Materials for Tribology

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The 2014 Nonlinear Mechanics and Dynamics Summer Research Institute
Sandia National Laboratories, Albuquerque, NM 87185

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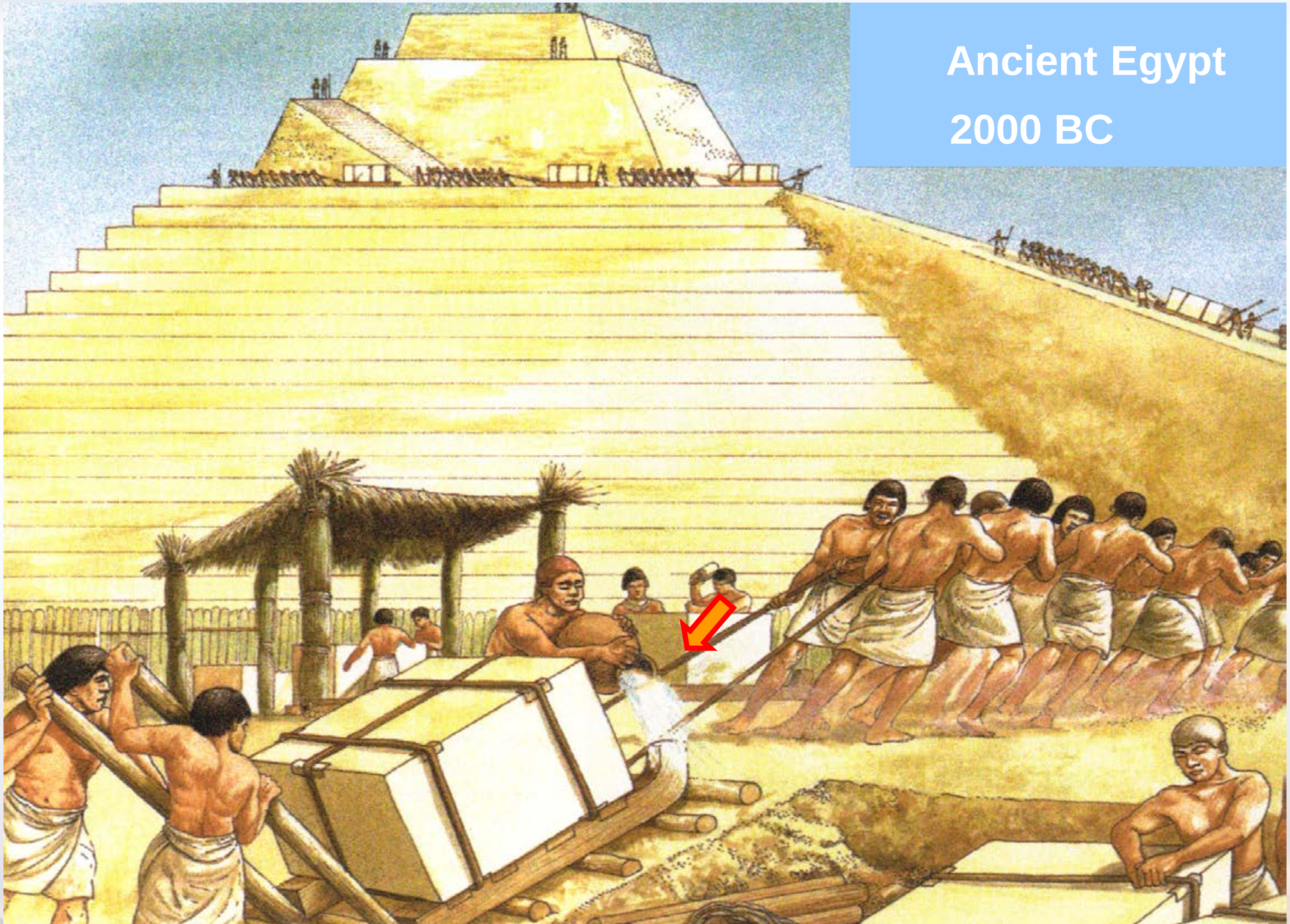
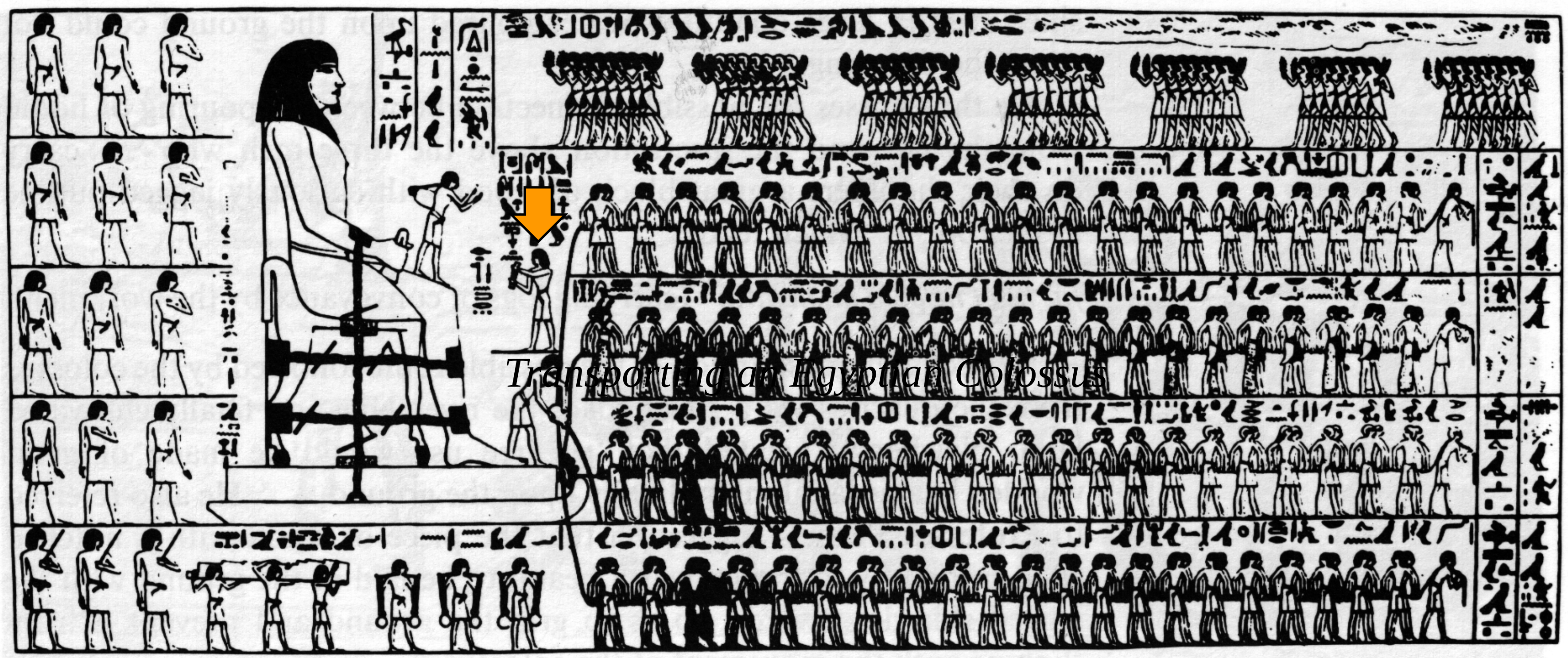
Egyptian Pyramids



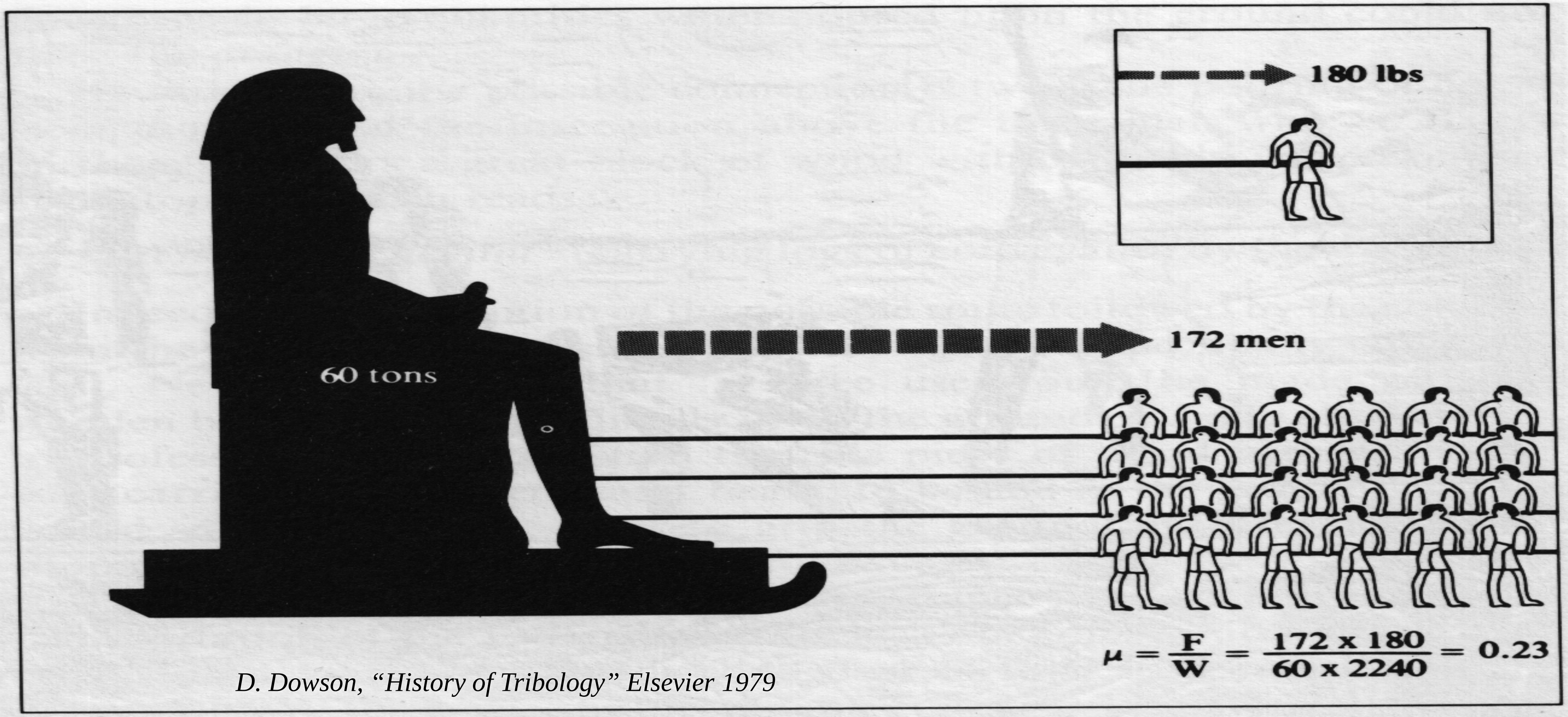
Ancient Egypt

2000 BC

Transporting an Egyptian Colossus



Painting from a Grotto at El-Bersheh
Source: Duncan Dowson, History of Tribology , Elsevier, 1979



D. Dowson, "History of Tribology" Elsevier 1979

Bowden and Tabor, "Friction and Lubrication of Solids-Part I" Oxford 1950

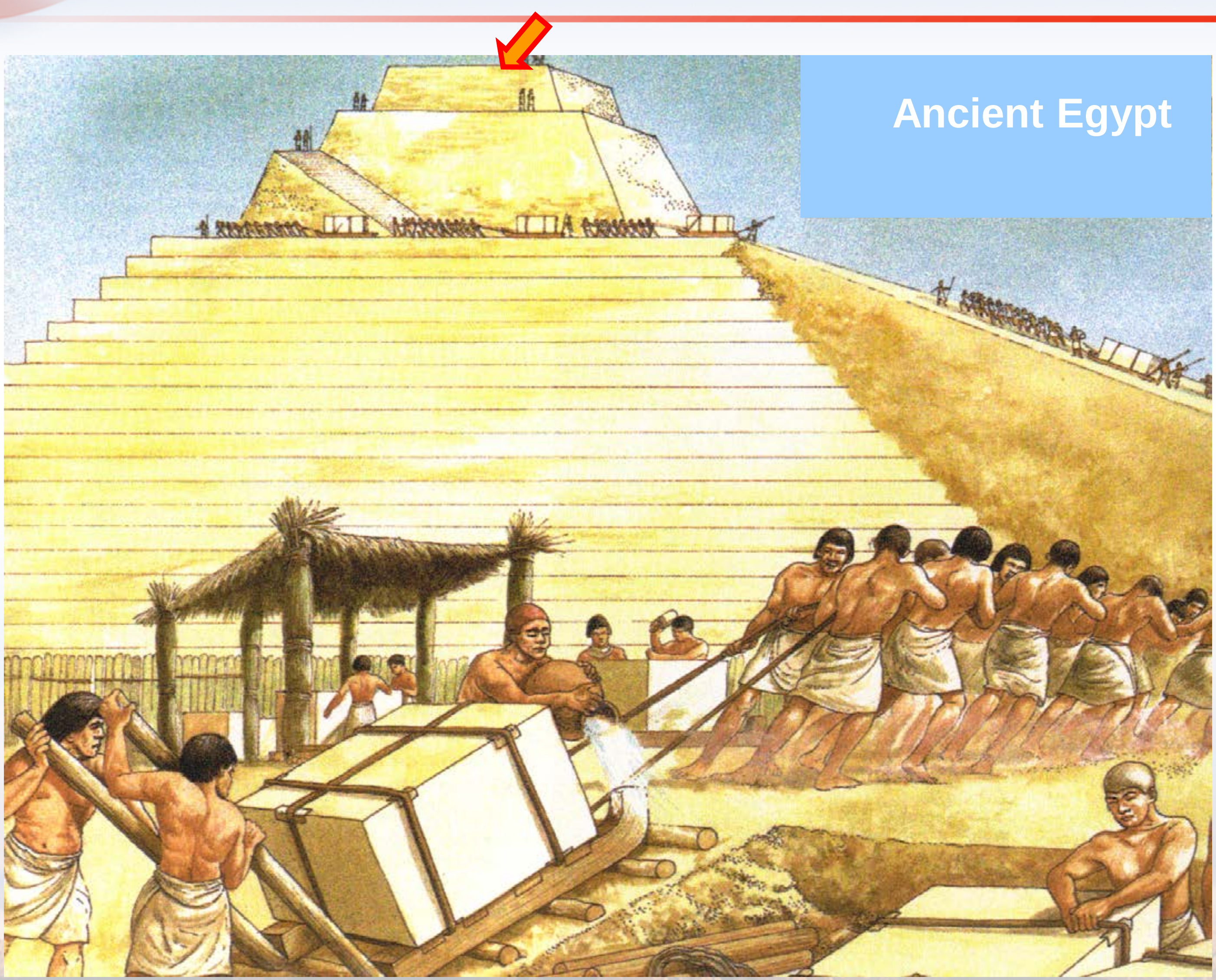
•The coefficient of friction, μ, for hard wood sliding on wet/moist wood is 0.2

•The coefficient of friction of wood-on-wood in dry condition is 0.45-0.50

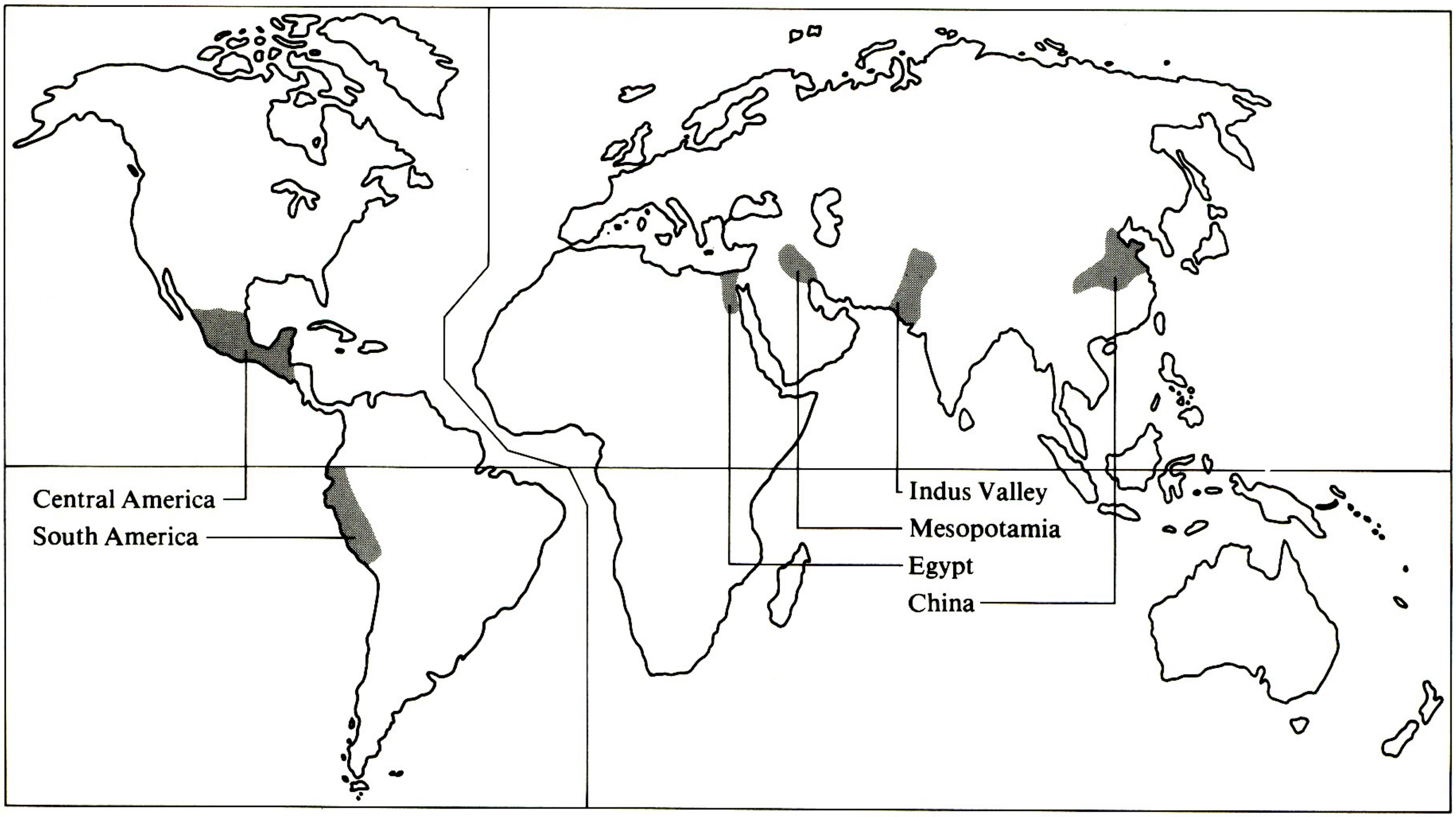
In ancient Egypt, about 100, 000 men were employed each year to transport massive objects.

Without a lubricant, 200, 000 for a state in 2000 BC can be large expense even if the monarchs fed them only one meal and paid no wages!!!

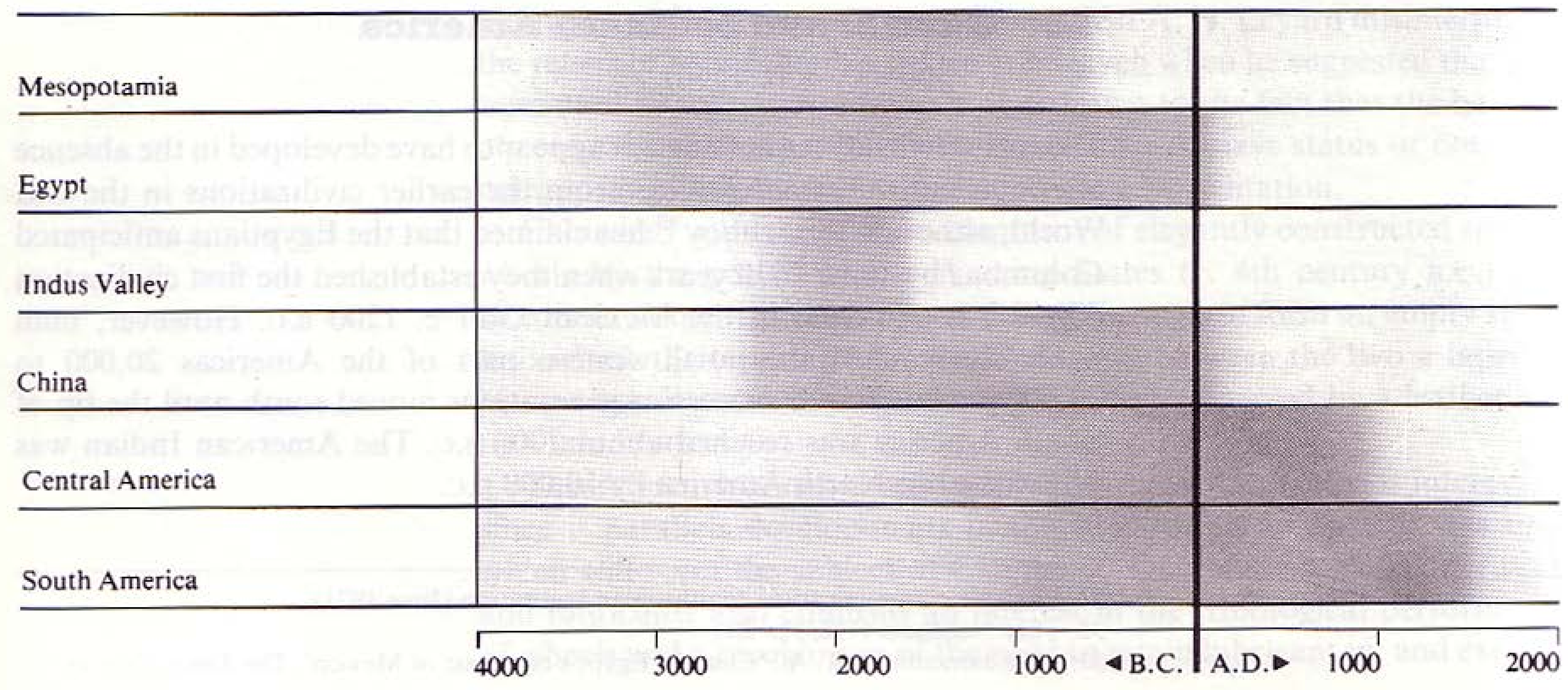
Limited space as the apex is reached



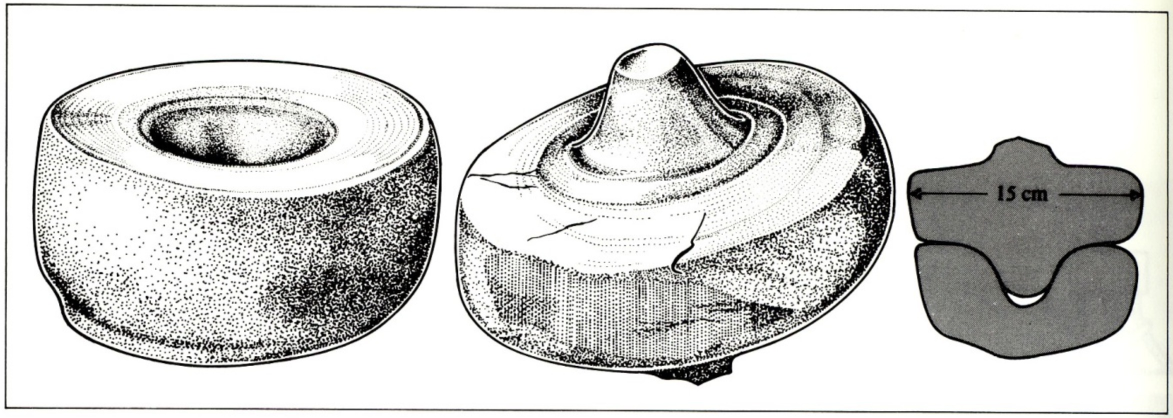
Early Civilizations Across the World



Approximate dates of the early civilizations



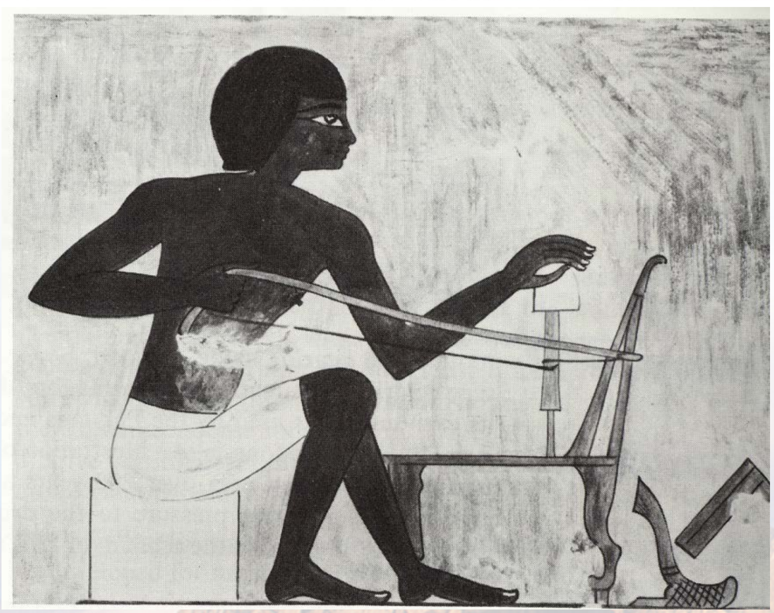
Tribological inferences from carvings



Potter's Wheel

Sumer	3250 B.C.
Syria & Palestine	3000 B.C.
Egypt	2750
England	50 B.C.
Americas	1550 A.D.

Sledge and wheeled vehicle (3000 B.C.)



Egyptians using a bow-drill

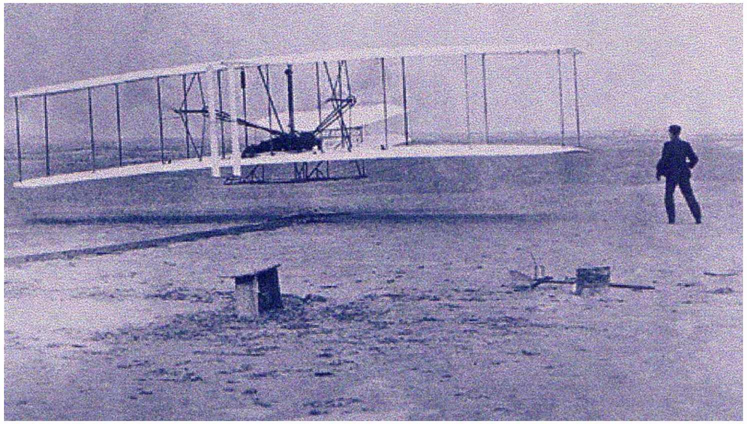
Man on skis: Stone painting from Northern Norway

Wright Cycle Company, W. Third Street, Dayton, Ohio

A Wright St. Clair bicycle. The horizontal wheel is part of an aeronautical experiment from 1901

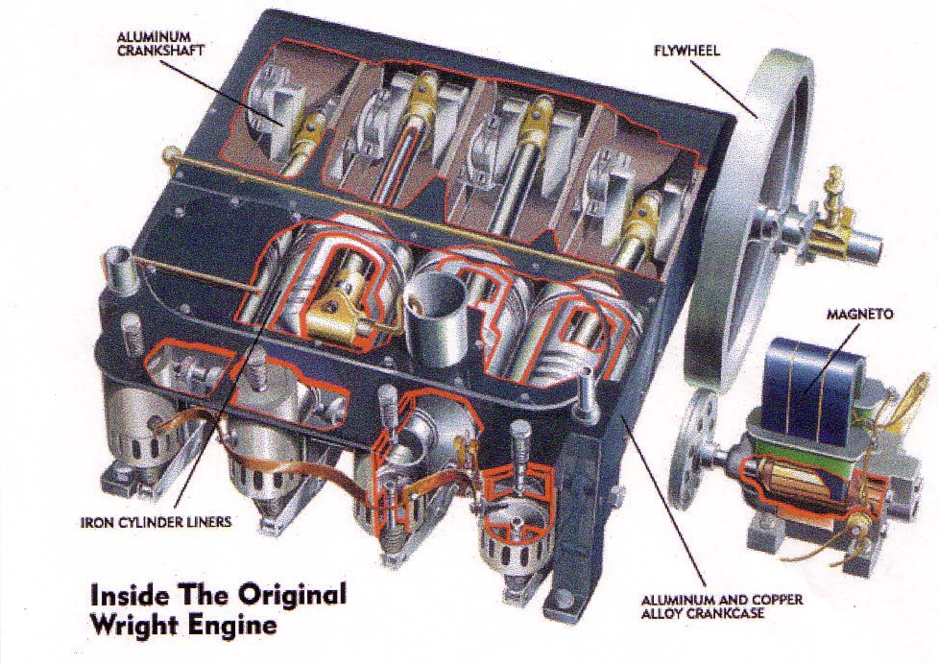
The Saga of Wright Brothers' Engine

1903



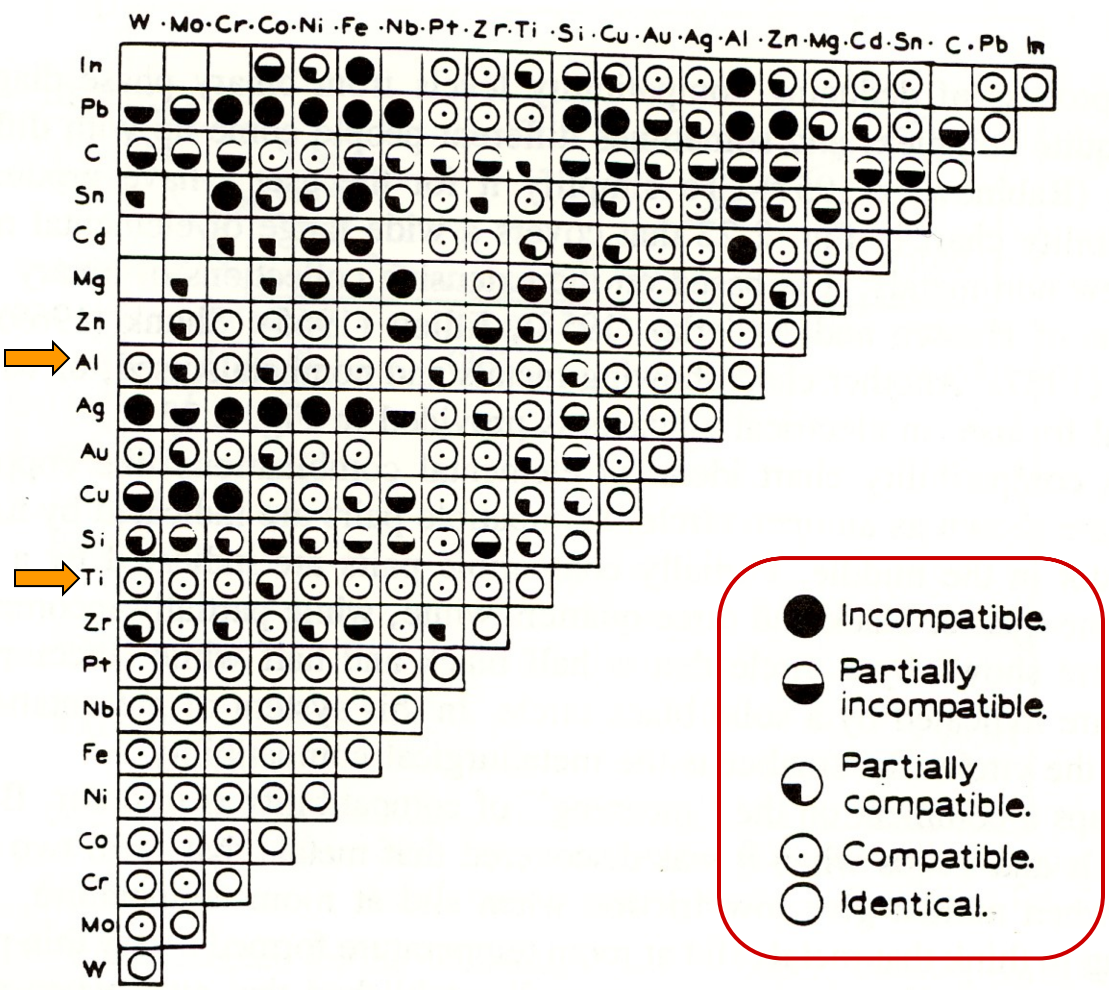
Mr. Charles Taylor (Mechanic)
Considered replacing Cast Iron with Al-Cu

- The Brothers needed an Engine with 8 HP weighing <180 lbs

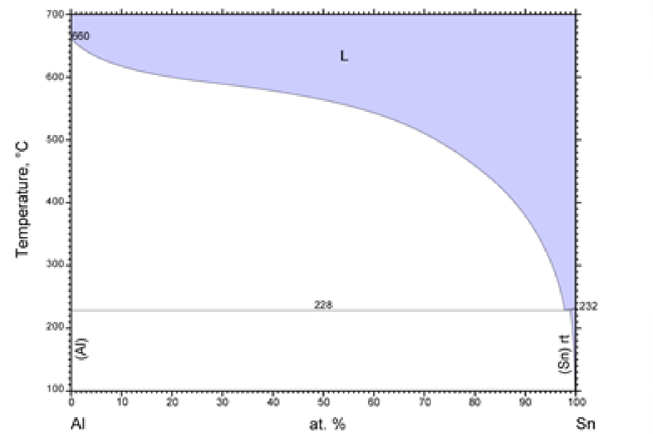


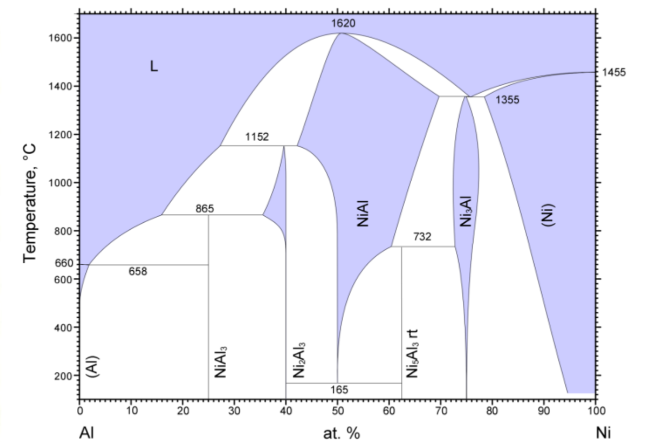
- 16 HP-12HP 178 lbs
- The Brothers used the extra weight allowance to strengthen the wings and frame
- But Al has a tendency for seizure and galling in the absence of complete fluid film lubrication

Avoid using similar metals in sliding contact (Rule of Thumb)



E. Rabinowicz, Friction and Wear of Materials, John Wiley & Sons





ASM Alloy Phase Diagrams Center, P. Villars, editor-in-chief; H. Okamoto and K. Cenzual, section editors; http://www.asminternational.org/AsmEnterprise/APD, ASM International, Materials Park, OH, USA, 2006, 2007, 2008, 2009, 2010

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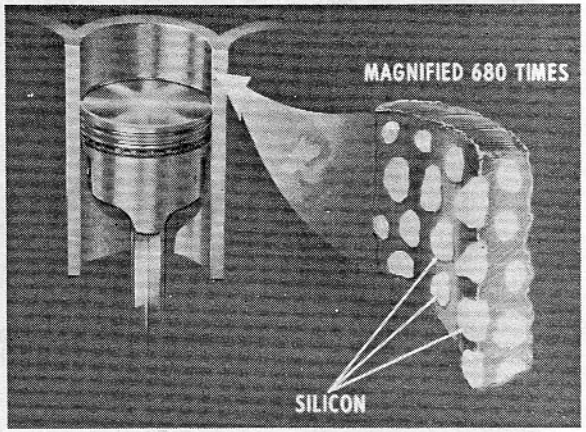
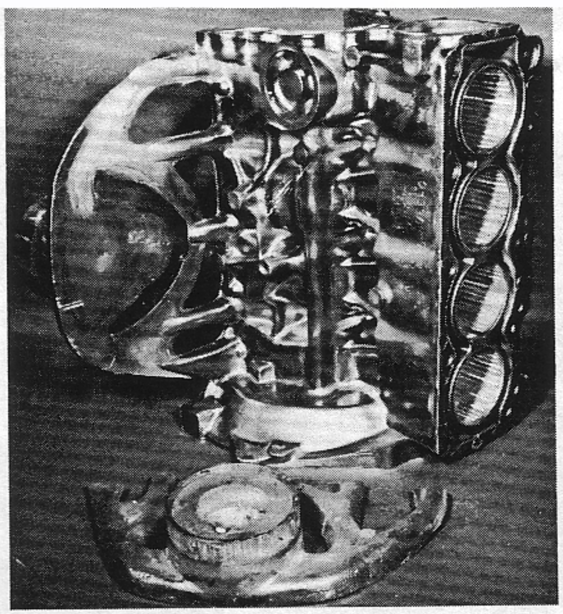
The (Short) Legacy of the Vega Engine



Silicon surface cylinder bores



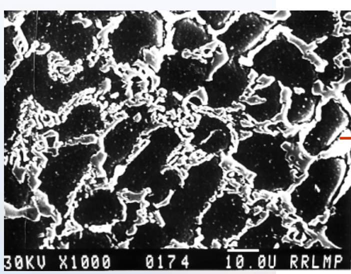
Vega engine block as removed from die

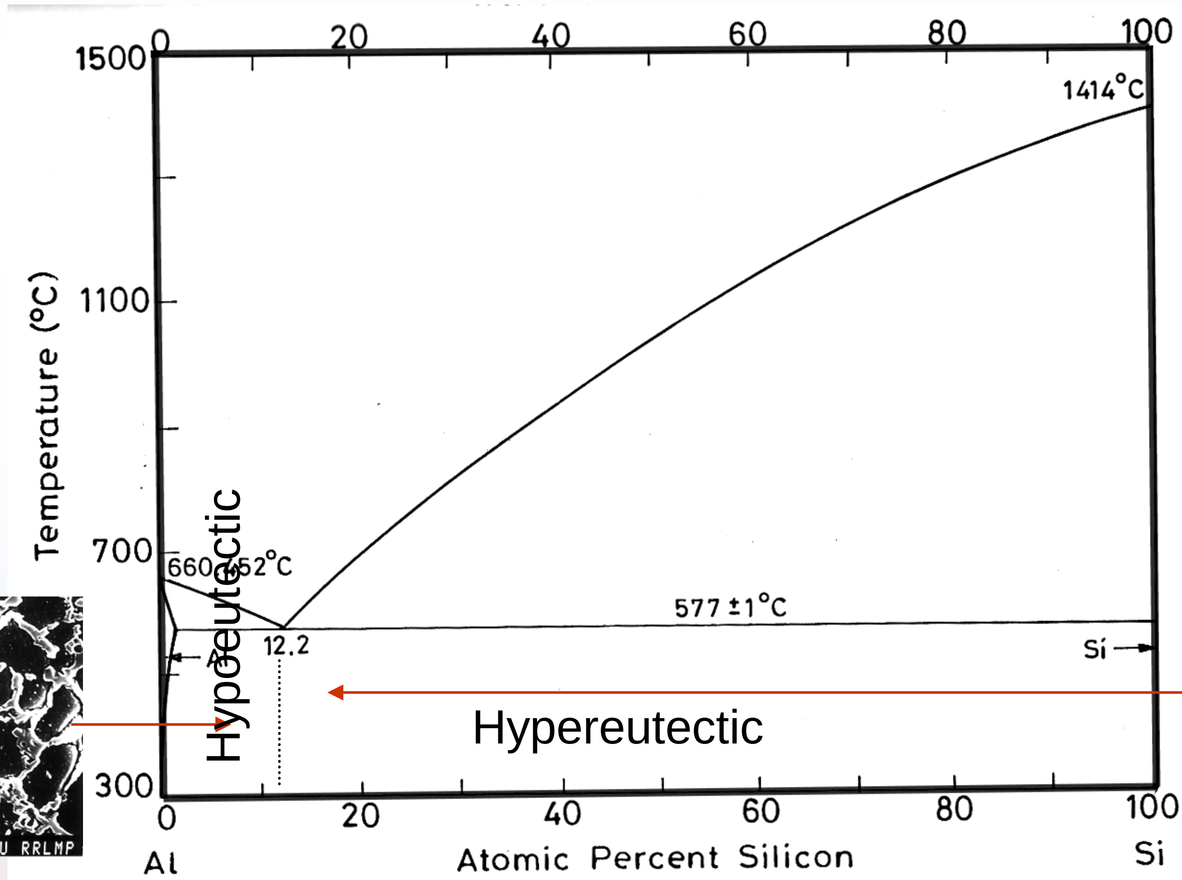
BASIC SPECIFICATIONS
VEGA 2300–140 cu in. Overhead Cam 4-cyl Engine

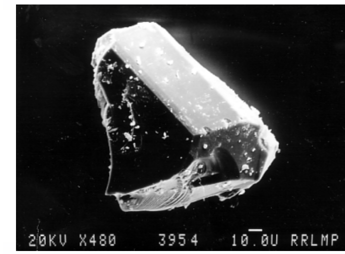
GENERAL	
Type	In-Line OHC 4-cyl (L-4)
Gross horsepower	
Standard engine	90 at 4600-4800
Optional engine	110 at 4800
Gross torque	
Standard engine	136 at 2400
Optional engine	138 at 3200
Compression ratio	8.00:1
Bore and stroke	3.501 × 3.625
Firing order	1-3-4-2
Engine installation angle	3 deg 50 min
Fuel	Regular leaded and nonleaded 91 Octane
Carburetor	
Standard engine	One-barrel, Monojet
Optional engine	Two-barrel, downdraft
CYLINDER BLOCK	
Material	Die-cast high-silicon aluminum alloy
Bore spacing (C/L to C/L)	4.00
Number of bulkheads	Five

The Vega 2300 Engine, SAE 710147

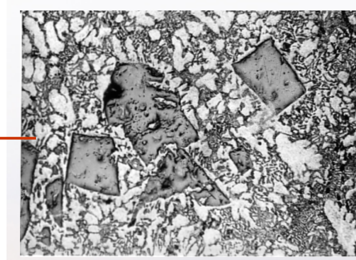
Both the eutectic and the primary Si have undesirable morphology



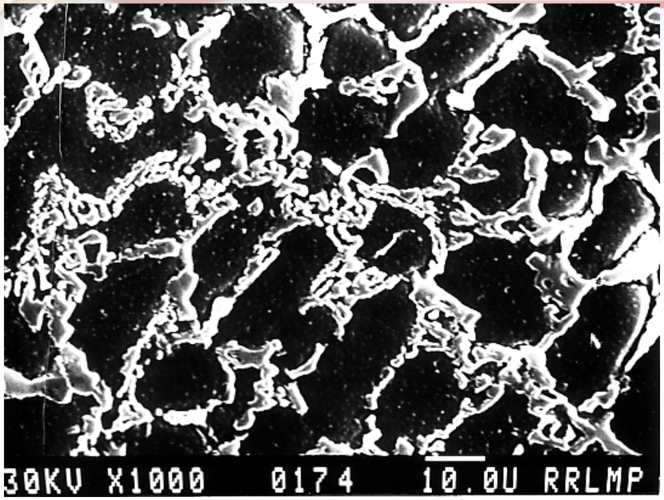


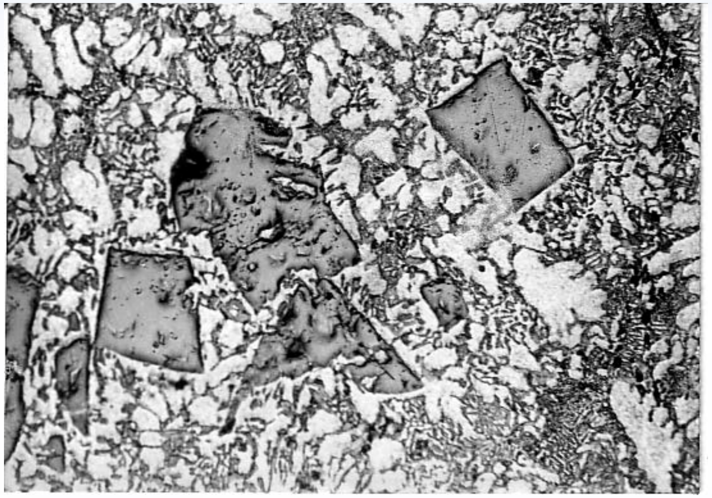


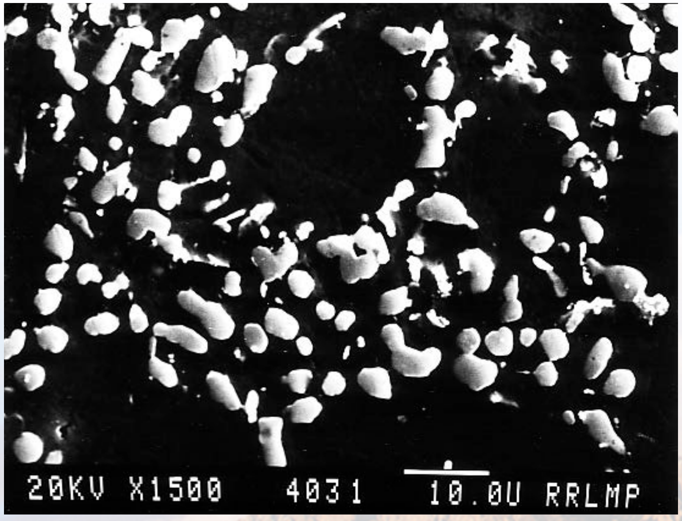
Silicon Debris
From Wear Test

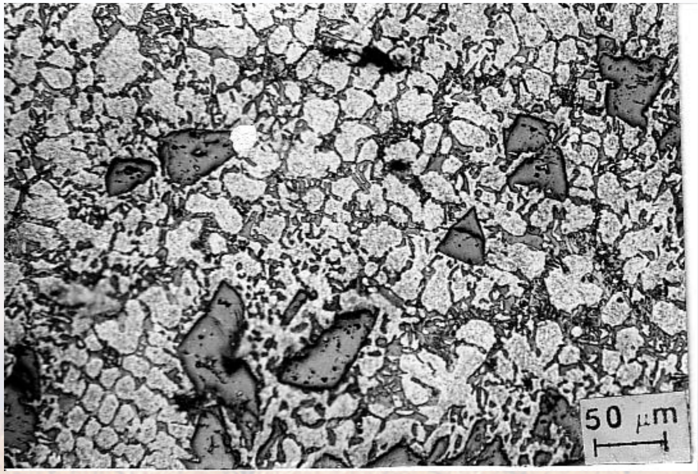


Microstructural Modification



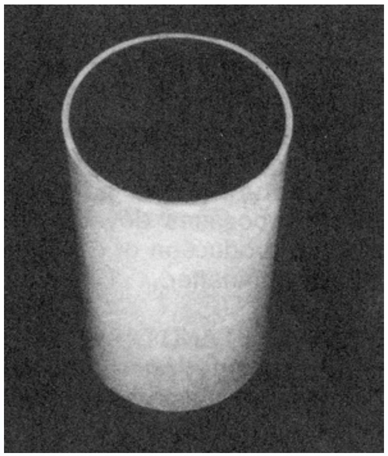






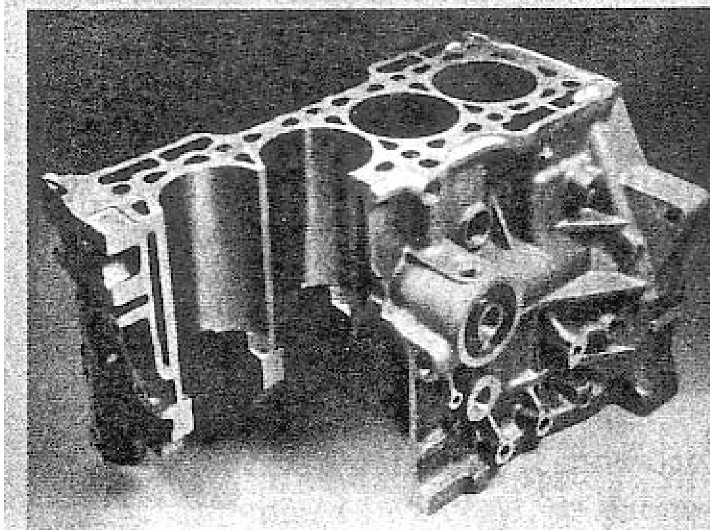
Thermal management (arising from poor thermal conductivity of Si) was an issue that wasn't factored during the initial engine development, which essentially killed the engine.

Integrally Cast MMC Cylinder: Honda Corporation



Preform

A porous hybrid material made out of Short alumina and Carbon fibers

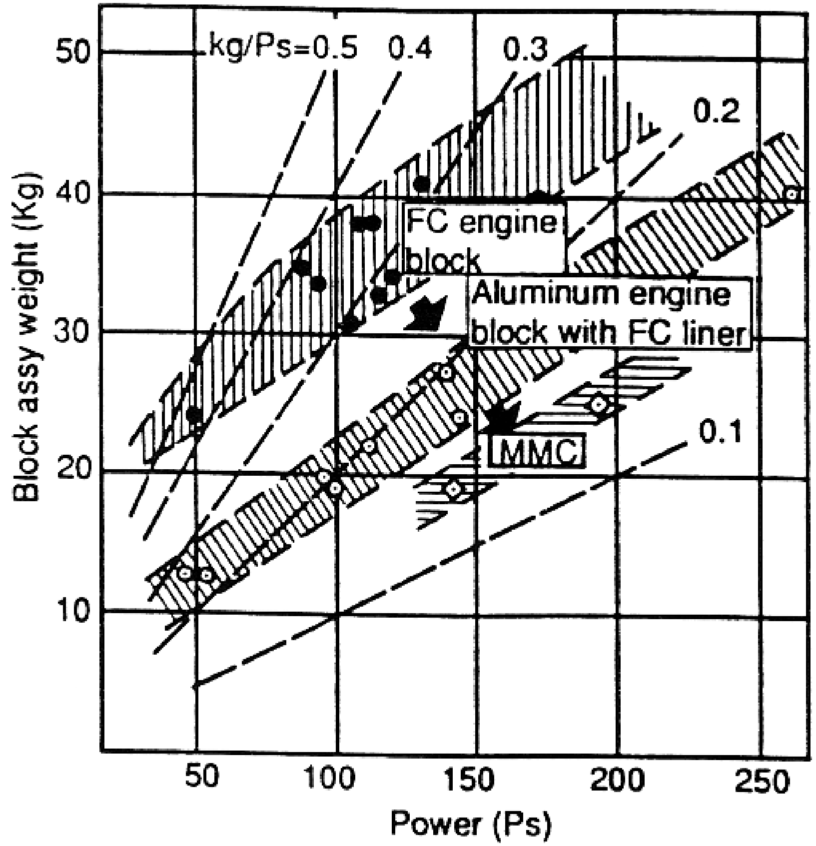


The integrally cast metal-matrix composite cylinder walls of the engine save weight and space, while improving its durability and ability to dissipate heat.

- **Ceramic "preform" production**
- **Pressure casting process**
- **Honing**

M. Ebisawa et. al, "The Production Process for MMC Engine Block", SAE 910835

Relationship between Power and Engine Block Weight



M. Ebisawa et. al, "The Production Process for MMC Engine Block", *SAE 910835*

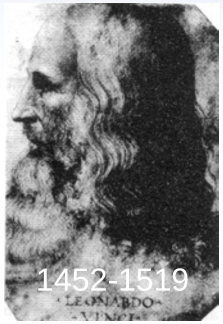
The new engine block features higher performance, further compactness and weight reduction compared to cast-iron engine blocks and those made out of Al alloy with cast-iron liners

S. V. Prasad and R. Asthana, "Aluminum Metal-Matrix Composites for Automotive Applications: Tribological Considerations", Tribology Letters, 17 (2004) 445-453.

Advanced Materials for Automotive Engines

World Tribology Congress-2010 Kyoto, Japan

Significant Milestones in Recorded History



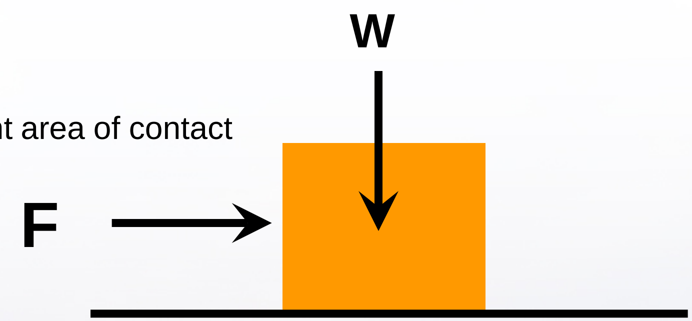
Leonardo da Vinci (quotes from his note books)

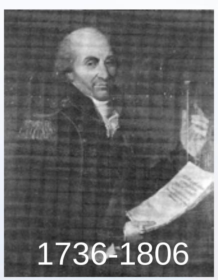
The very rapid friction of two thick bodies produces fire
That thing which is entirely consumed by the long movement of its friction will have part of it consumed at the beginning of the movement
Friction is independent of contact area
Friction resistance of a body is about ¼ of its weight

1663-1705

Guillaume Amontons (Unaware of da Vinci's recorded observations)

First published the two laws of friction:
Friction force is proportional to normal force
Magnitude of friction force does not depend on the apparent area of contact





Charles Augustin Coulomb

Verified the two laws of friction, and added the third law.
Friction force is independent of velocity once motion starts

Heinrich Rudolph Hertz

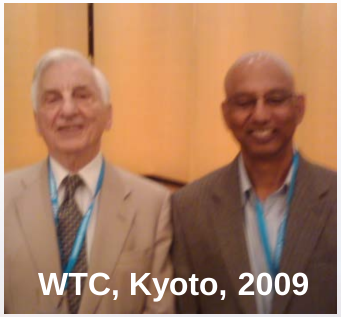
His most famous work on contact stresses and deformation is the basis upon which so many tribological concepts rest

Birth of the Phrase *"Tribology"*

SirPeter Jost, CBE

Methods by which financial savings could be made through improved tribological practice in UK industry. The percentages represent proportions of the total annual saving, which was estimated at £515 million (at 1965 prices) (from UK Department of Education and Science, Lubrication (Tribology): Education and Research, HMSO, 1966)

Reduction in energy consumption from lower friction	5%
Reduction in manpower	2%
Savings in lubricant costs	2%
Savings in maintenance and replacement costs	45%
Savings in losses resulting from breakdowns	22%
Savings in investment through greater availability and higher efficency	4%
Savings in investment through increased life of plant	20%



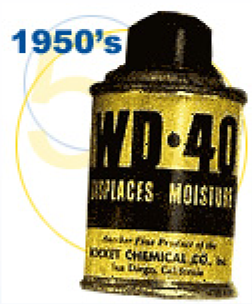
WTC, Kyoto, 2009

British Government Report published on 9 March 1966

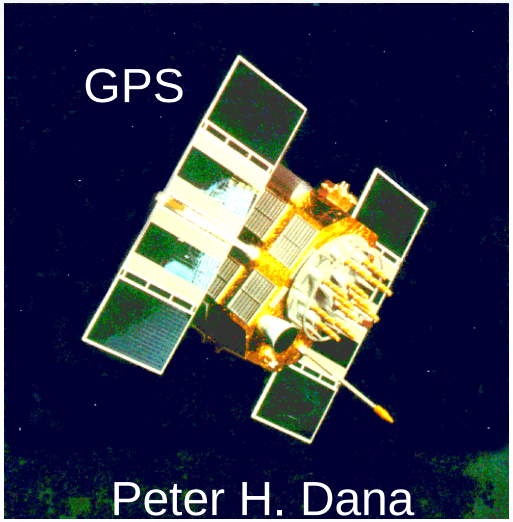
After much consideration, the concept was defined as being "the science of interacting surfaces in relative motion and associated practices" (later amended to associated subjects and practices), and after consultation with the *Editor of the Oxford Dictionary*, given the name "Tribology", based on the Greek "Tribos" (rubbing)

From Wright Brothers to the 21st Century

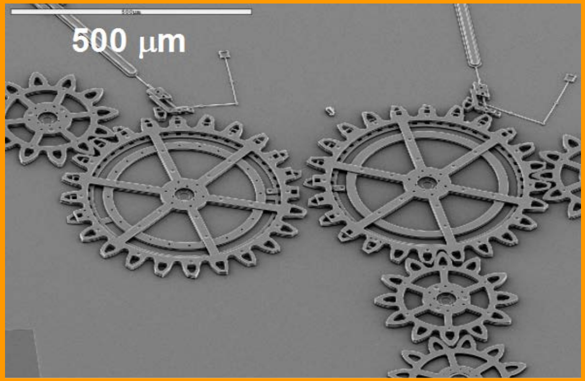
- **Satellites**
  - Communications

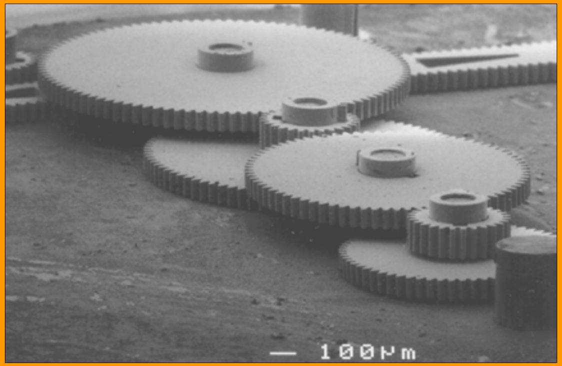


- **Electromechanical Switches**
  - Reliability
  - Safety



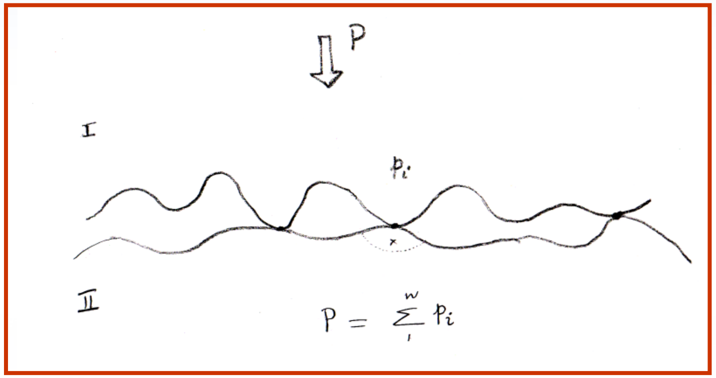
Miniaturization





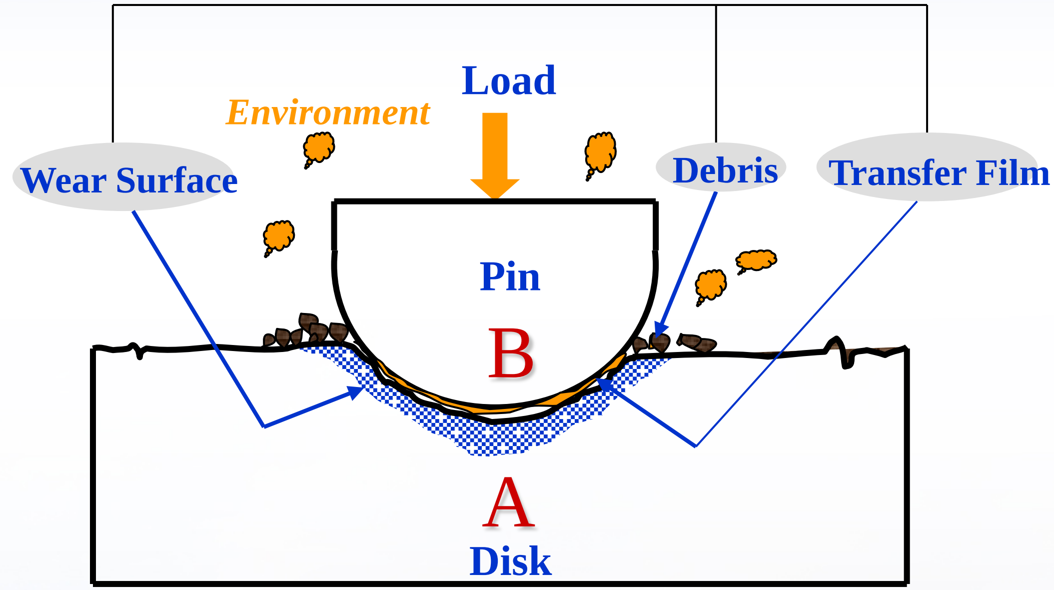
Moving Mechanical Assemblies: MEMS

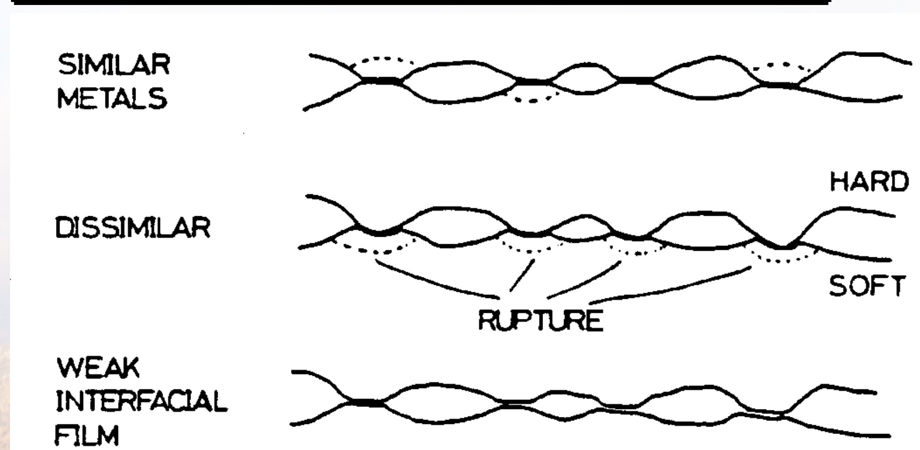
Tribology is a systems property



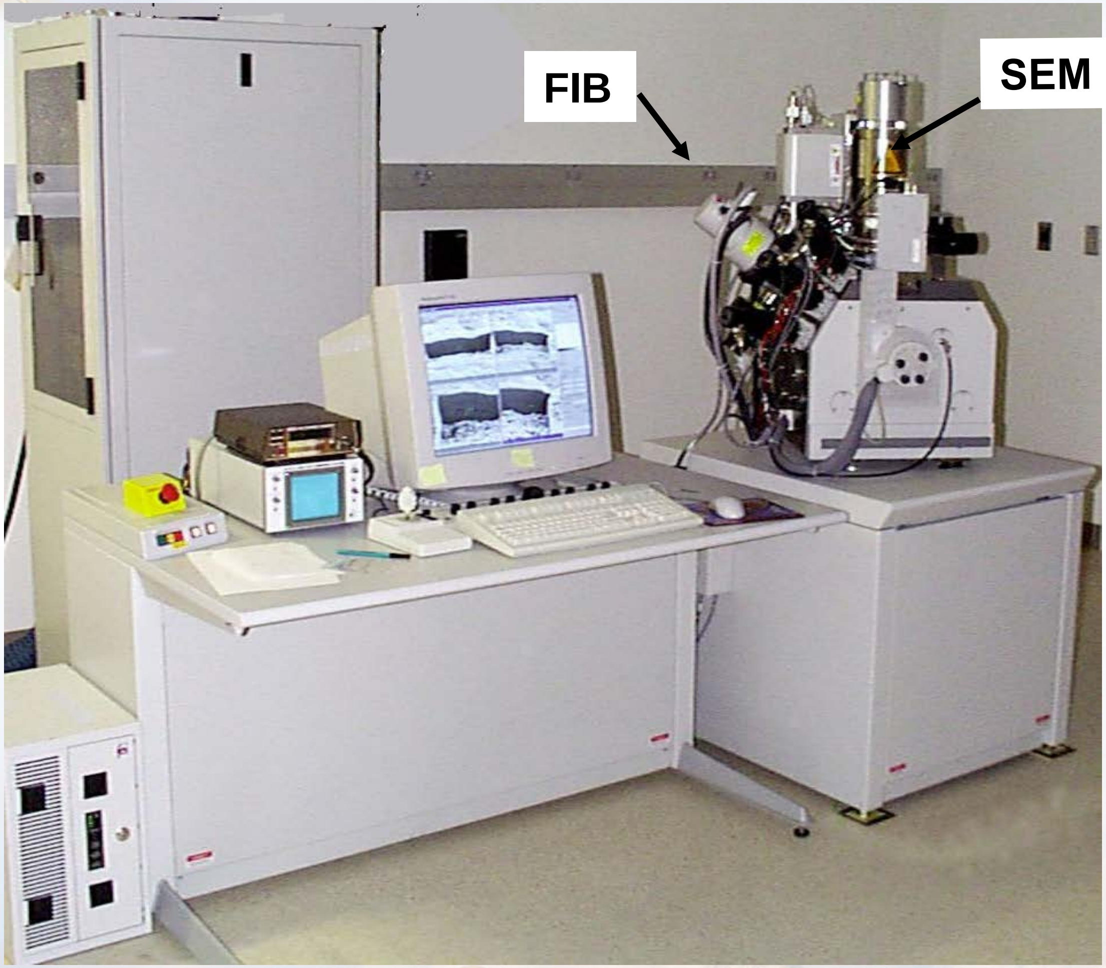
Recognize the limitations of the laws of friction

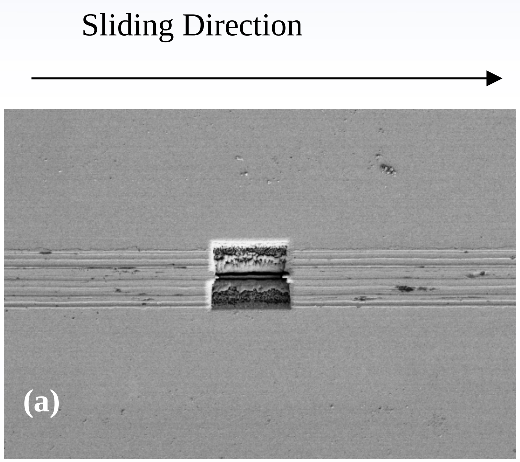
- Engineering surfaces are not atomically flat
- Friction influences the (Hertzian) contact
- Sliding contact results:
  - Plastic deformation
  - Diffusion
  - Tribochemistry and Environmental reactions

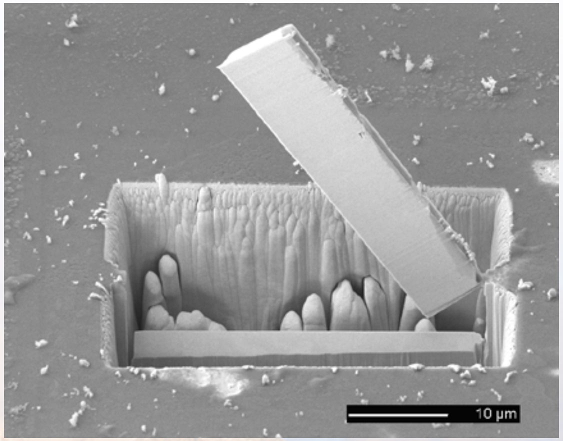




Visualization of suburfaces

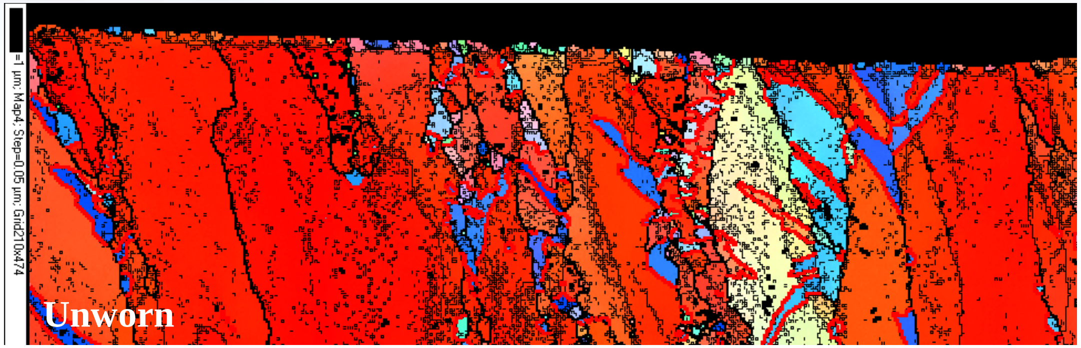


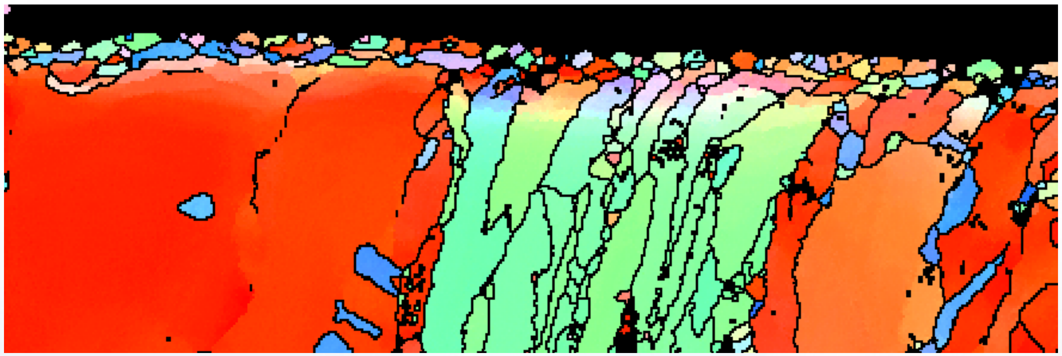


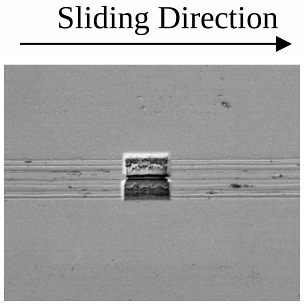


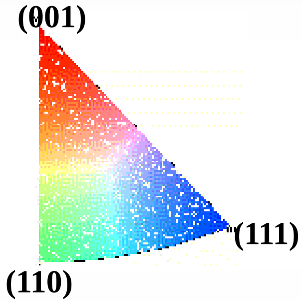
Dual-beam system from FEI: Both a FIB column and a SEM column are present on one sample chamber.

Visualization of suburface deformation: FIB, EDBSD TEM

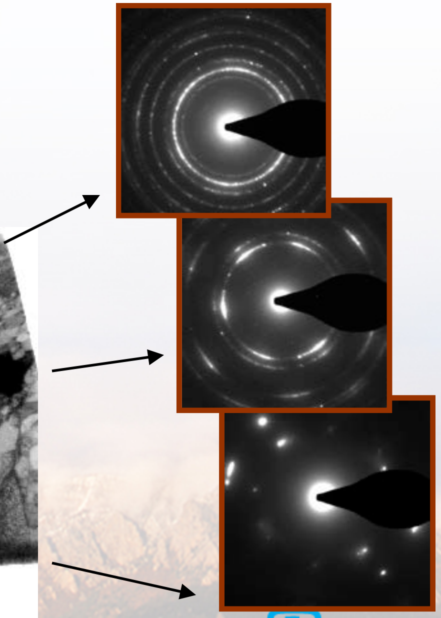






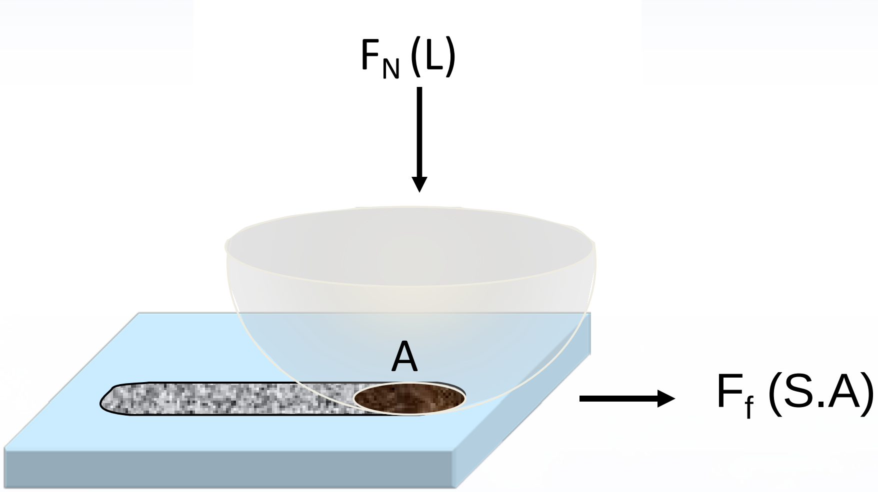


Cross sections through wear scars



Prasad SV, Michael JR, Christen TR, Scripta Materialia 48 (2003) 255

Is “Coefficient of Friction” independent of load?



$$P = F_N / A$$

$$F_f = S\,A$$

$$S = S_o + \alpha\,P$$

Elastic Contact (Sphere-on-Flat)

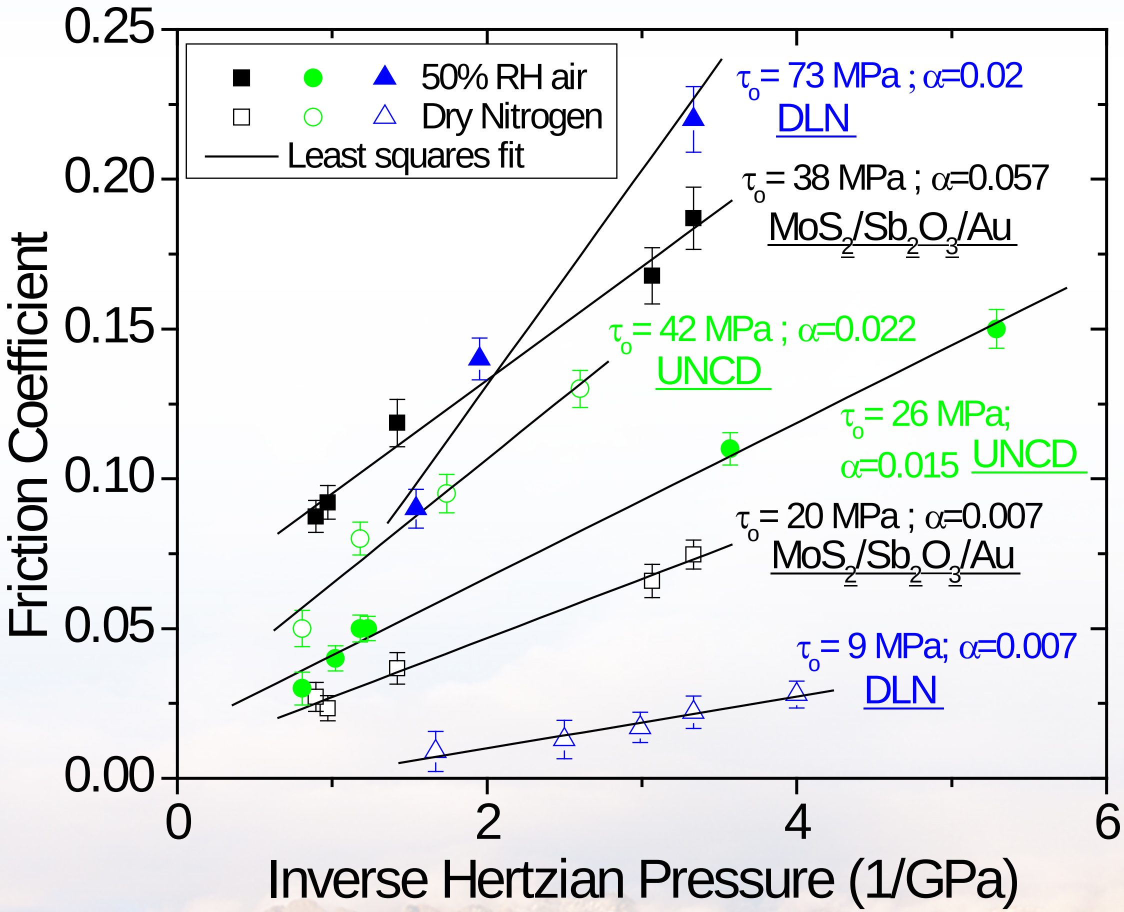
$$\mu = S_o \pi \left(3R/4E\right)^{2/3} L^{-1/3} + \alpha$$

$\mu = F_f/F_N = S.A/P.A$

S_o is the interfacial shear strength (a ‘velocity accommodation parameter’), a property of the interface.
α is a fit constant (the pressure-dependence of ‘S’)

F. P. Bowden and D. Tabor, “The Friction and Lubrication of Solids”, Oxford Science Publications, 1986
I.L. Singer, et al. *Applied Physics Letters* 57, 995 (1990).
B.J. Briscoe and D.C.B. Evans, *Proc. R. Soc. Lond. A* 380, 398 (1982).

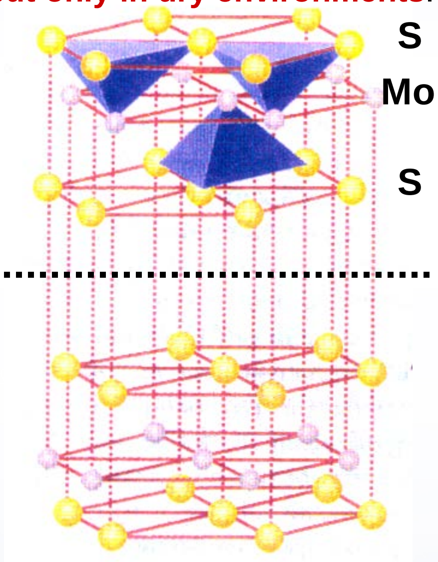
Inverse Hertzian Behavior of Most Solid Lubricants

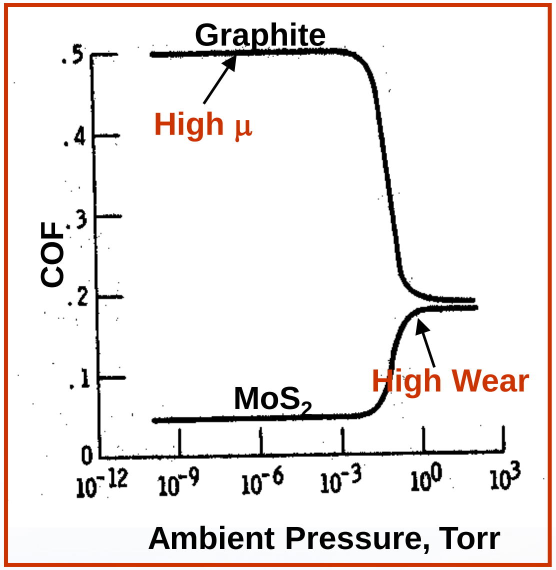


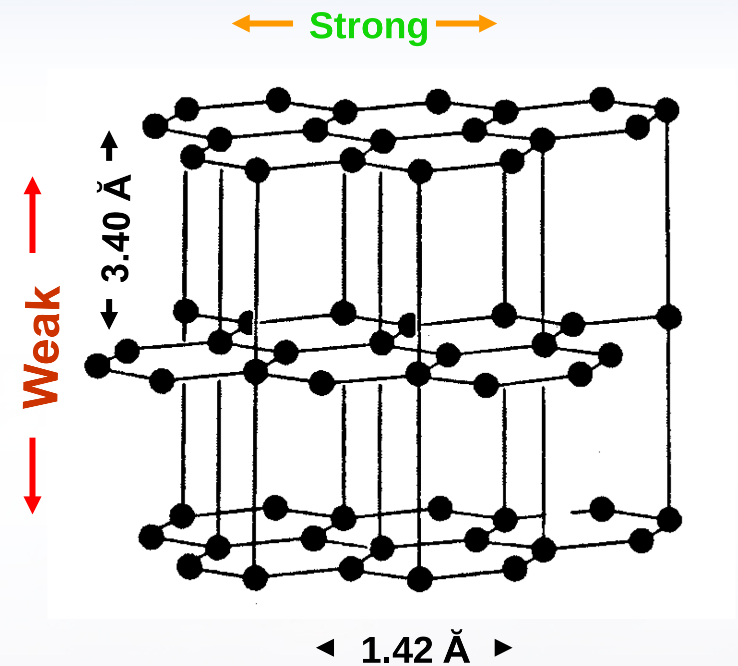
T. W. Scharf and S. V. Prasad, J Mater. Sci. ***48*** *(2013) 511–531.*

No material can act as a solid lubricant in all environments and under all operating conditions

MoS_2: Extremely low COF (0.01-0.05) and long wear life, **but only in dry environments**.



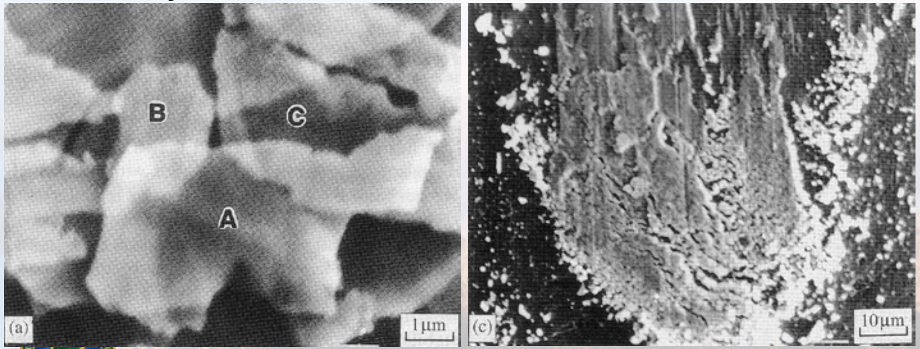




Mo/W Disulfide

Graphite

They form thin transfer films on the counterface



- Graphite needs moisture or adsorbed gases in the environment (>100 ppm) (they either act as intercalants, or passivate the dangling covalent bonds) to lubricate.
- In vacuum, graphite exhibits high friction and wear—a phenomenon known as “dusting”, first observed in the late 1930’s on graphite brushes in aircrafts that exhibited accelerated wear at high altitudes.

S. V. Prasad and J. S. Zabinski, J. Mater. Sci. Lett. 12 (1993) 1413-1415

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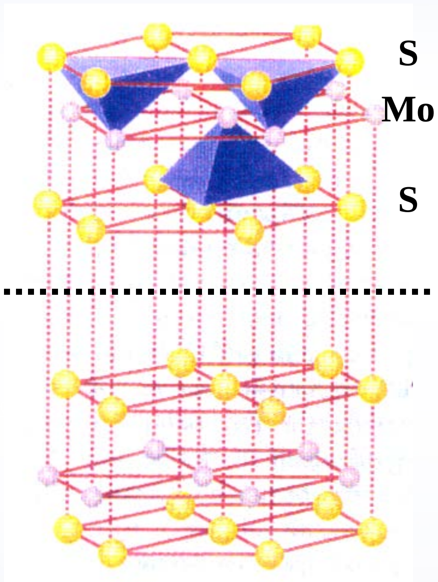
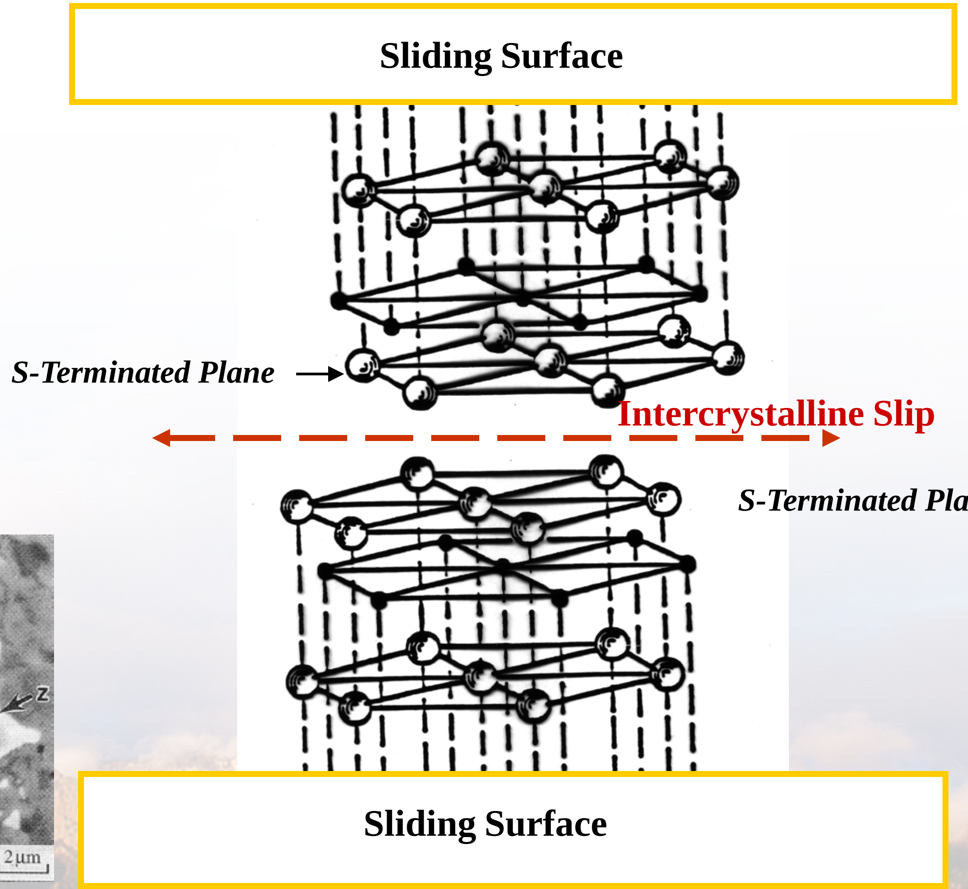
Transition metal dichalcogenides (MoS_2, WS_2)

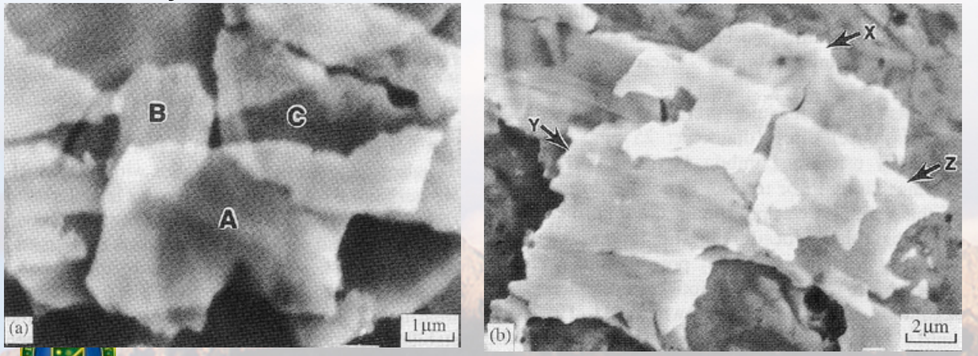


Mo/W Disulfide

Extremely low COF (0.01-0.05) and long wear life (millions of wear cycles for a micron thick MoS_2 film), **but only in dry environments**.

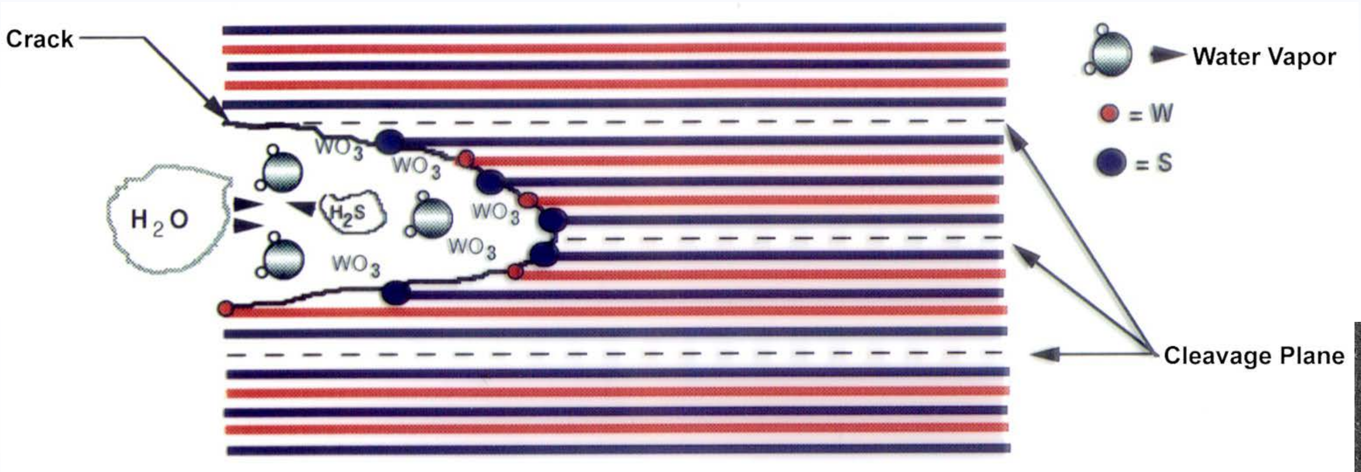


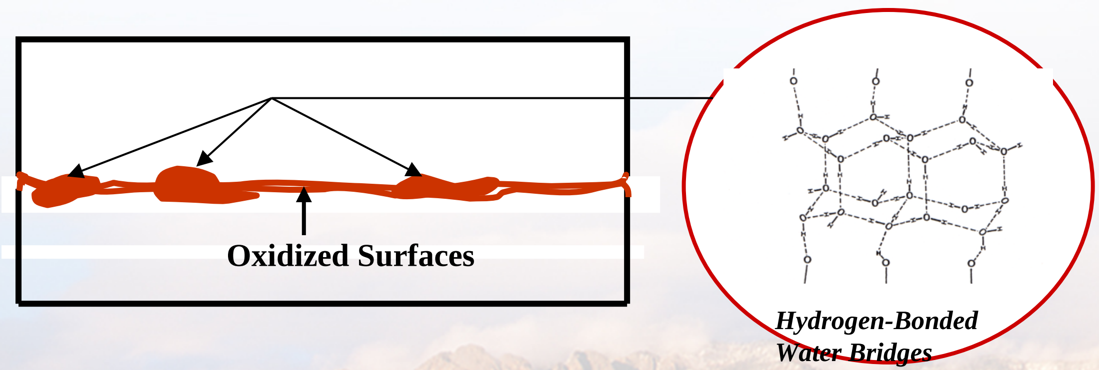
They form thin transfer films on the counterface

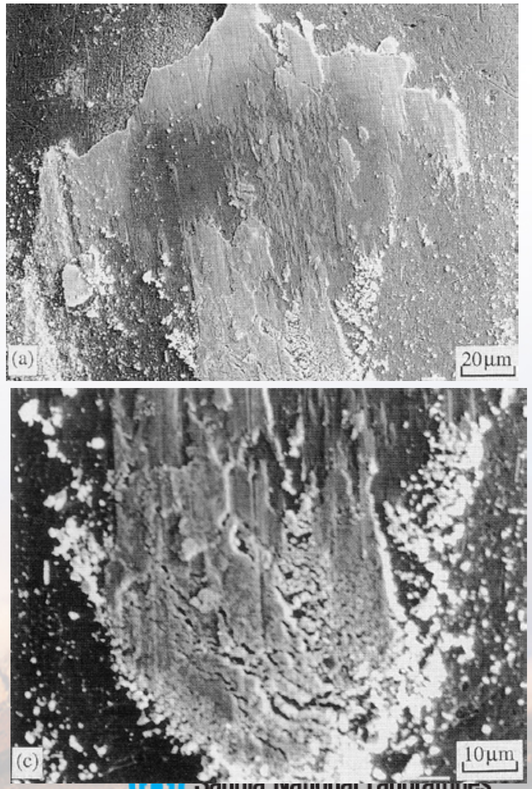


S. V. Prasad and J. S. Zabinski, *J. Mater. Sci. Lett*. 12 (1993) 1413-1415

Oxidize in humid environments, losing their ability to lubricate



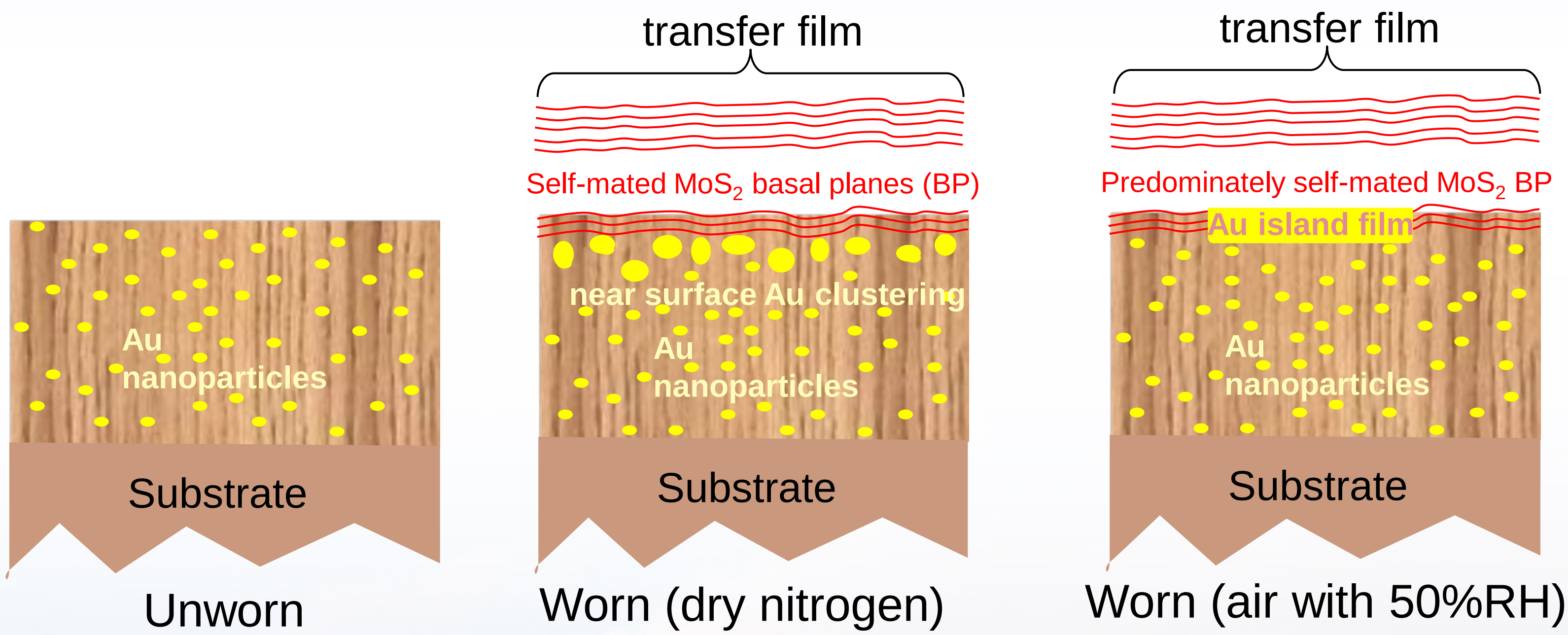




Typical transfer films (WS_2) in humid air

S. V. Prasad, J. S. Zabinski and N. T. McDevitt, *Tribology Transactions*, 38 (1995) 57-62

Environmental Robustness through Microstructural Design



- Mechanical mixing and the development of vorticity; MD evidence [Rigney and co-workers]
- The role of 'Diffusion'
- Adsorption of oxygen and water vapor in humid air: Is there a relation to the observed Au patchy islands on wear surfaces?

COF in air is higher but the wear rate is almost identical, indicating the environmental robustness of the nanocomposite ($MoS_2/Sb_2O_3/Au$) coating

T. W. Scharf, P. G. Kotula and S. V. Prasad, Acta Materialia, ***58*** *(2010) 4100-4109.*

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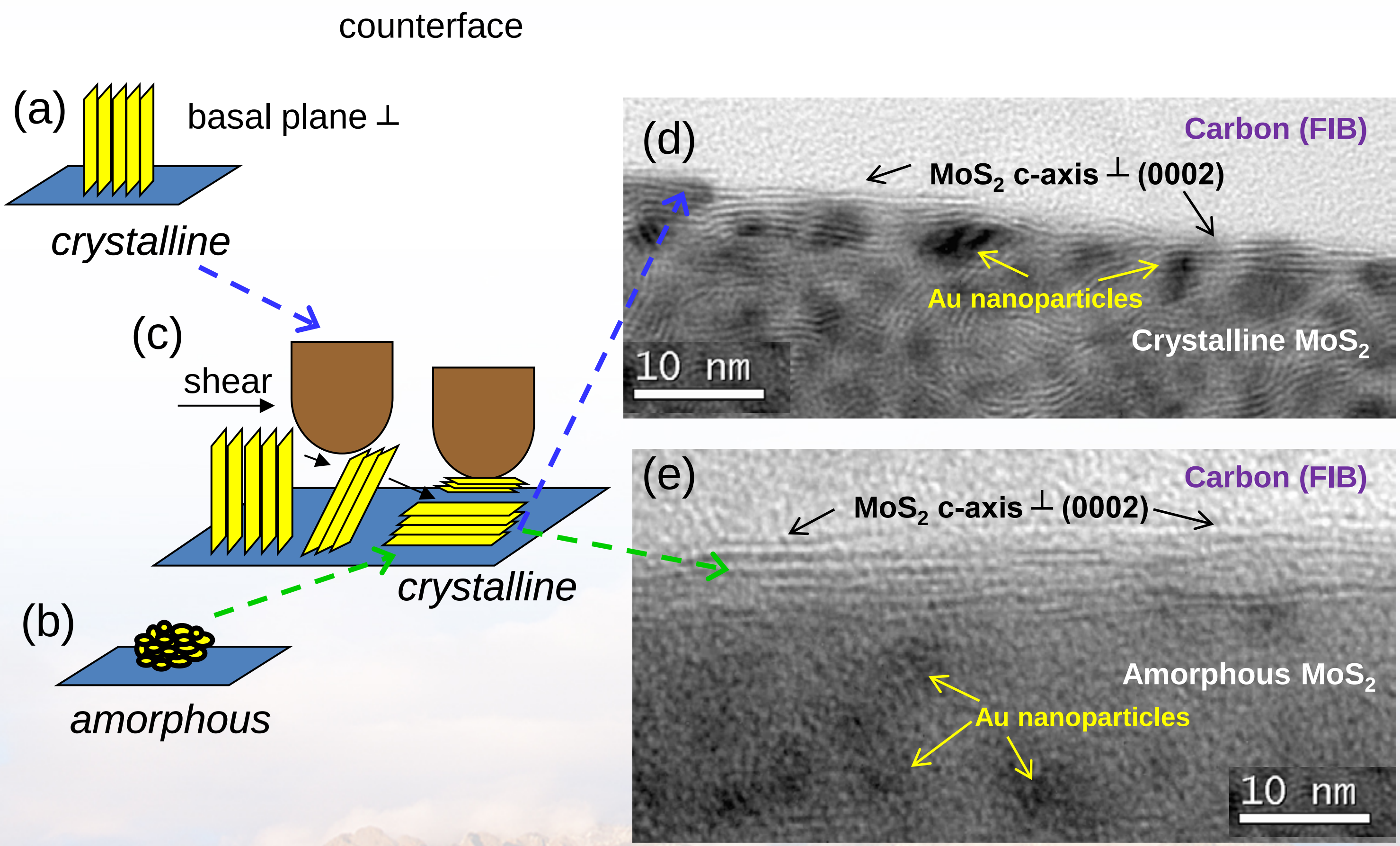
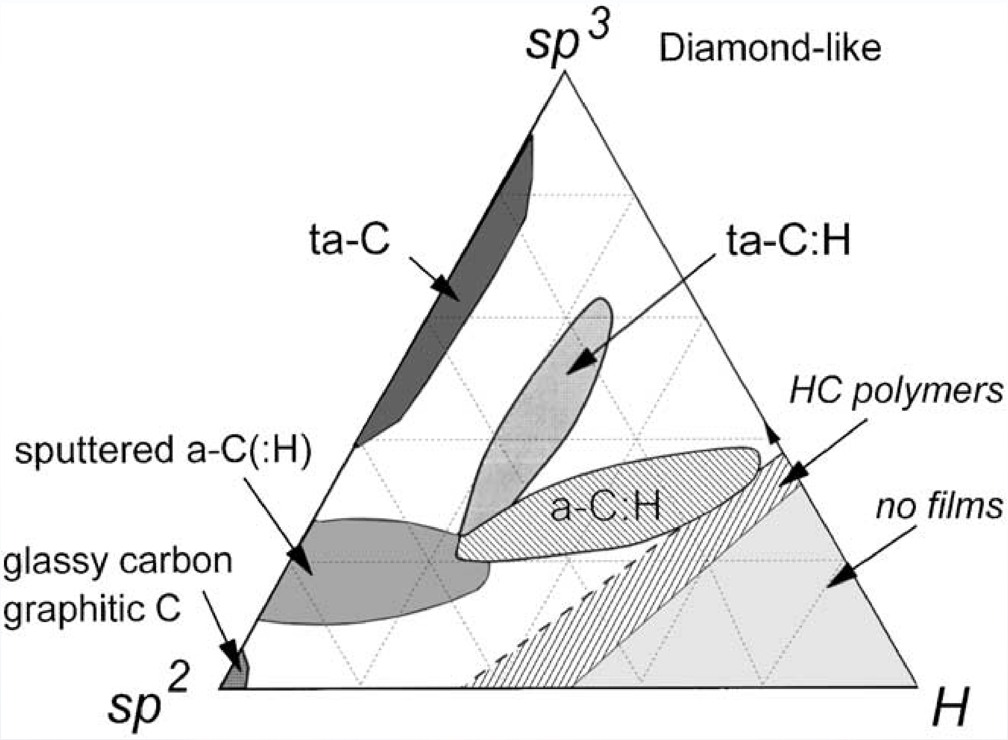
Friction-induced crystallization and reorientation of basal planes



T. W. Scharf and S. V. Prasad, J Mater. Sci. ***48*** *(2013) 511–531.*

T. W. Scharf, P. G. Kotula and S. V. Prasad, Acta Materialia, ***58*** *(2010) 4100-4109.*

Ternary phase diagram of bonding in amorphous carbon-hydrogen materials

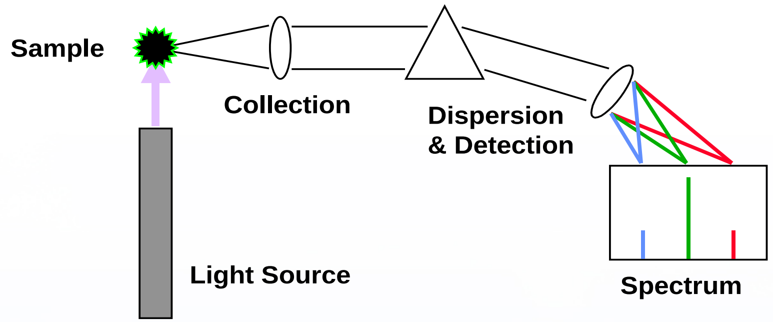


- Diamond-like Carbon (mixed sp^2/sp^3 bonding with majority being metastable sp^3 unless it is stabilized with C-H bonds).
- DLC is an amorphous (a-C) or hydrogenated amorphous carbon (a-C:H) coating (typically 10-50 atomic % H)..

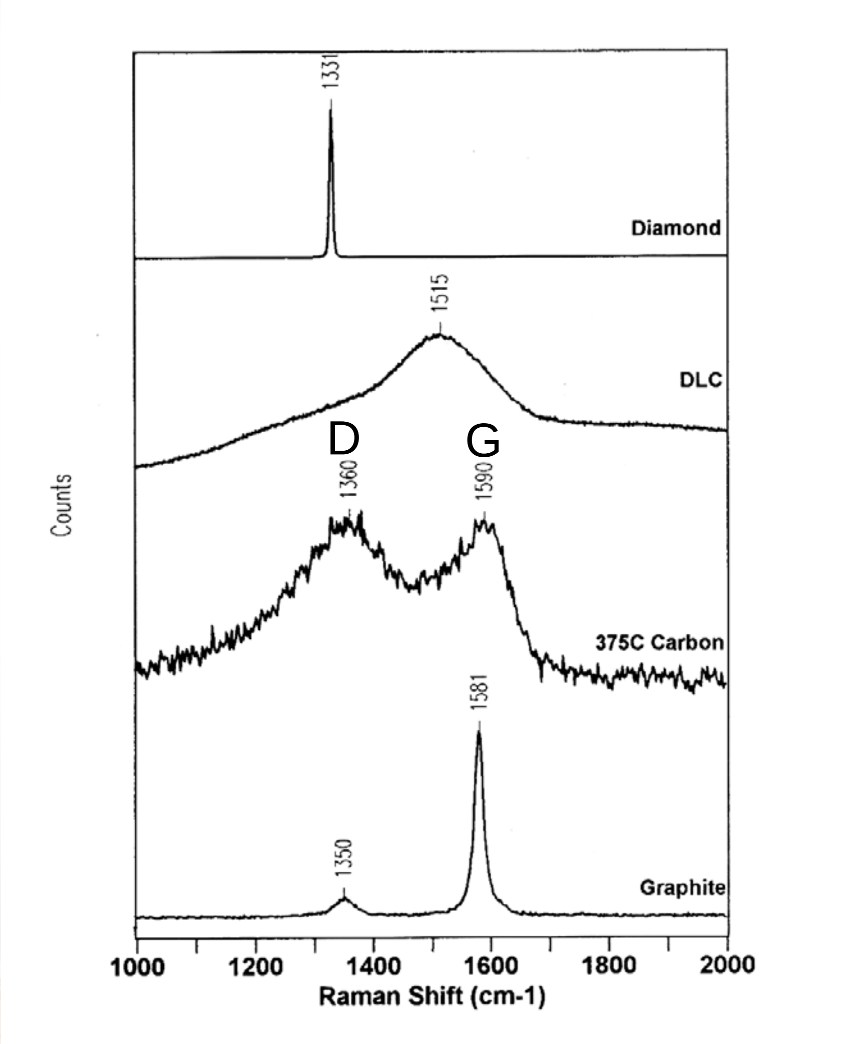
The various types are typically classified according to their fraction of sp^2, sp^3 bonding and hydrogen from a ternary phase diagram

From J. Robertson (2002) Mater Sci Eng R 37: 129.

Micro-Raman is an unique tool for carbon coatings analysis



Argon laser: 458 nm wavelength
Spot size: 1 μm (Microscope Accessory)



D. R. Tallant et. al, *Diamond and Related Materials* 4 (1995) 191-199

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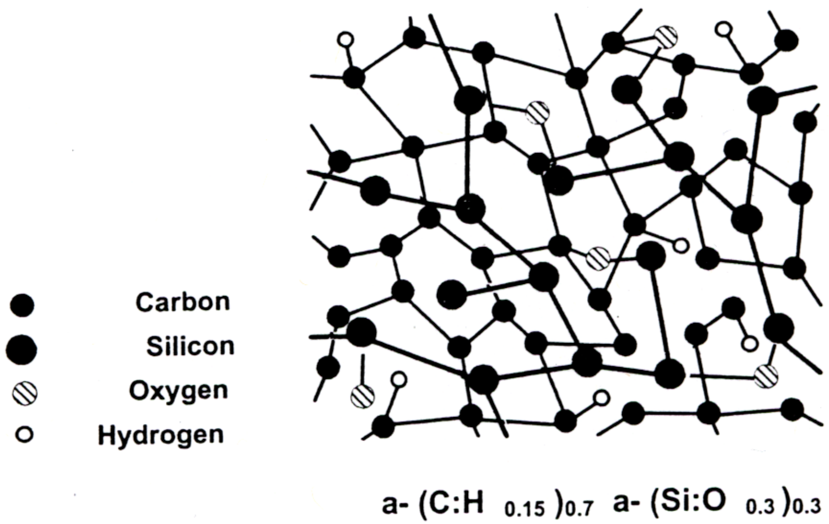
Diamond-Like Carbon
(Source: Bekart Advanced Coating Technologies)

Plasma Enhanced CVD

Ployphenylmethylsiloxane precursor



Schematic of DLN atomic structure.

Interpenetrating random networks DLC (a-C:H) and glass like a-Si:O

- Conformal coatings could provide coverage of sidewalls
- Substrate temperatures do not typically exceed 150 to 200 ºC

Hardness: 9-17 GPa
Modulus: 90-140 GPa

V. F. Dorfman, *Thin Solid Films*, 212 (1992) 267-273

D. J. Kester, C. L. Brodbeck, I. L. Singer and A. Kyriakopoulos, *Surface and Coatings Tech*. 113 (1999) 268-273.

C. Venkatraman, C. Brodbeck and R. Lei, *Surface and Coatings Tech*. 115 (1999) 215-221.

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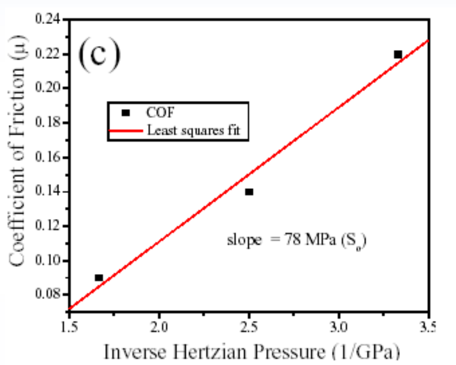
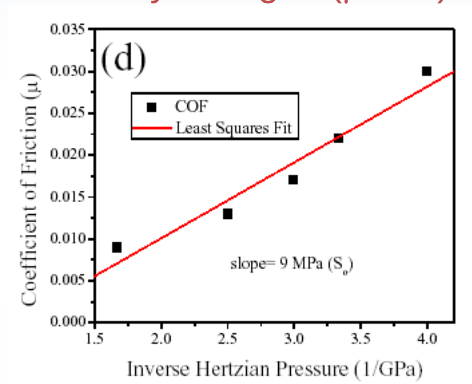
ToF-SIMS illustrating the Chameleon Nature

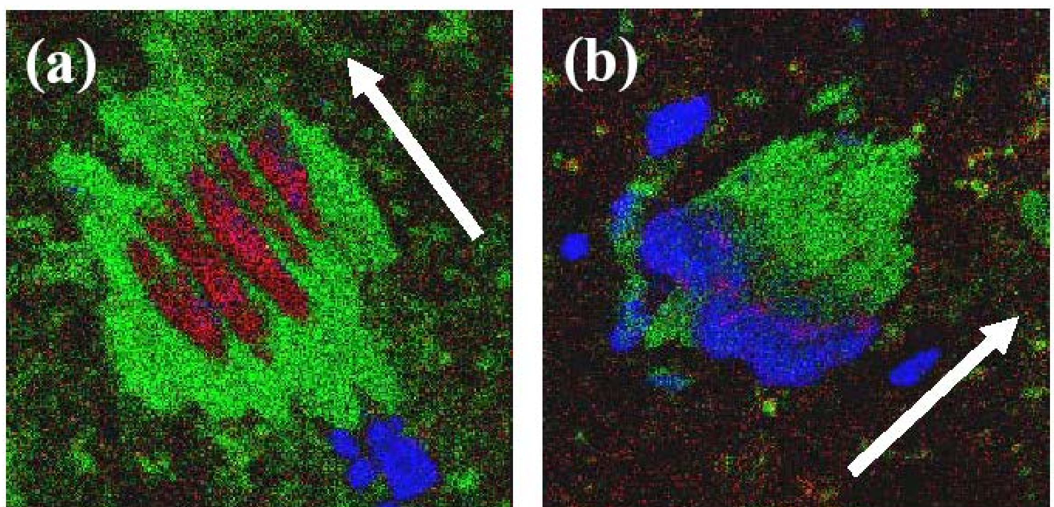
Humid Air (μ~.2)



Dry Nitrogen (μ~.02)

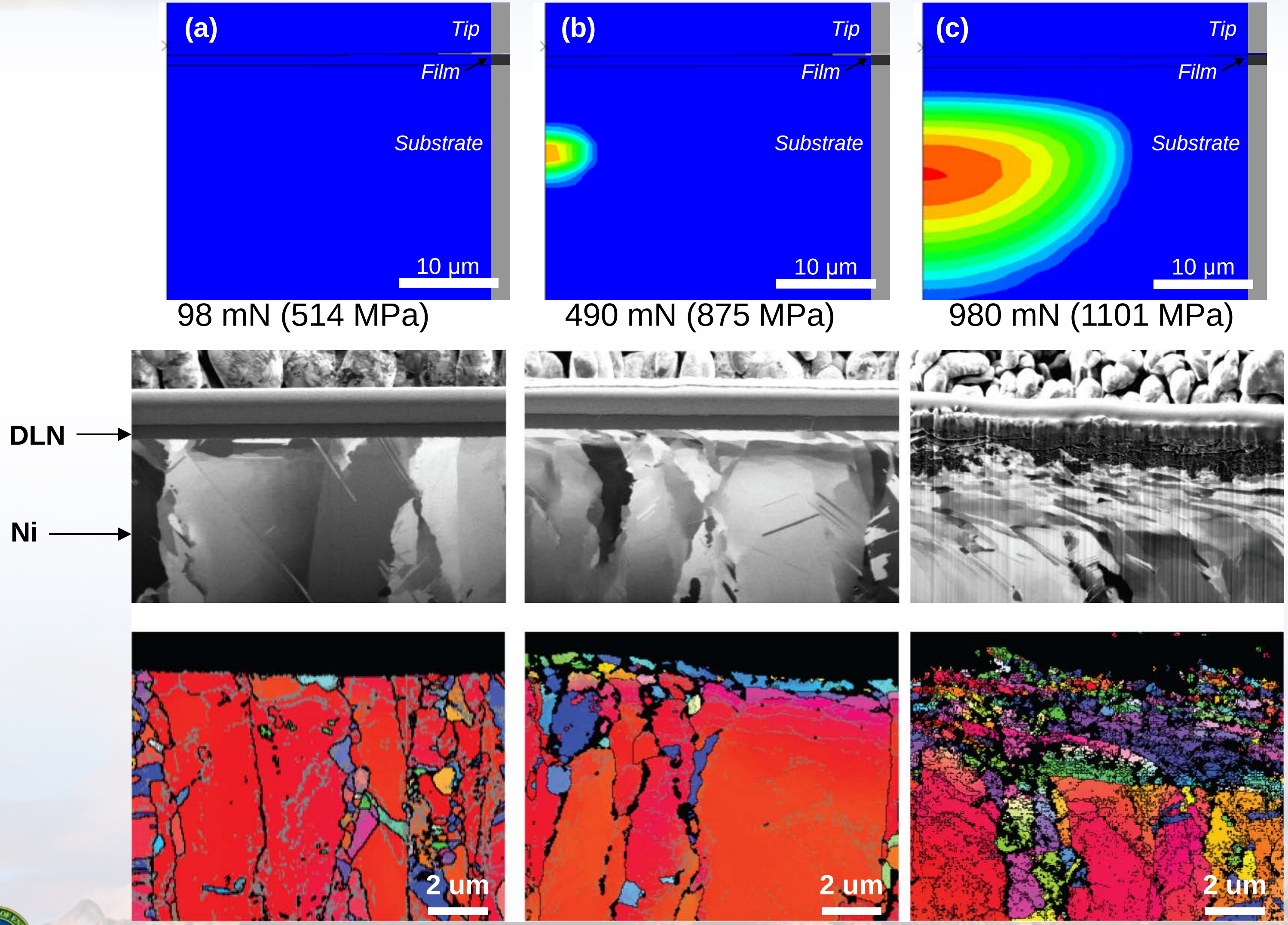


ToF-SIMS



Red: SiO_2 ($O + Si + SiO_2 + SiO_3$)
Green: Long Range Carbon (C_1 to C_4 fragments)
Blue: Hydrogenated Carbon ($CH + CH_2 + C_2H$)

Watch for plastic deformation in the substrate



S.V. Prasad, J.R. Michael T. R. Christenson, Scripta Materialia, 48 (2003) 48.

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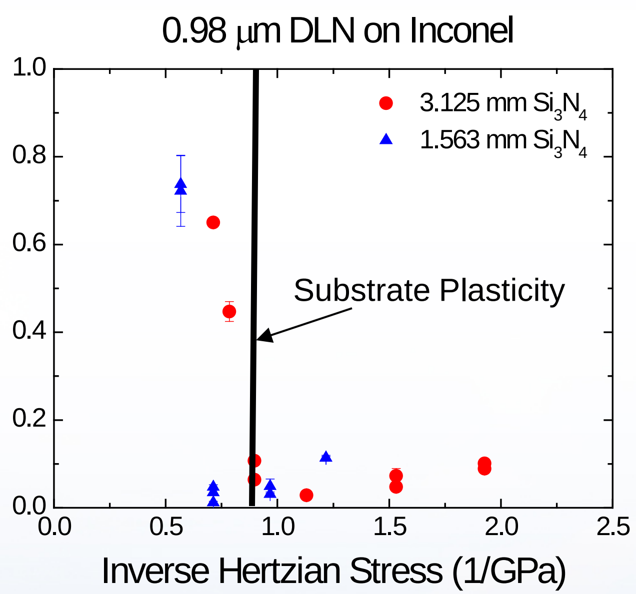
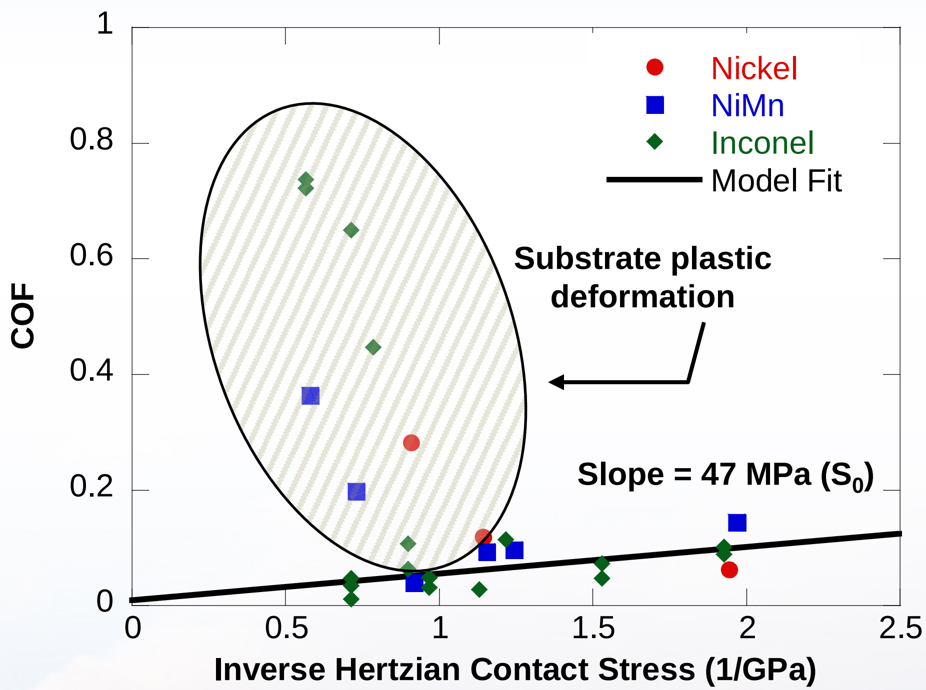
Deviations from predicted behavior





FEM predictions of substrate plastic deformation agree with observed deviations in Hertzian contact model

J.M. Jungk, J.R. Michael and S.V. Prasad, Acta Materialia, (2008) 1956-1966.

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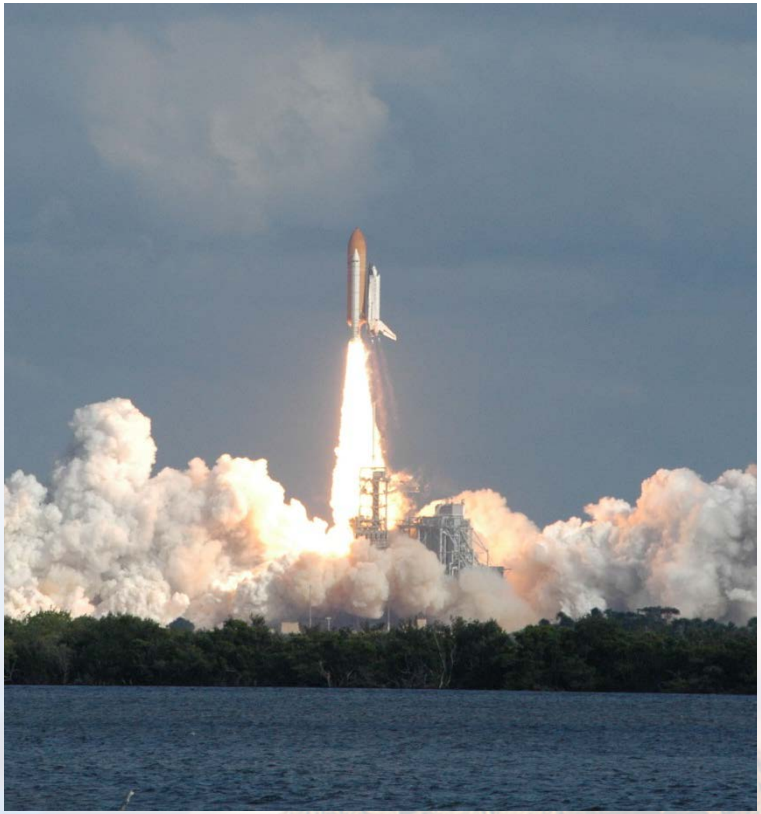
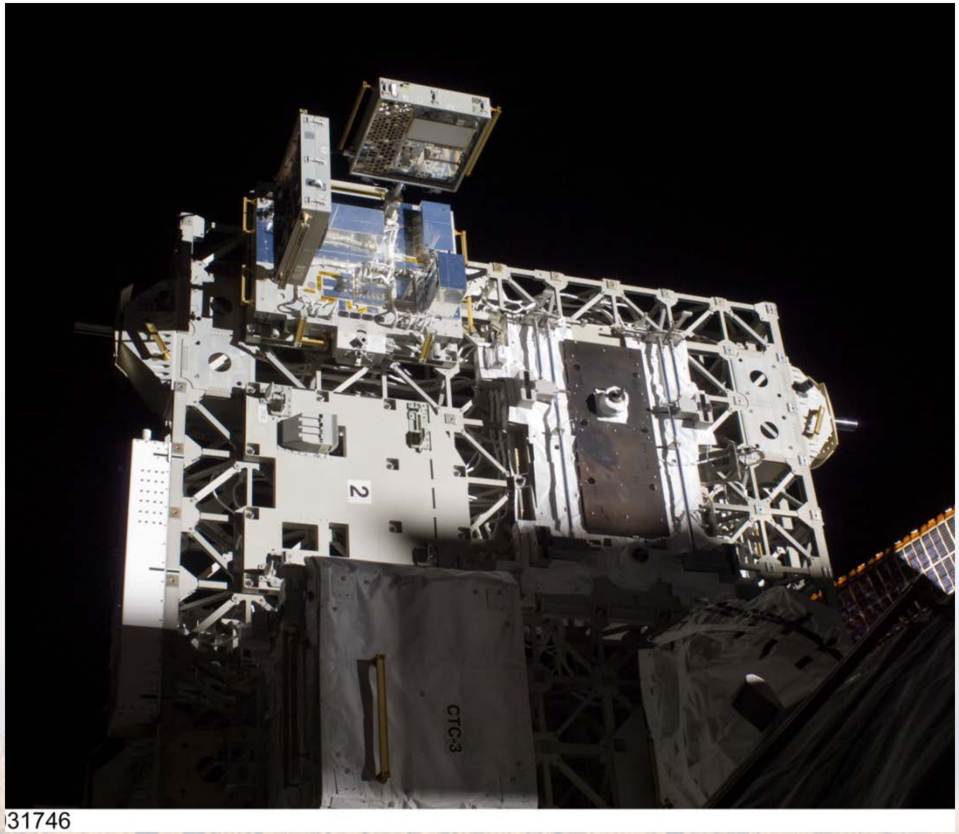
Testing and evaluation in space environments

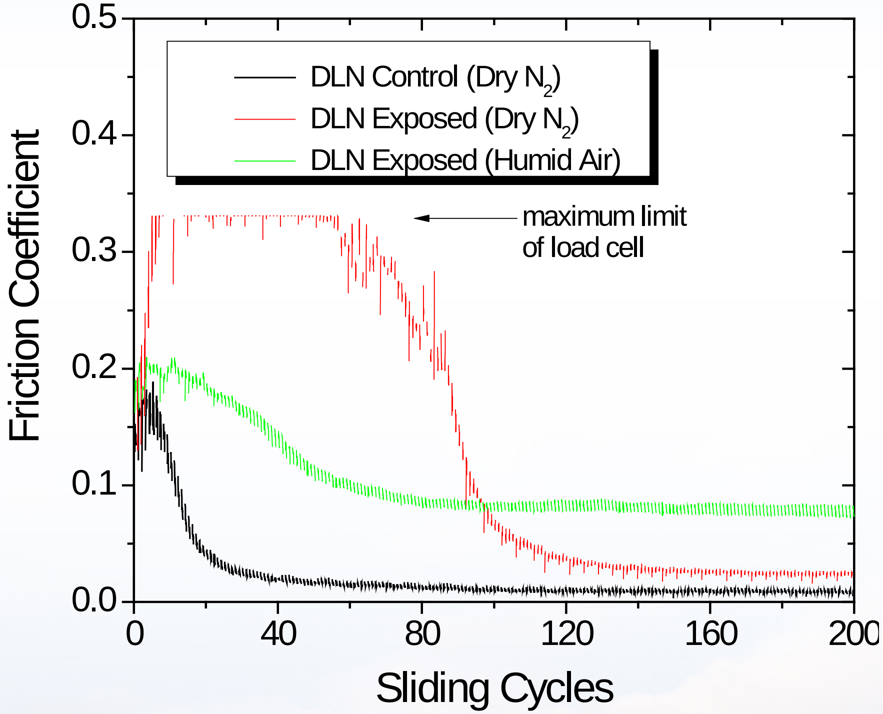
MISSE-7

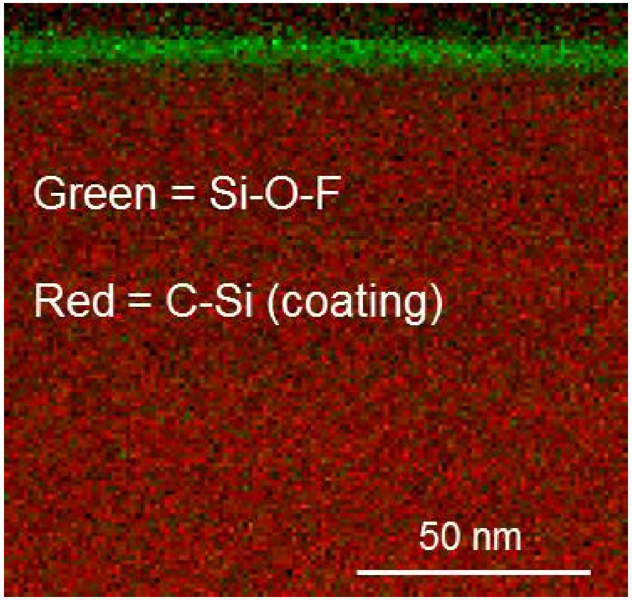
Materials on the International Space Station Experiment





The Effects of LEO environments: DLN





- Surface Contamination
- Increase in the Run-in Period

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Concluding Thoughts

- Materials designed for friction and wear mitigation, commonly referred to as tribological materials, must also meet mechanical and physical property requirements. This balance makes it very challenging from a practical design perspective .
- Avoid using metals/alloys that are prone to galling (Rabinowicz's Compatibility Chart)
- Solid lubricant coatings are needed, specifically when the operating conditions are beyond the liquid realm or in situations where liquids cannot be introduced.
- No single phase material can give low friction and wear in all environments and under all operating conditions
  - Many Solid Lubricant Coatings Exhibit Load Dependence on Friction
  - Environment plays a very significant role in determining the tribological behavior
- Introduce multilayer coatings if subsurface plastic deformation cannot be avoided.
- Use systems approach for the design of tribological contacts.

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- Rob Carpick (U Penn)
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