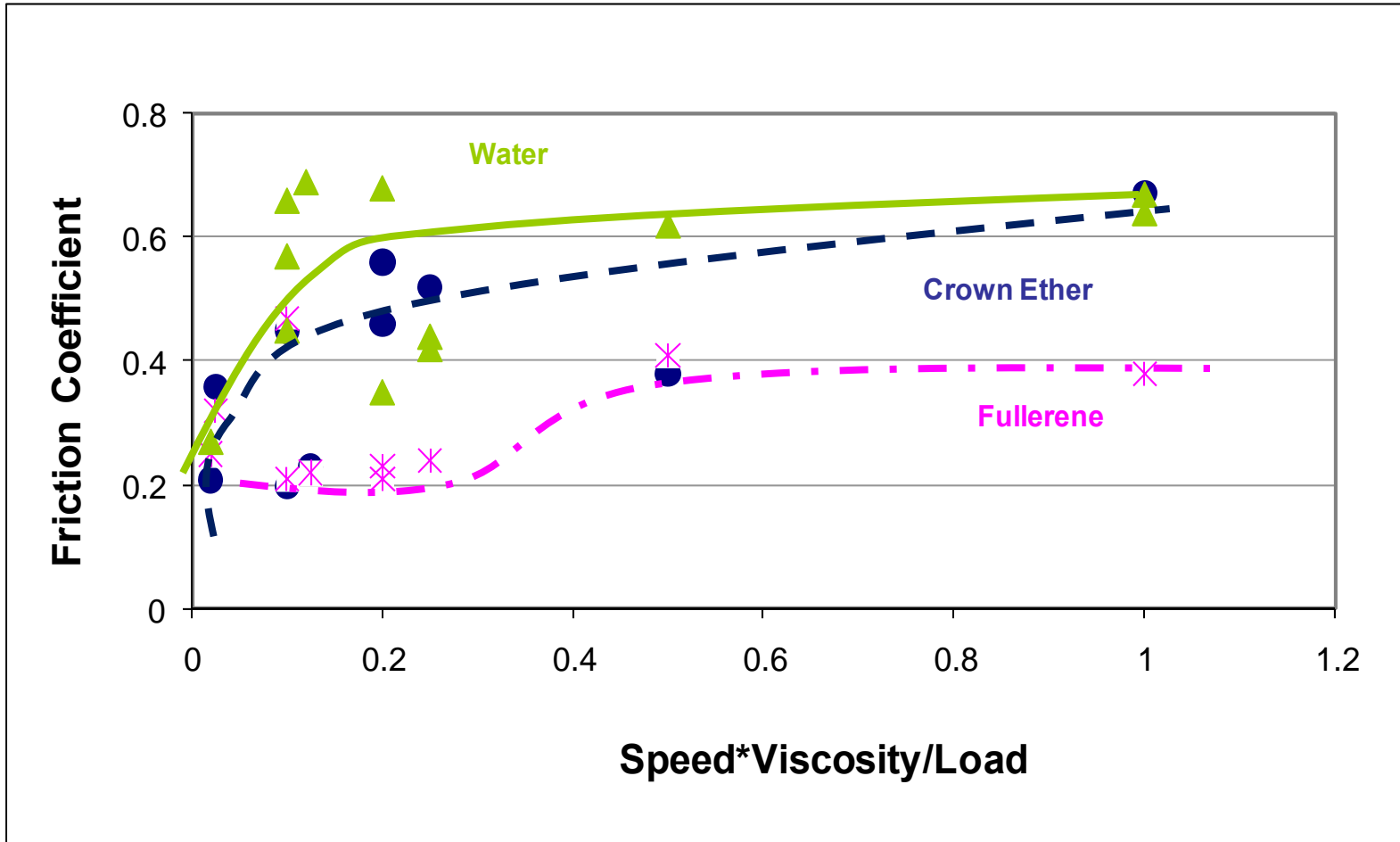
# As additives to base fluids



**Fullerene C<sub>60</sub>; Hydroxylated Fullerene C<sub>60</sub> (OH)<sub>24</sub>, Crown Ether**



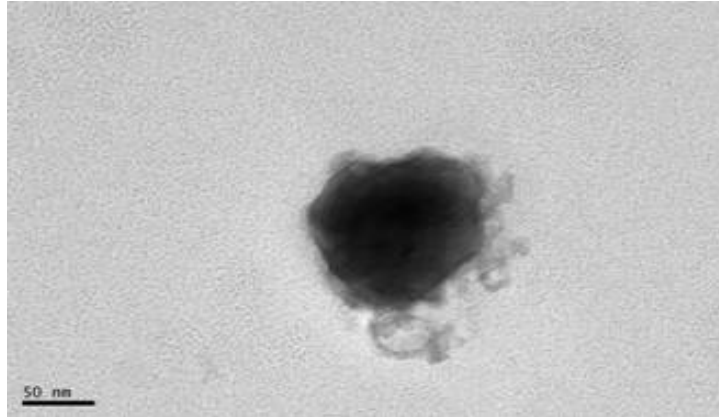
# As additives to base fluids



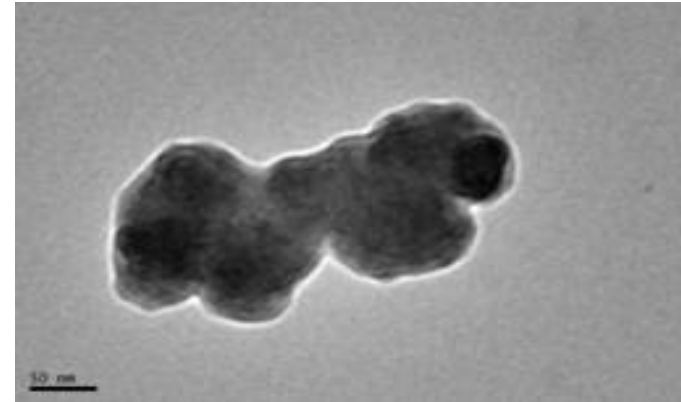
Pendleton and Liang et al., in review.

# Tribo-reactions in NPs

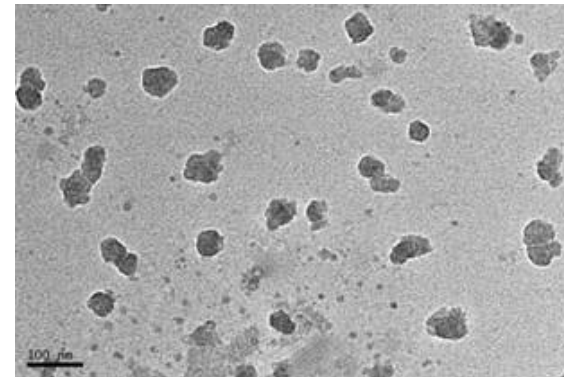
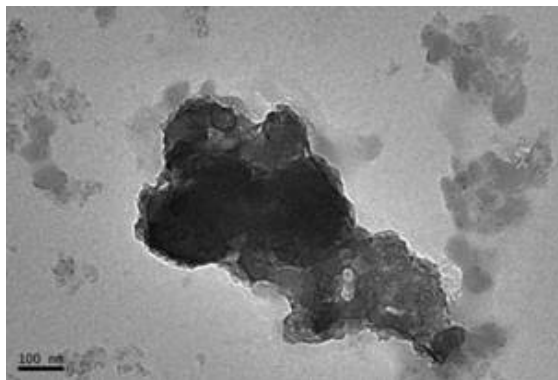
Before test



After test



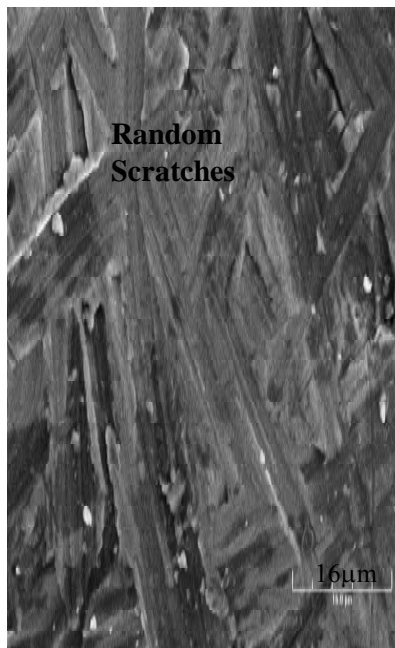
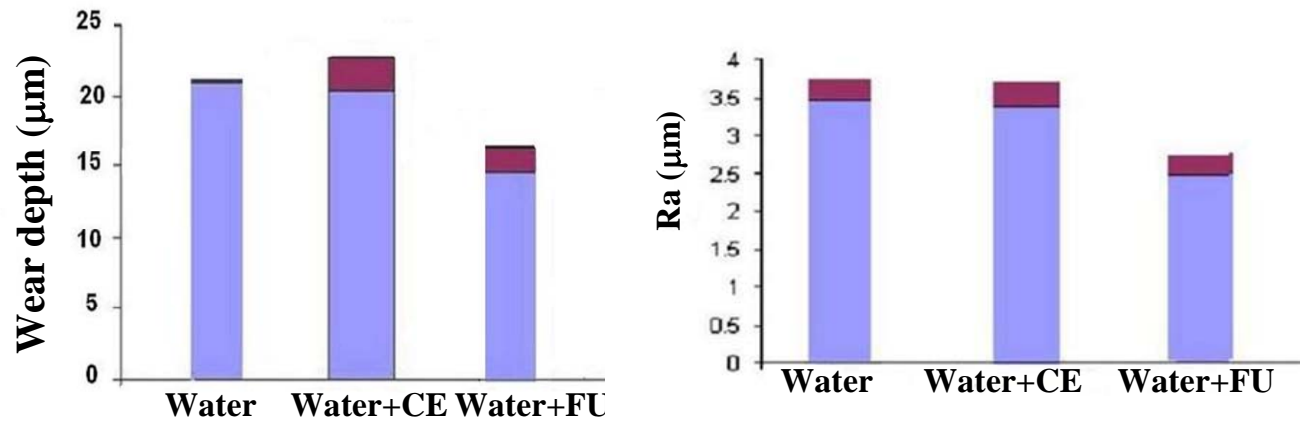
Crown Ether



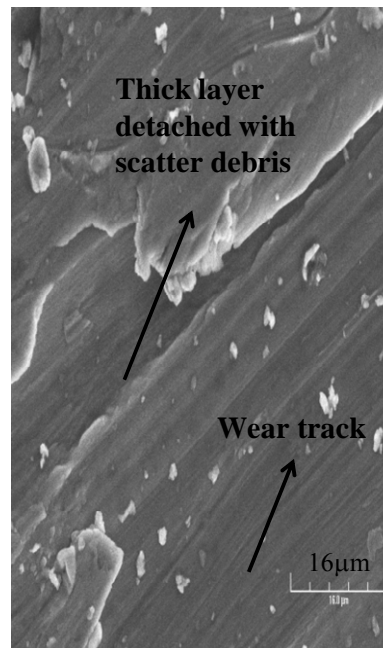
Fullerene

Pendleton and Liang et al., JNR, (2009).

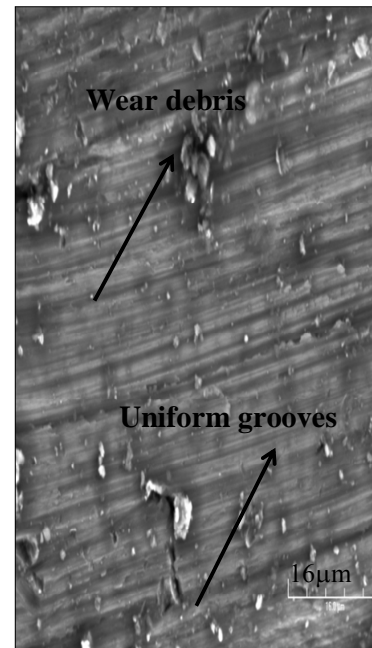
# Wear mechanisms due to nanofluid



Original Ti Surface

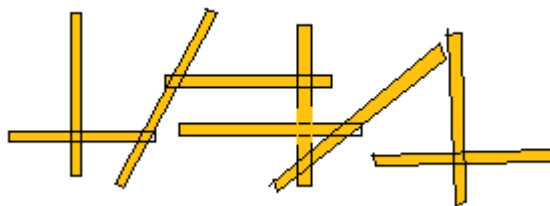
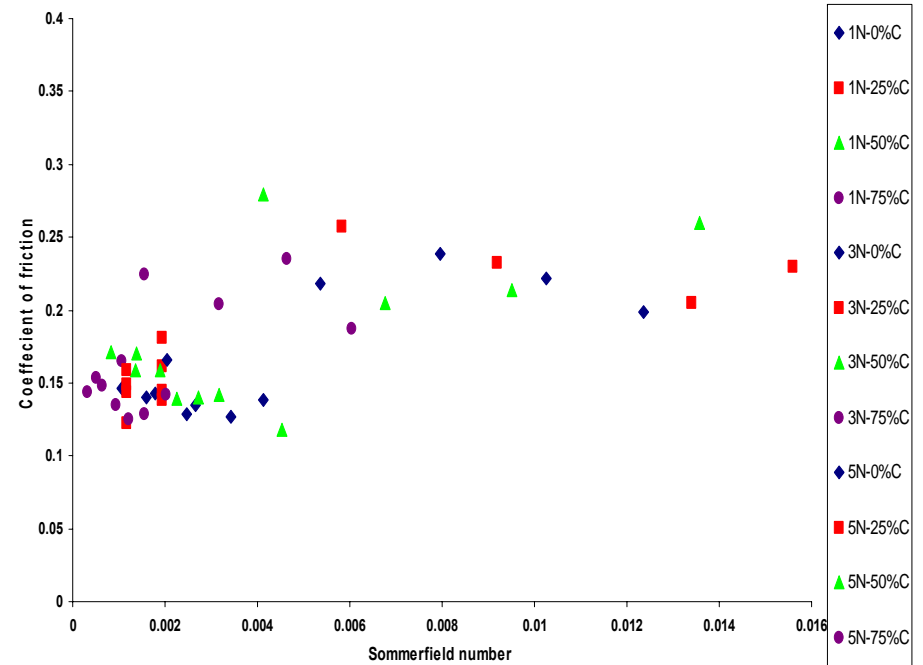
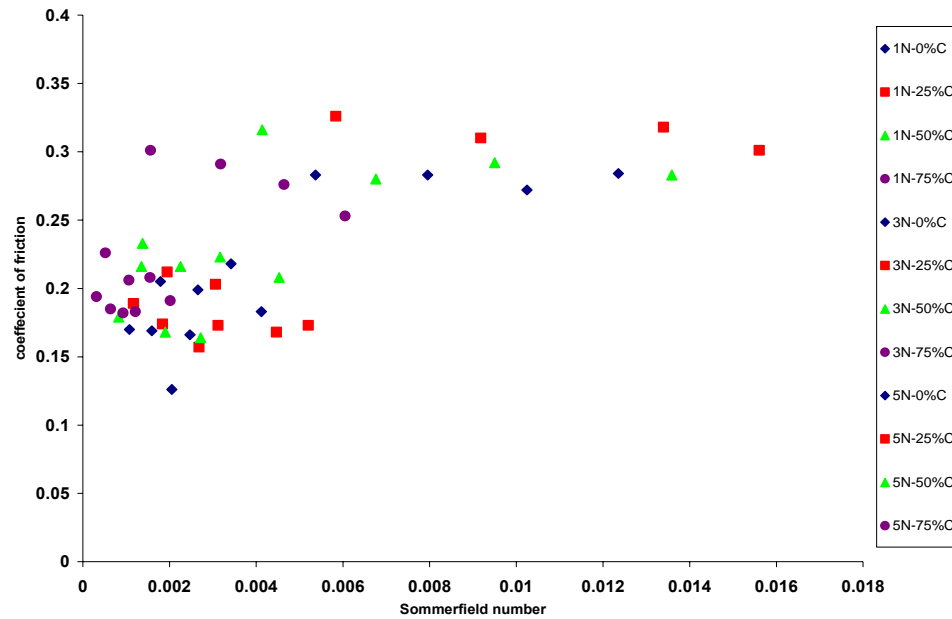


Water+CE

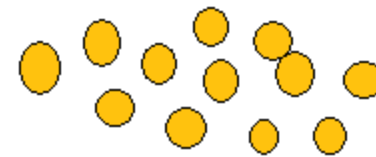


Water+FU

# Shape effects on friction

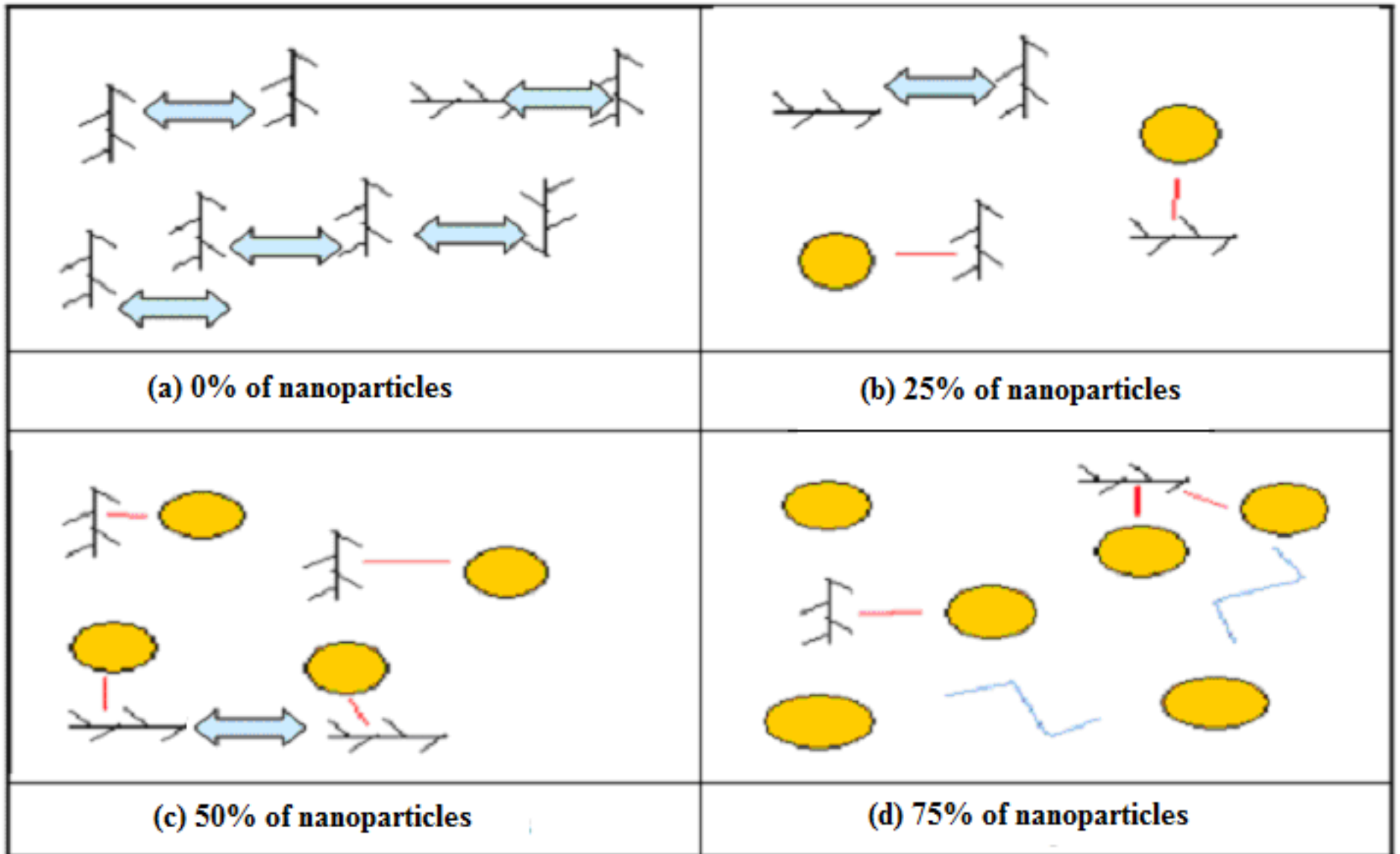


***ROD-SHAPED  
NANOPARTICLES***



***SPHERICAL  
NANOPARTICLES***

# Effects of concentration on friction



# NP – fluid interaction

*Electrostatic attraction* →

Positively charged particle

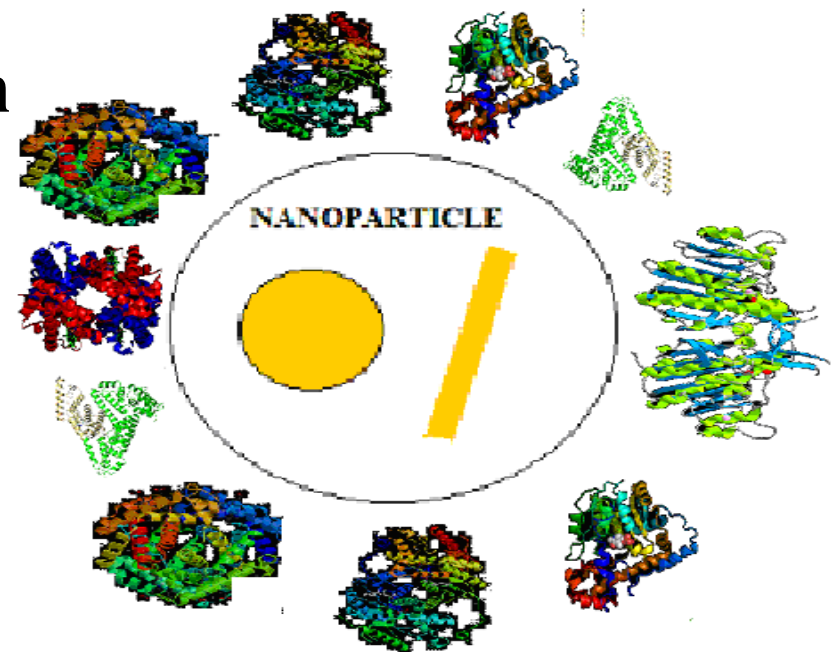
+ negative regions of protein

→ CORONA

*Repulsive force* →

Positively charged particle

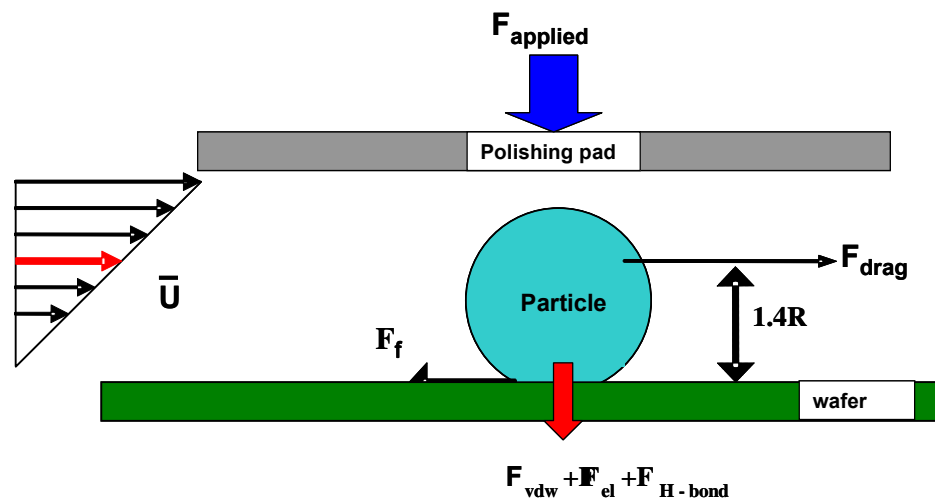
+ positive regions of protein



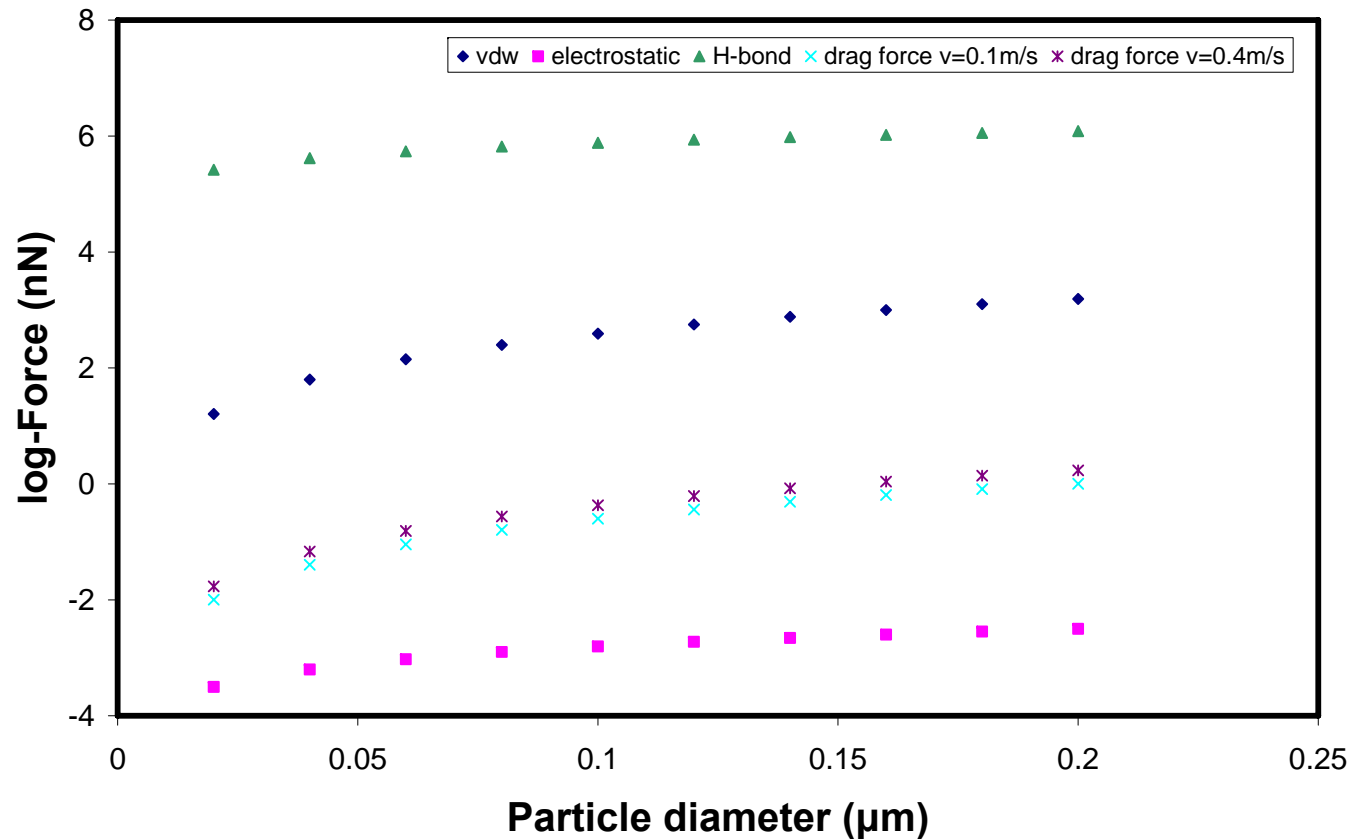
# In CMP

## Interfacial forces in wafer-particle-pad interfaces

- van der Waals
- Electrostatic
- H-bond
- Fluid drag
- Friction

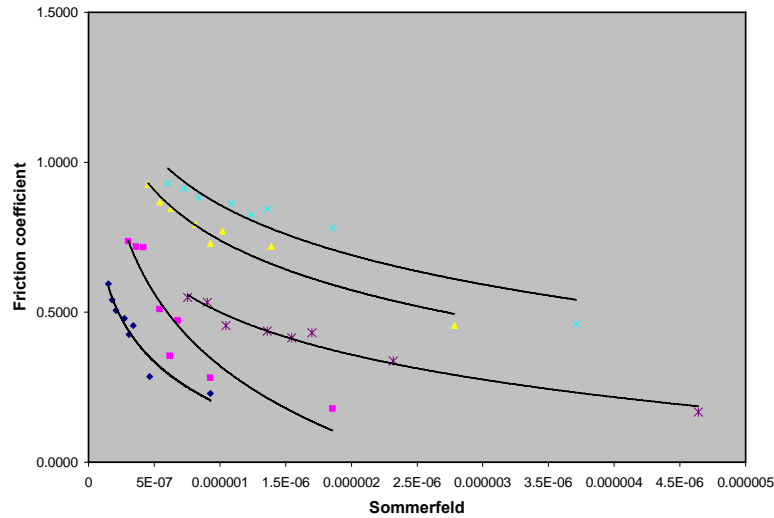


# Interfacial forces as a function of particle radius

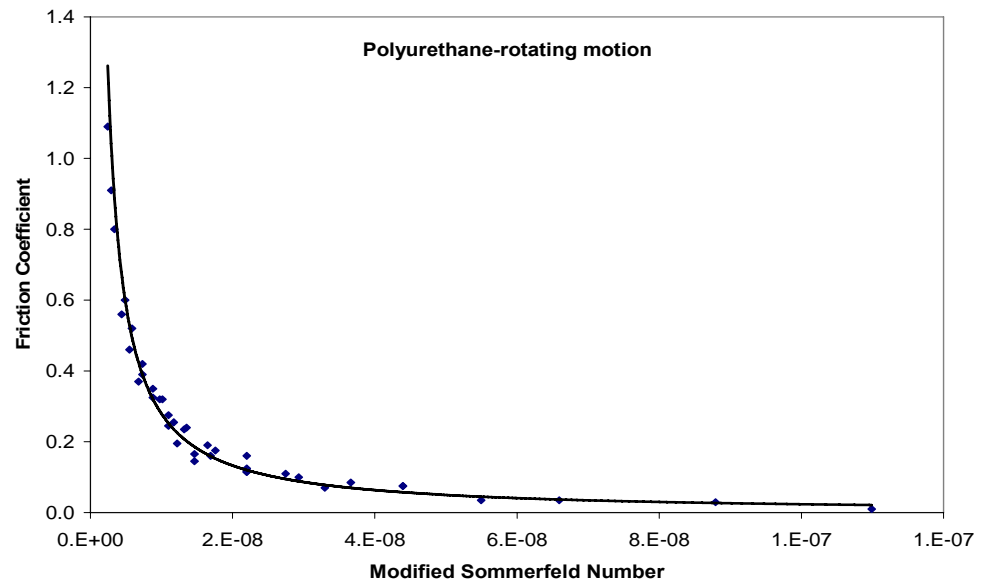


Ng & Liang, *ASME J. Tribology* (2007)

# Modified Stribeck curve for CMP:

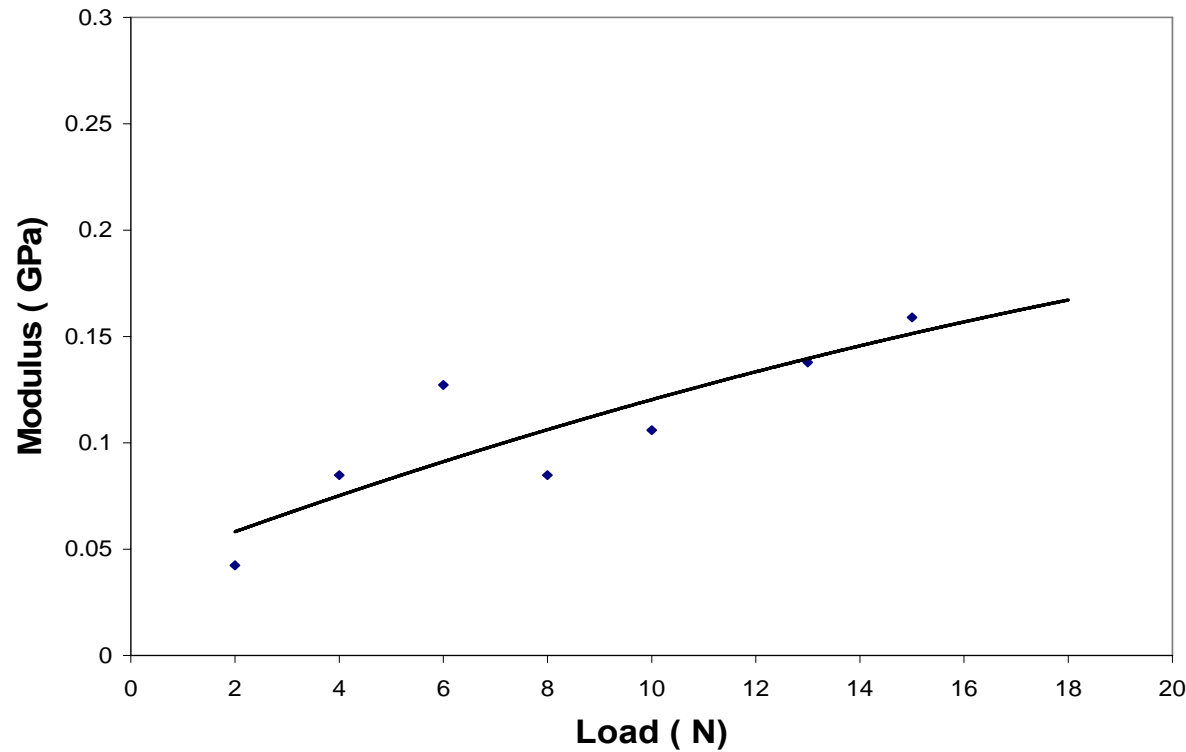


Without modification



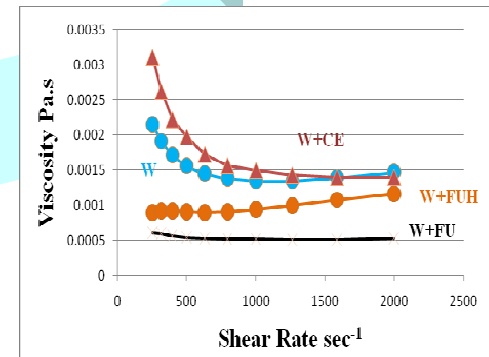
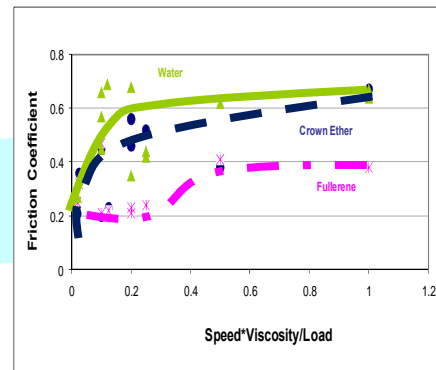
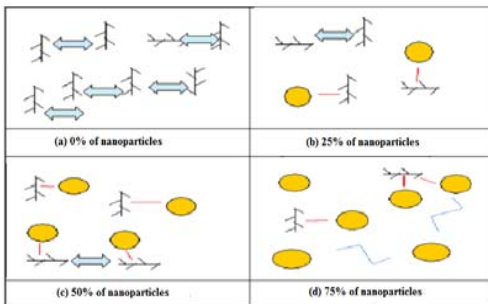
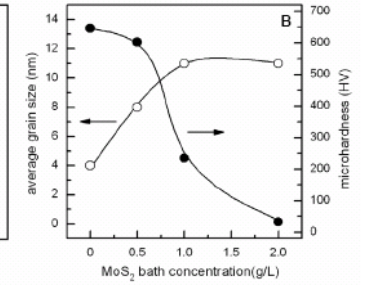
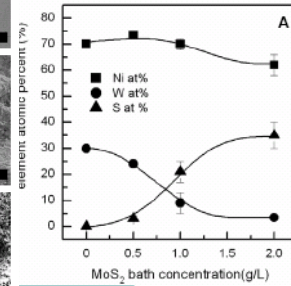
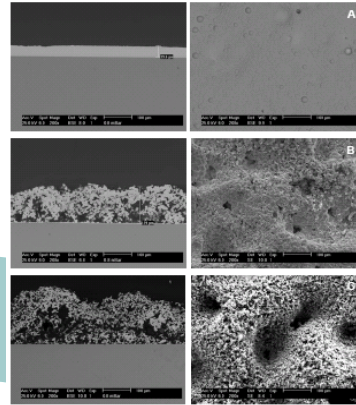
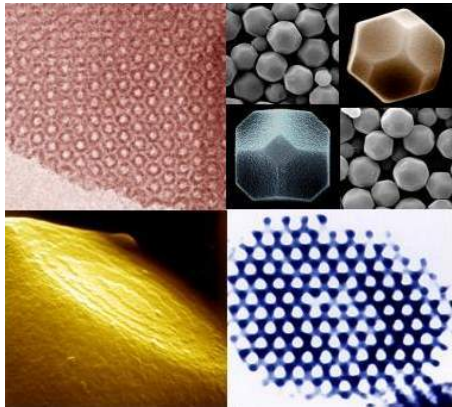
Modified Stribeck curve for rotational Polyurethane pad

# Change in composite modulus for the polyurethane pad



Composite modulus:  $E' = k_{N-L} E_{bulk} (1 - \alpha^2)$

# Summary



# Outlook

- Novel nanomaterials emerge in near future
- New understanding is needed in nanomaterials-properties-tribological performance
- Unconventional applications