Elastohydrodynamic Lubrication Fundamentals

Wind Turbine Tribology Seminar

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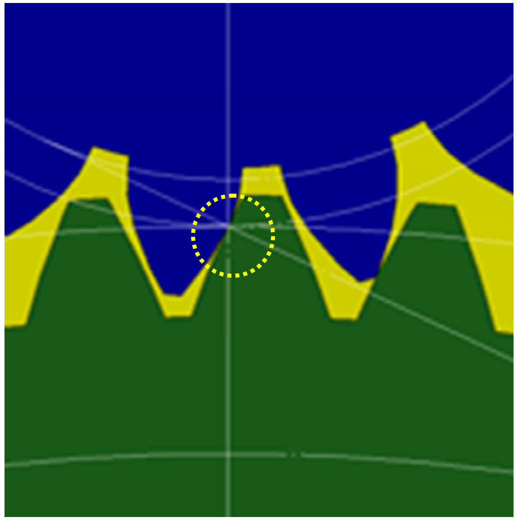
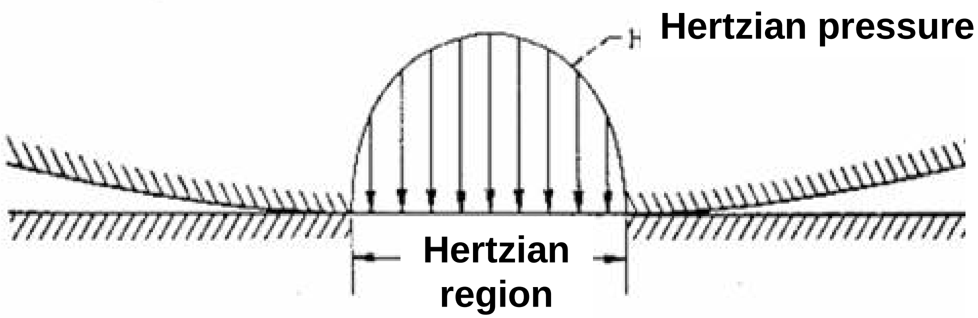
Elastohydrodynamic Lubrication Fundamentals

Focus on
Concentrated Contacts
Hertzian Contact Geometry





How Do Gear/Bearing Surfaces Fail?

Mechanistic processes

Wear

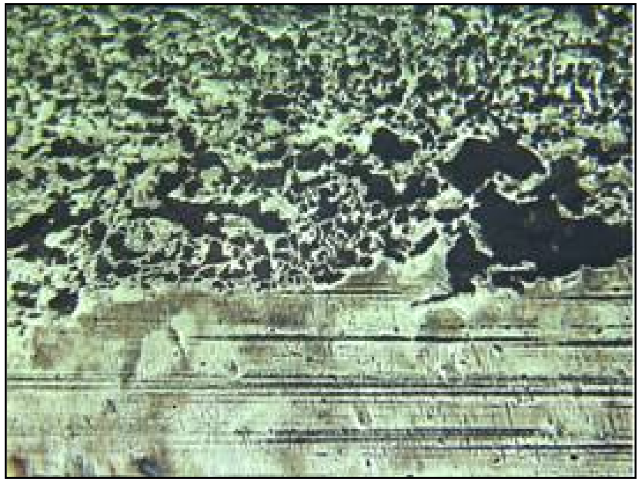
- Polishing
- Adhesive
- Abrasive
- Oxidative
- Corrosive

Scuffing

- Micro-scuffing
- Macro-scuffing

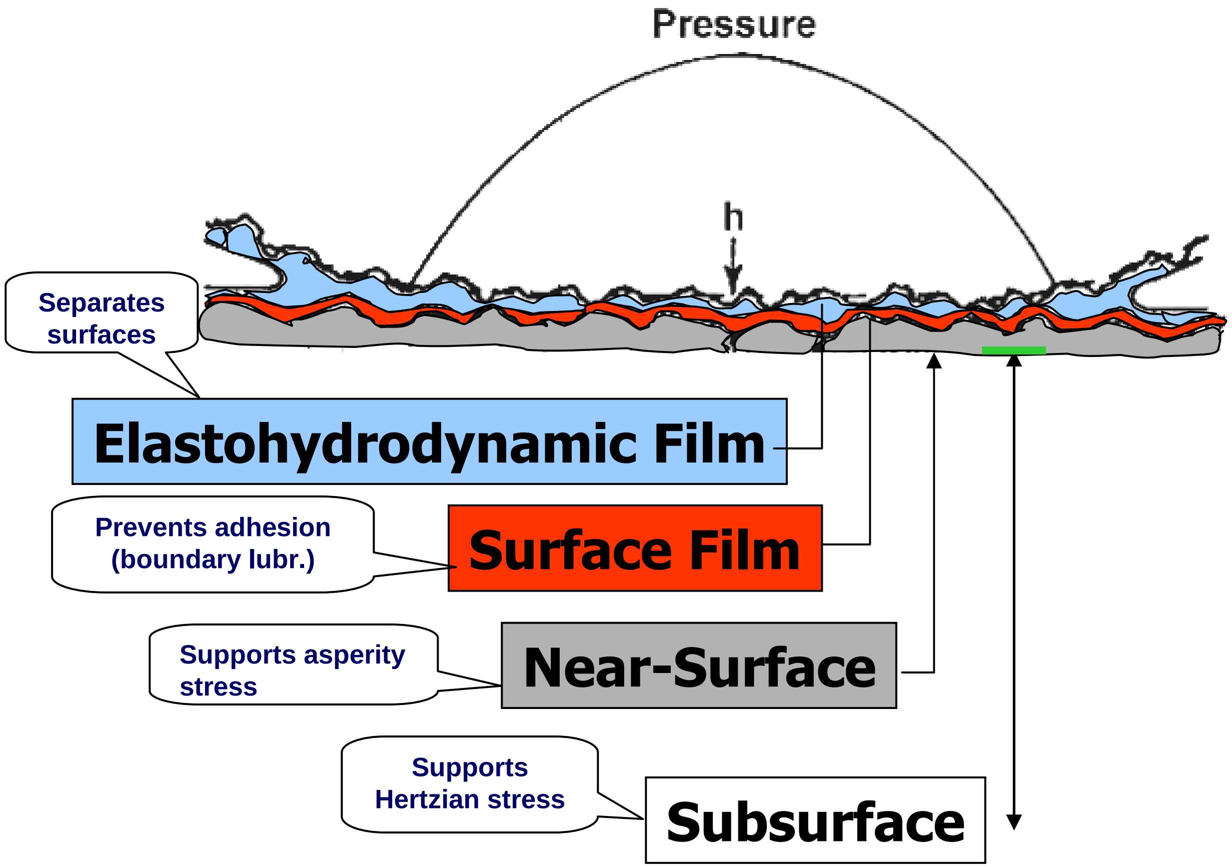
Fatigue

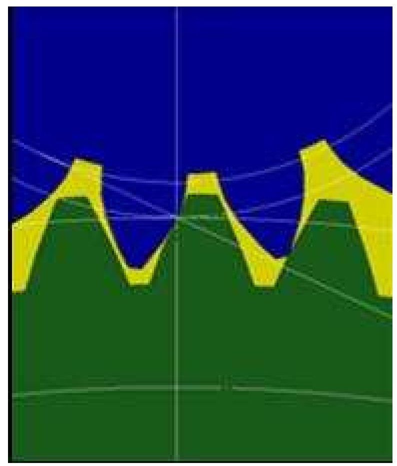
- Micro-pitting
- Spalling



Contact Structural Elements

Functions and technologies to prevent wear scuffing and fatigue processes

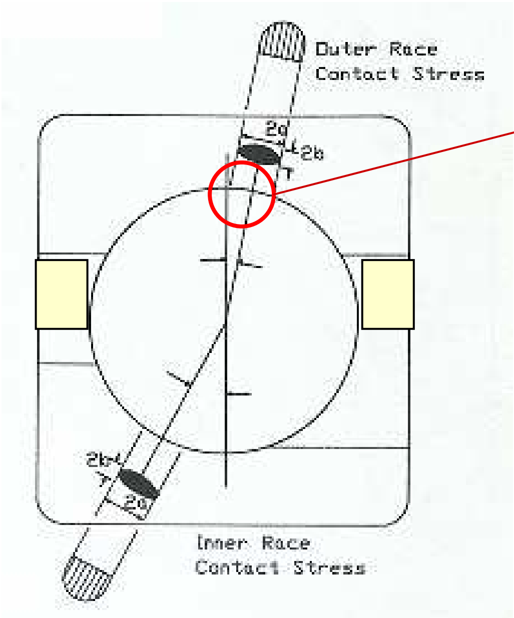


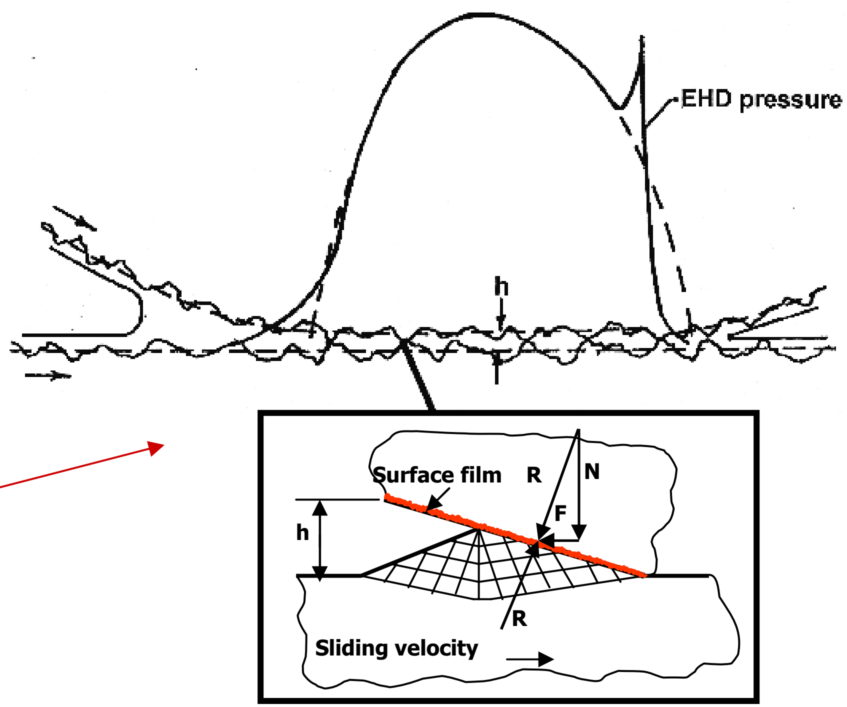


Boundary lubrication creates & maintains integrity of surfaces to promote EHD mechanisms

EHD - The Miracle Mechanism

High stress rolling/sliding motion





EHD film generation

EHD - The Miracle Mechanism

Elastohydrodynamic Lubrication

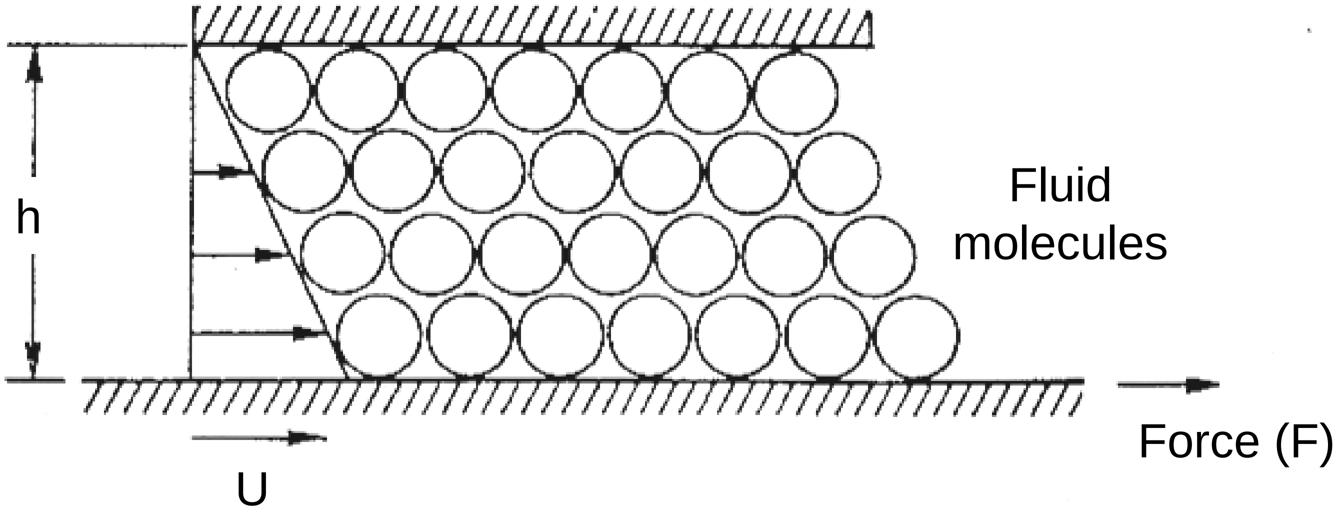
The physics behind the mechanism

The MIRACLE Mechanism

Seven features create the miracle of EHD Lubrication

M
I
R
A
C
L
E

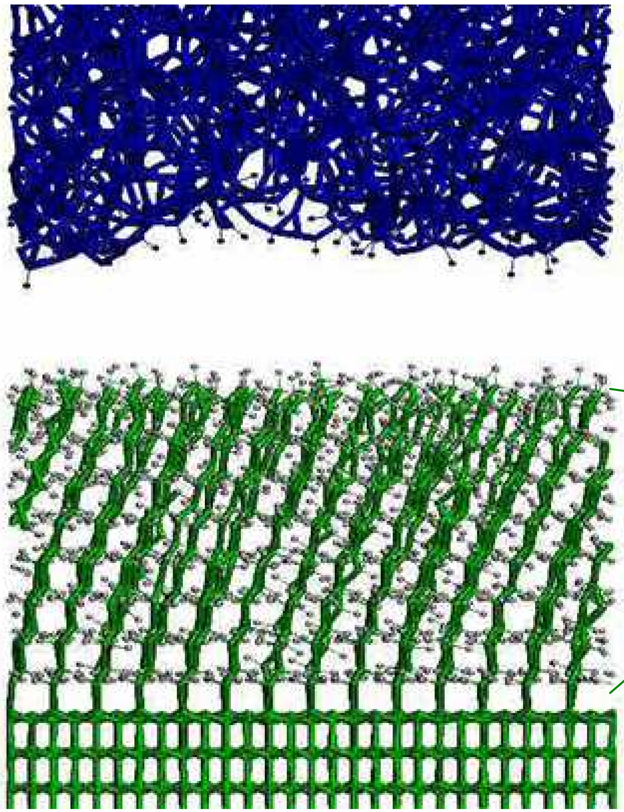
Viscous Flow Between Parallel Surfaces



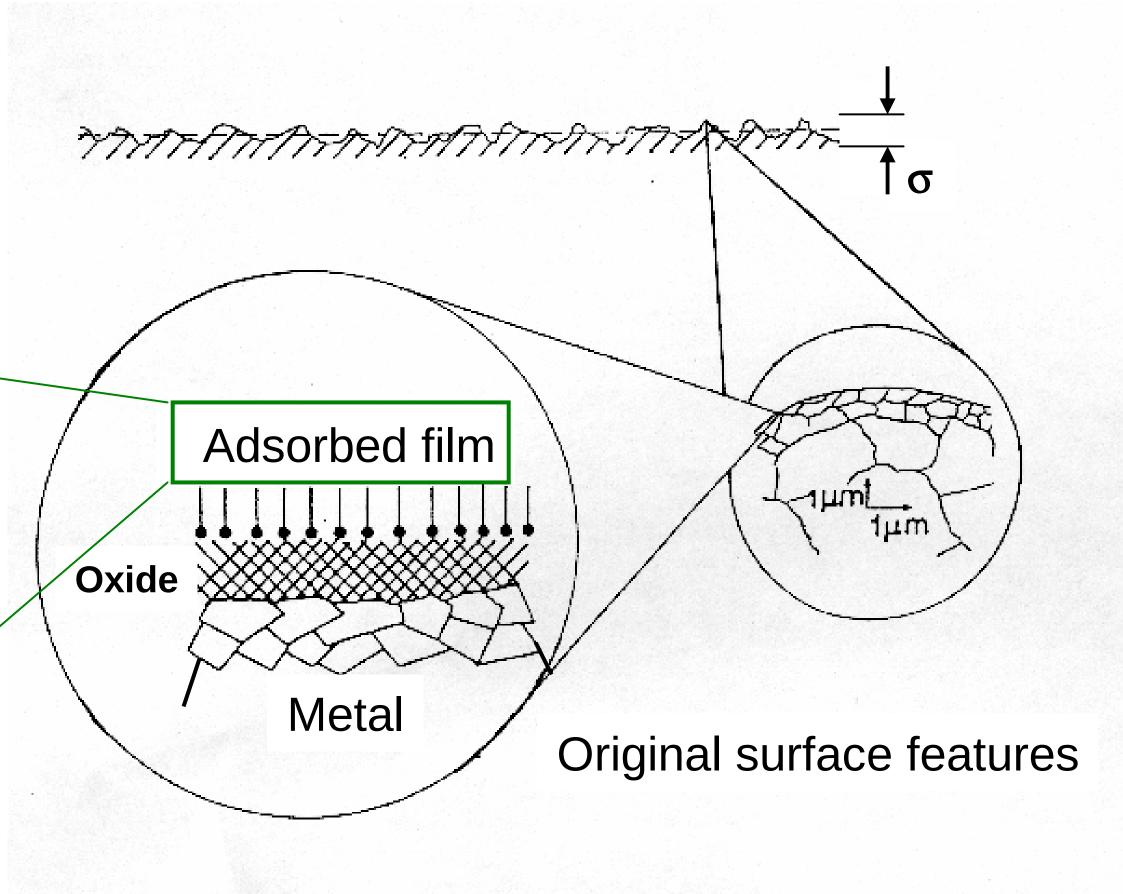
Viscous flow between parallel surfaces

$$\textbf{Viscosity } (\mu) = \frac{\textbf{Shear stress}}{\textbf{Shear rate}} \quad \frac{F/A}{u/h} \quad \frac{\text{N sec}}{\text{m}^2} \quad \textbf{(poise)}$$

Adsorbed Films

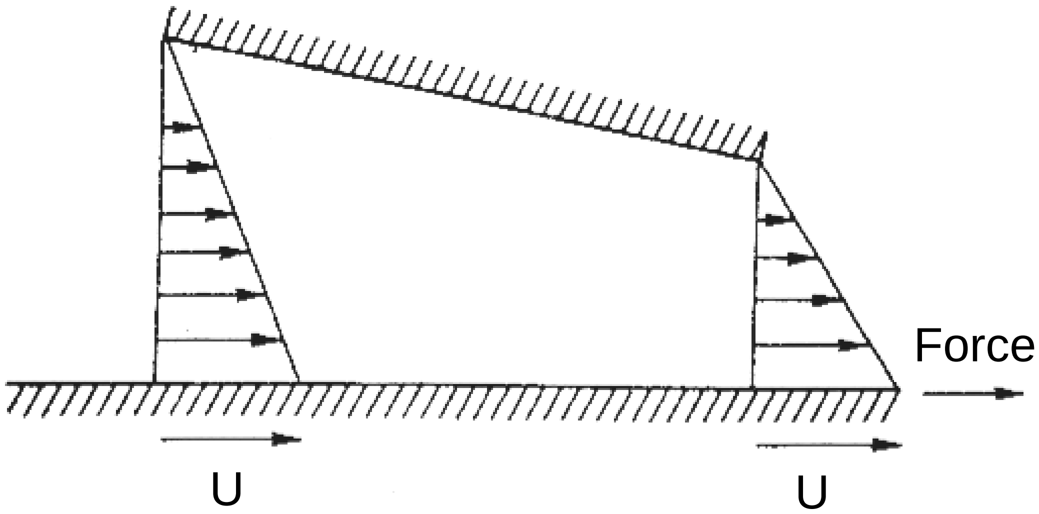


Judith A. Harrison
United States Naval Academy



M = <u>M</u>olecular attraction

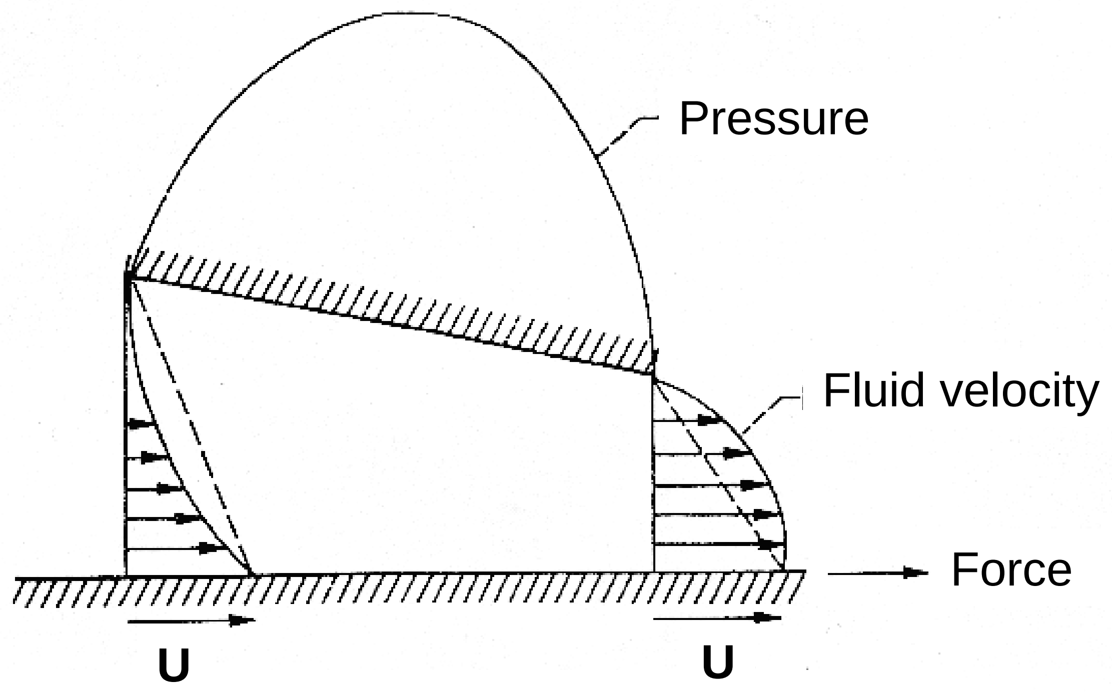
Viscous Flow Between Non-Parallel Surfaces



Flow in cannot be greater than flow out

Viscous flow between nonparallel surfaces

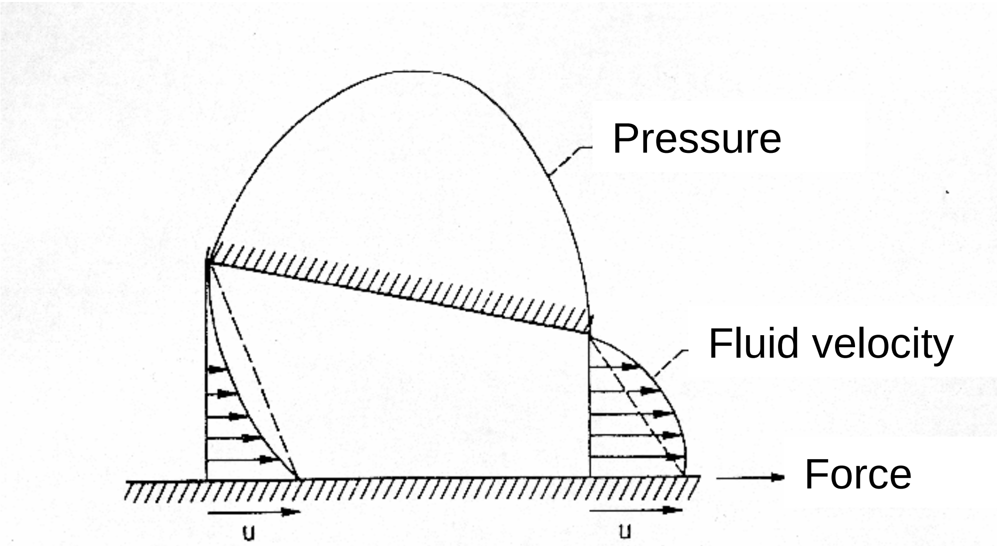
Hydrodynamic Pressure Generation



Hydrodynamic pressure generation

Viscous flow between parallel surfaces

Requirements for Pressure Generation

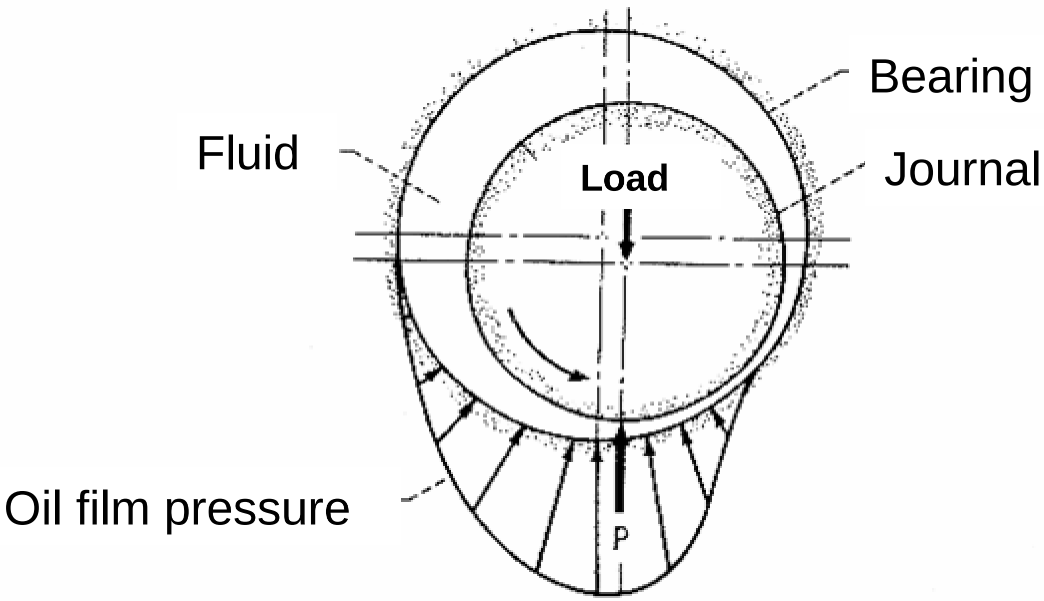


Hydrodynamic pressure generation

Viscous flow between parallel surfaces

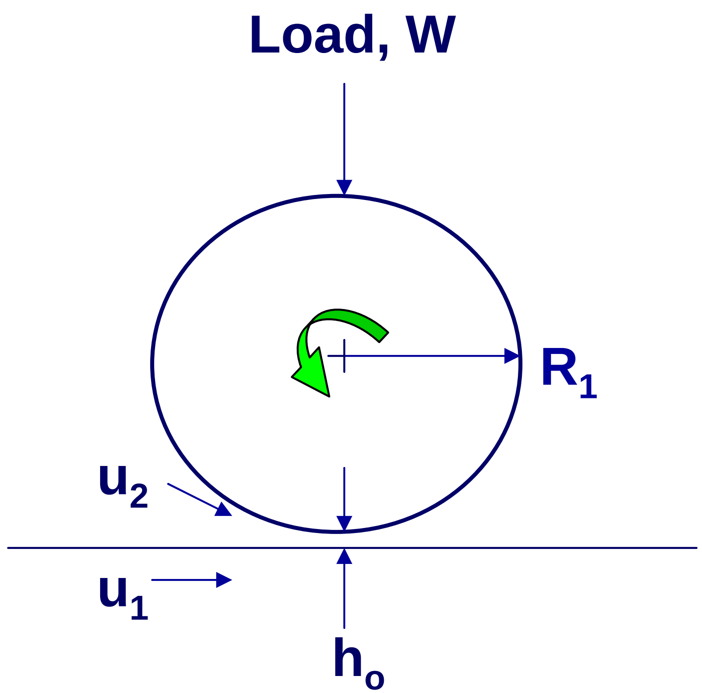
1. **Converging geometry**
2. **Viscous fluid media**
3. **Surface motion**

Pressure Generation in a Journal Bearing



Journal bearing

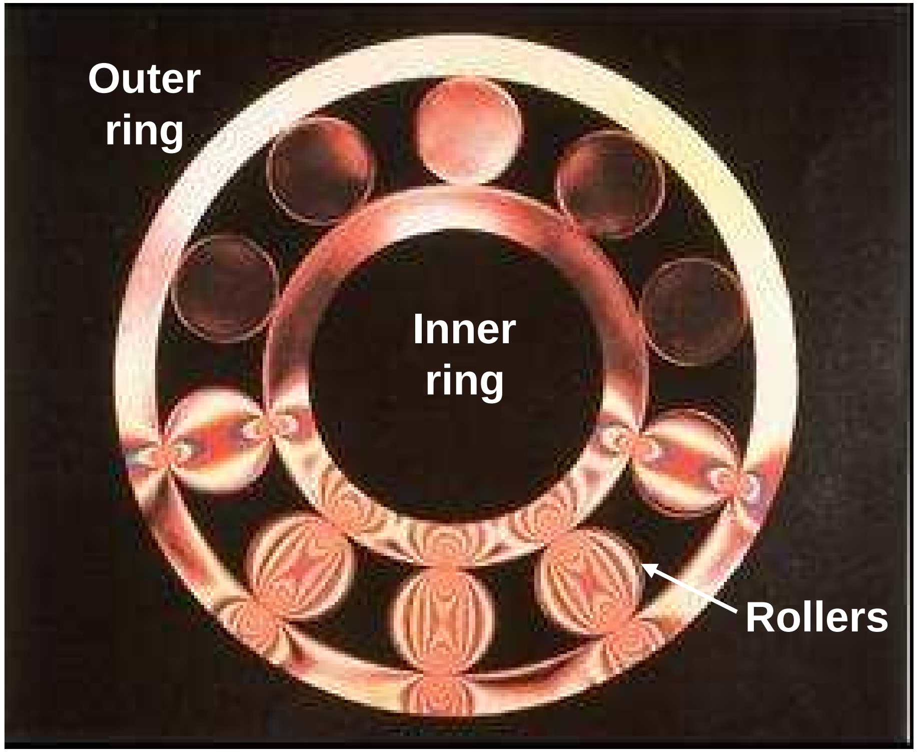
Film Thickness Equation (general form)



$$\frac{h_o}{R} = \frac{4.896\, U_e\, \mu_0}{W}$$

μ_0 = viscosity
W = load
U_e = surf vel., 1/2 (u_1+u_2)
R = radius of curvature

Conformal and Non-conformal Contacts



Roller Bearing Components

Hertzian Contact

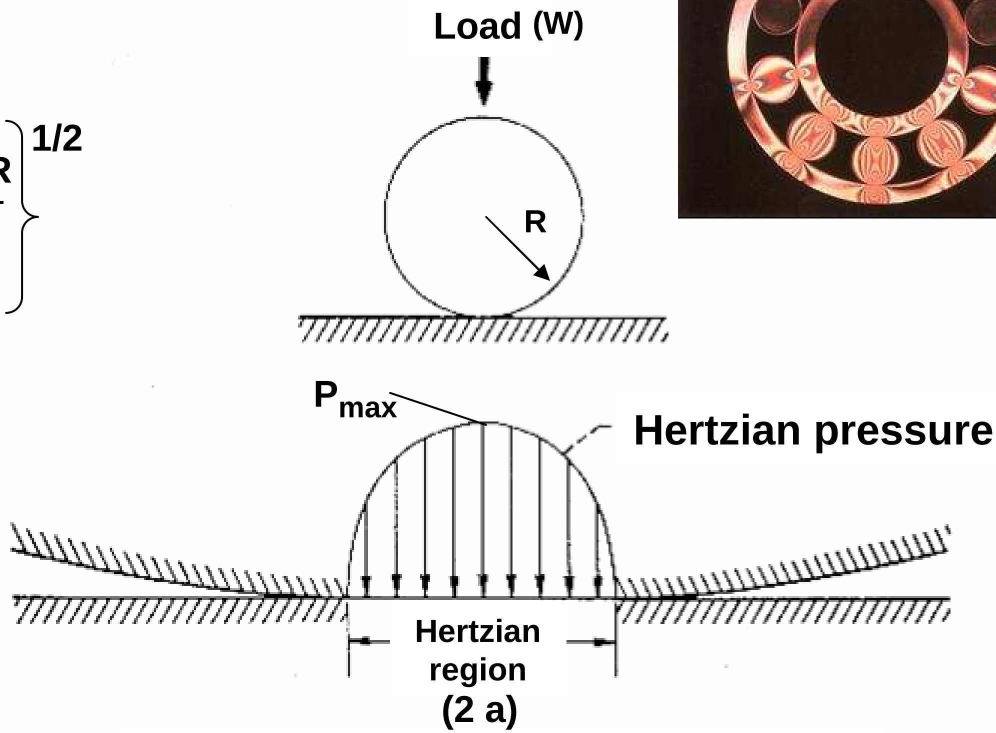
$$a = \left\{ \left[\frac{1-\sigma_1^2}{E_1} + \frac{1-\sigma_2^2}{E_2} \right] \frac{4\,W\,R}{\pi\,L} \right\}^{1/2}$$

$$P_{max} = \frac{2\,W}{\pi\,L\,a}$$

E = elastic modulus

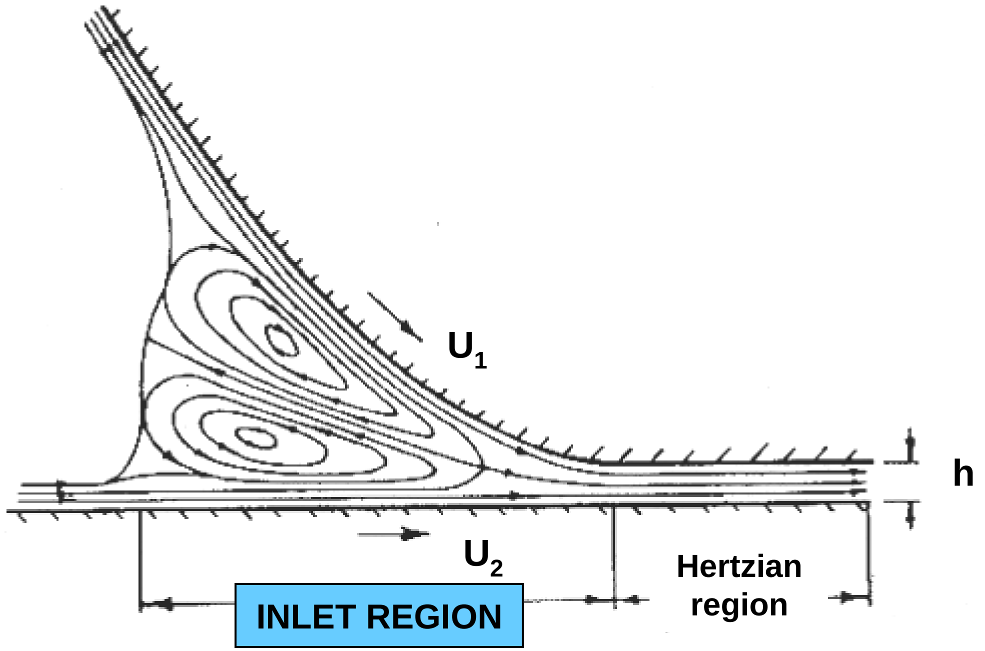
σ = Poisson's ratio

L = length of roller



Hertzian condition for dry contact

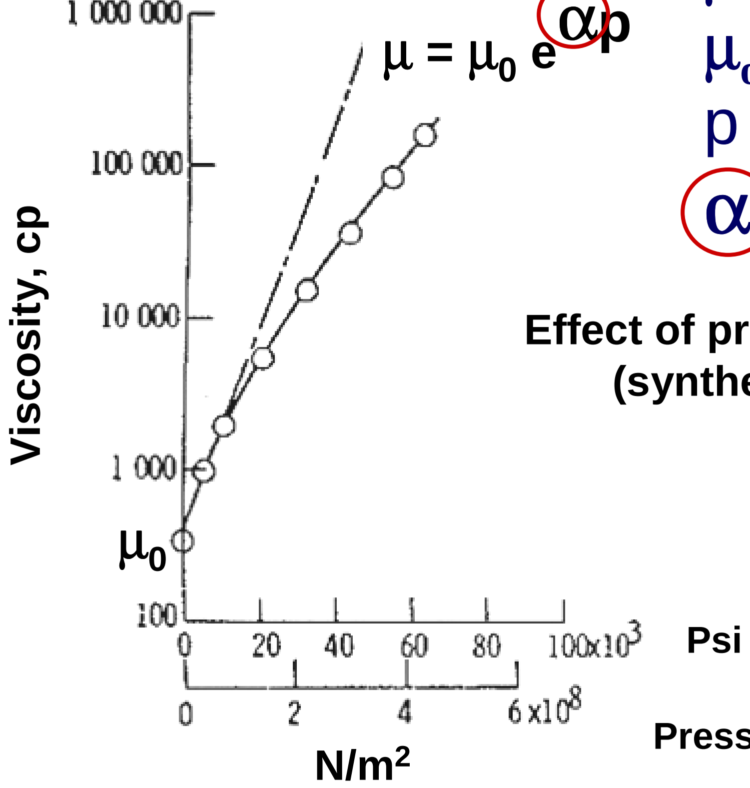
Fluid flow in Convergent Inlet Region



Flow distribution within the convergent inlet region

I = In-flight refueling

Effect of Pressure on Viscosity



μ = viscosity

μ_o = viscosity at p = 0

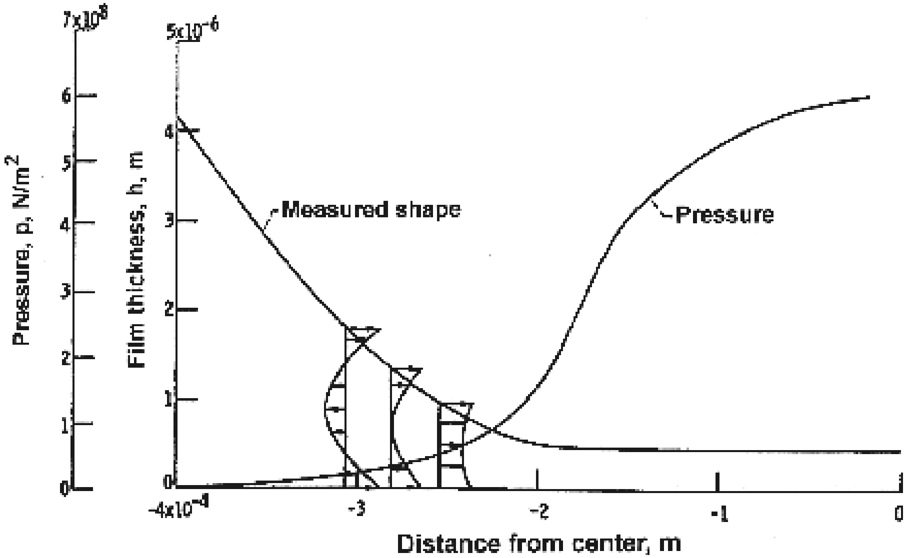
p = pressure

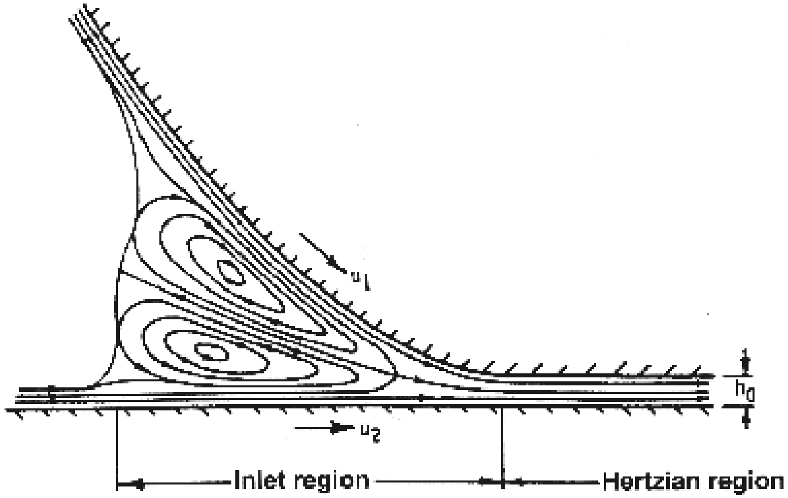
α = pressure-viscosity coef.

Effect of pressure on viscosity (synthetic oil at 38 °C)

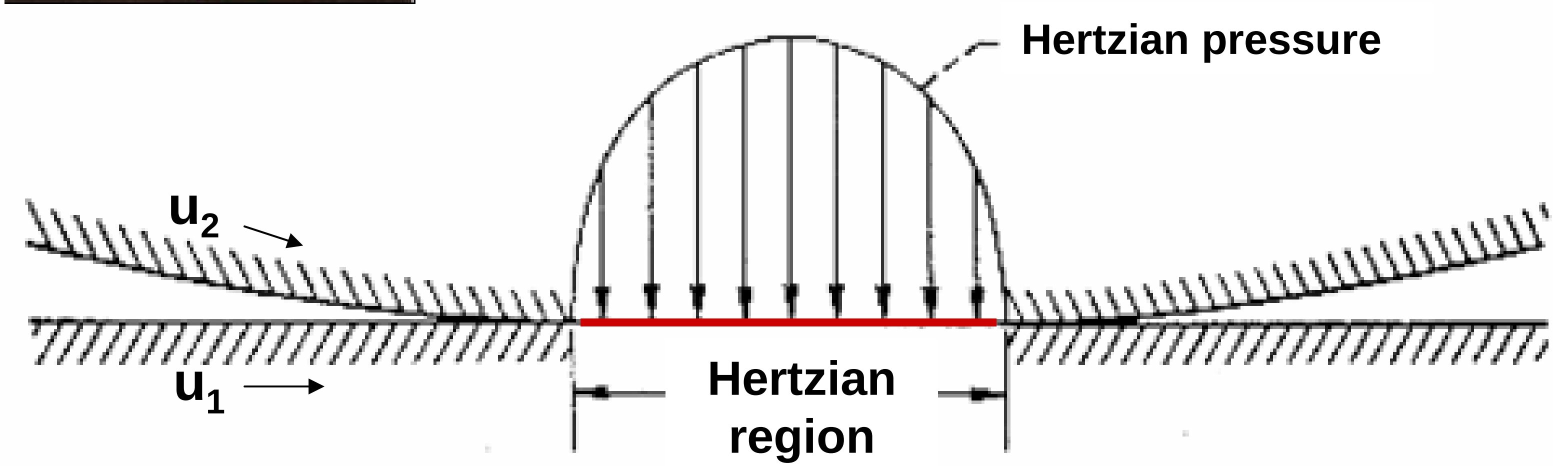
R = Radical increase of viscosity with pressure

Fluid Flow and Pressure in Inlet Region

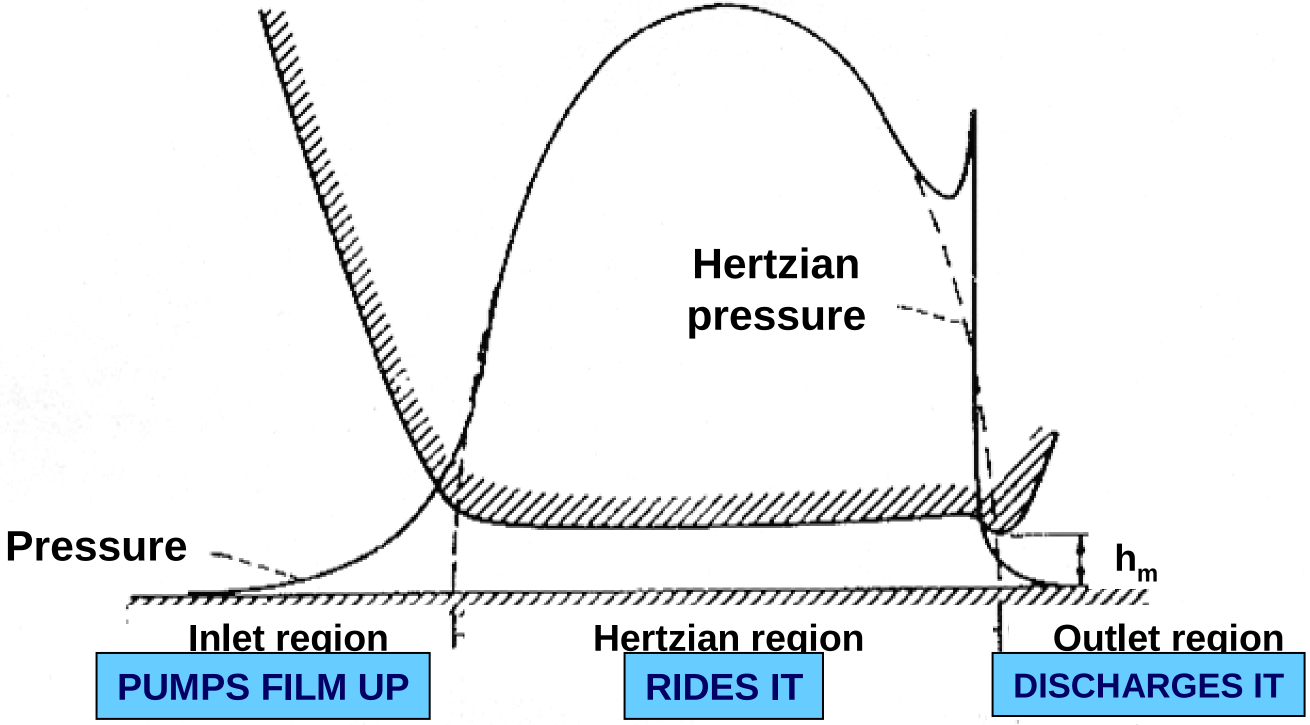




Perspective of Lubricated Contact

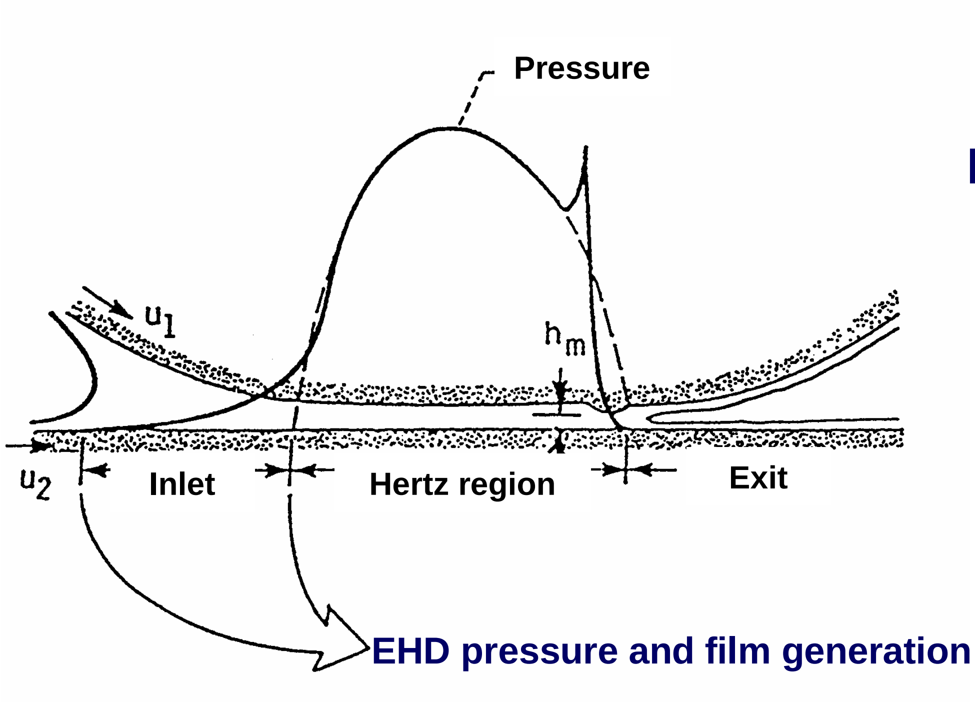


Three Functional Regions of an EHD Contact



Elastohydrodynamic pressure and shape

EHD Film Thickness Equation

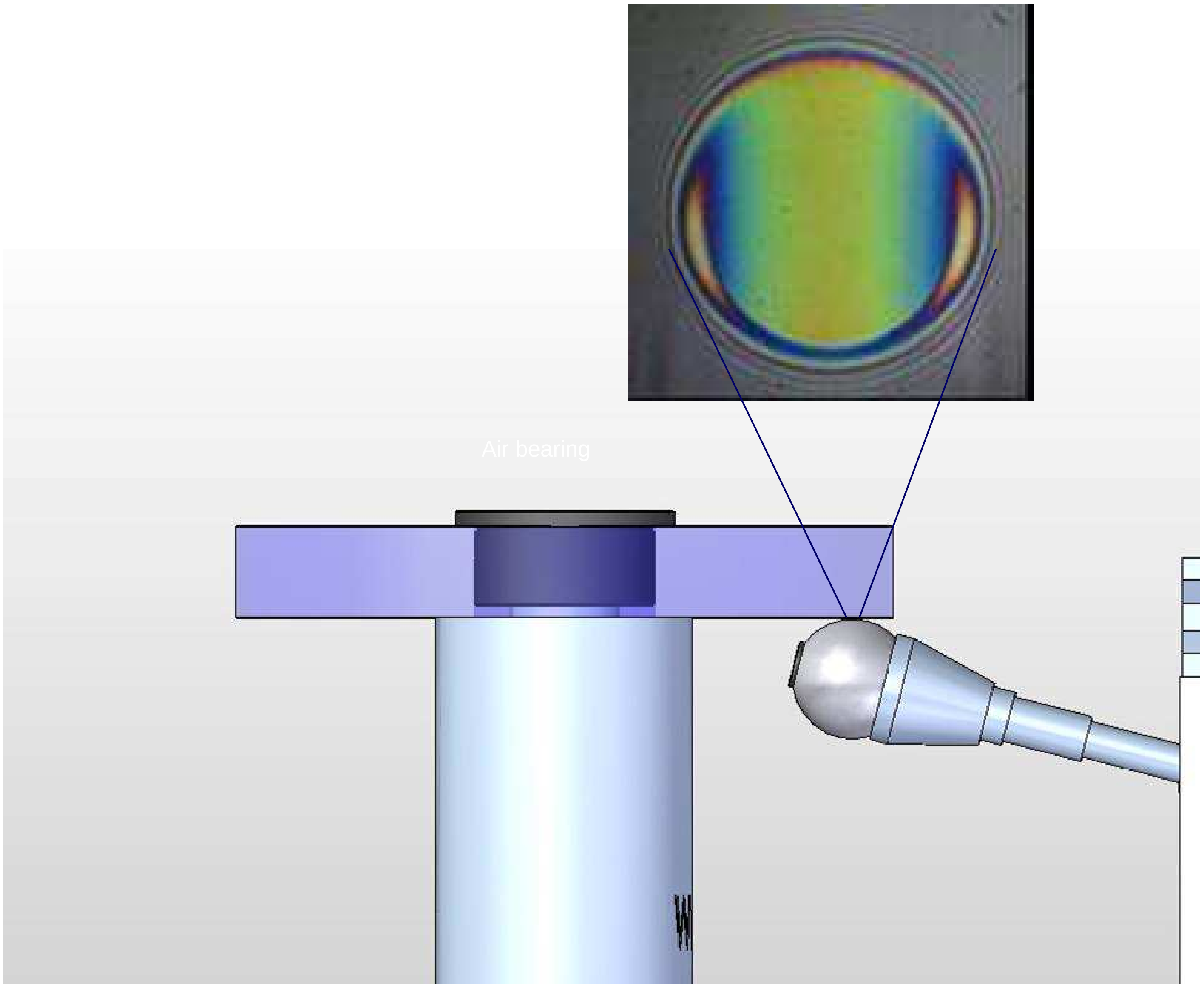


$$h_m = 3.07 \frac{(\mu_o U_e)^{0.71} \, \alpha^{0.57} \, R^{0.40}}{E'^{0.03} \, w^{0.11}}$$

h_m = min. film thickness
μ_o = viscosity at atm press
U_e = entraining velocity, ½(u_1 + u_2)
α = pressure-viscosity coef.
R = combined radius of curvature
E' = combined elastic modulus
w = applied load

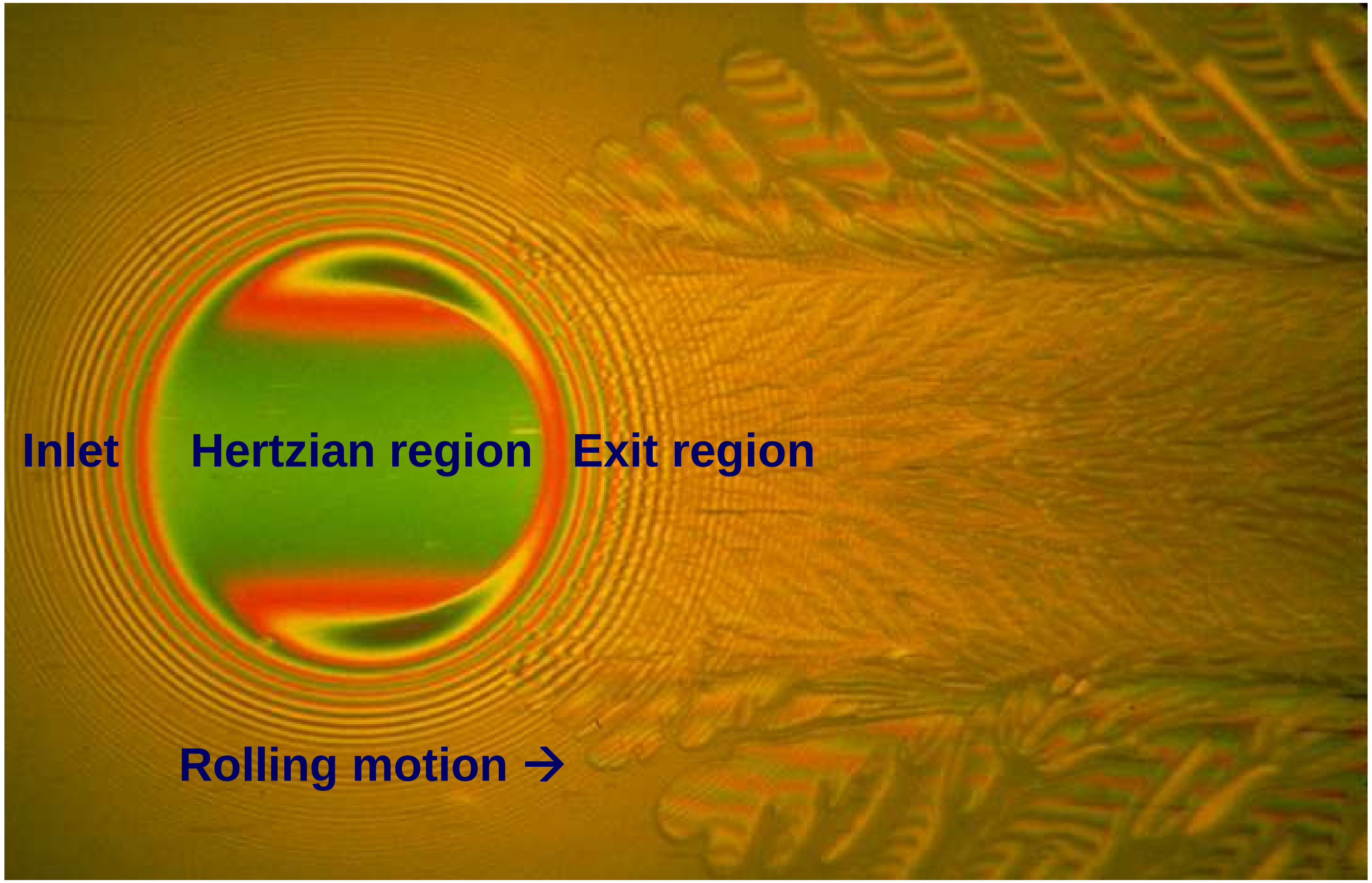
A = Accommodation of stress

Contact with Optical Configuration



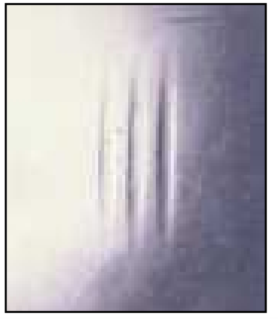
Interference Colors from EHD Oil Film

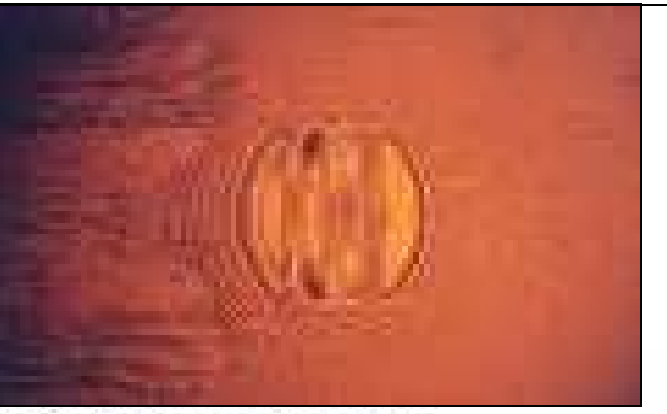
Optical interference colors showing thickness of EHD oil film

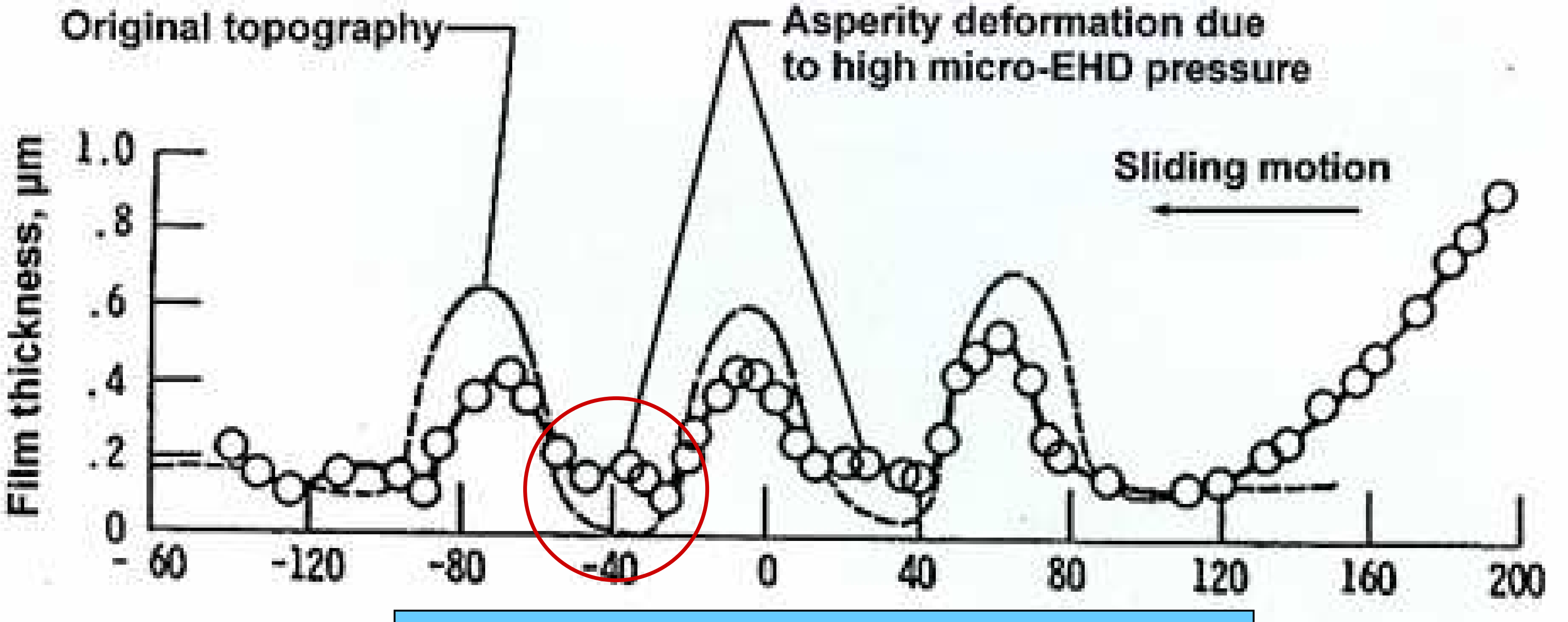


Center film thickness 0.4 μm (16×10^{-6} inch)

Micro-EHD Lubrication

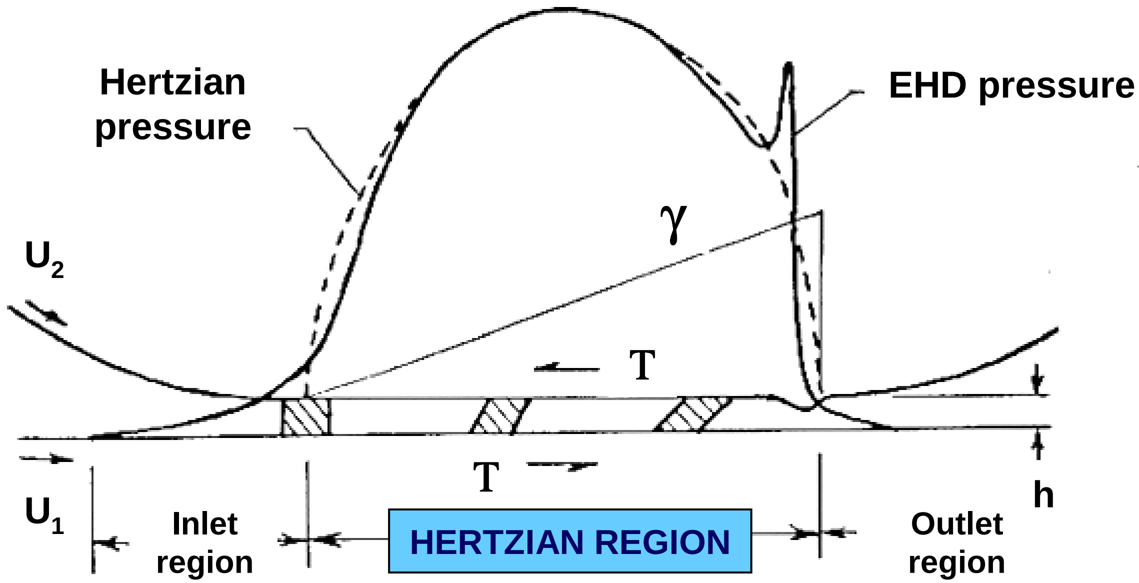






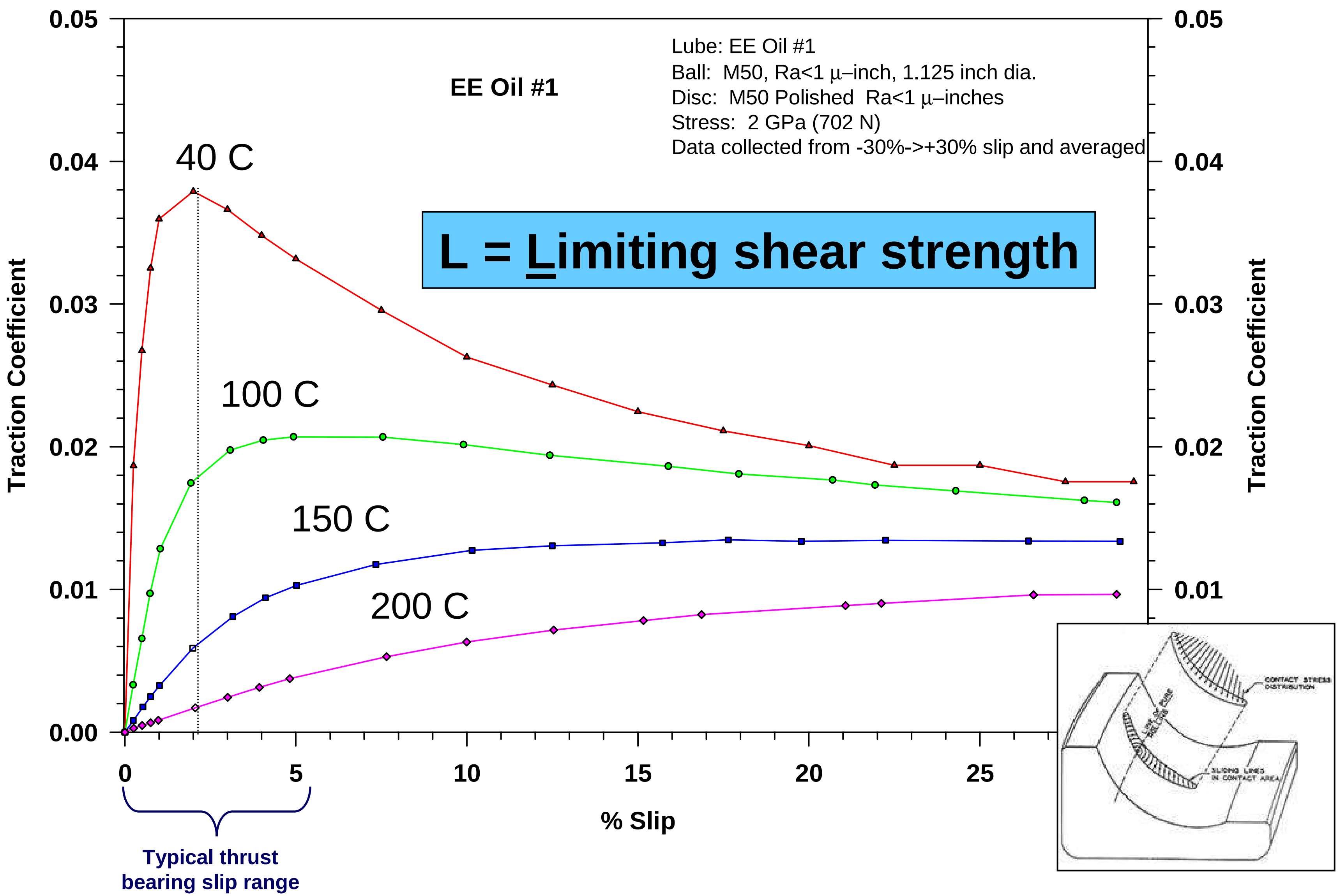
C = Cushioning of asperities

Traction (Friction) –
Tangential Shear of Pseudo-Solid Film

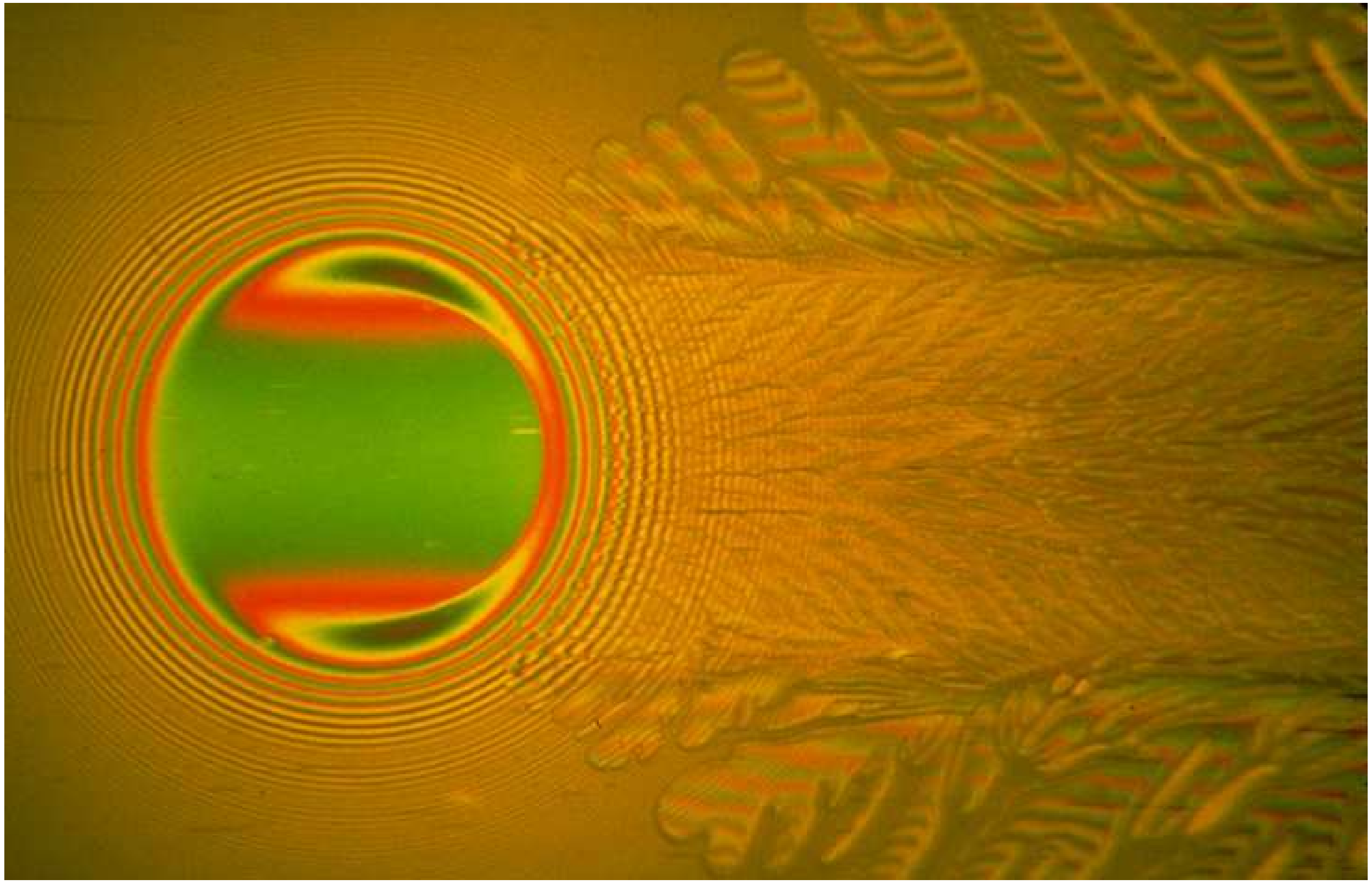


Traction

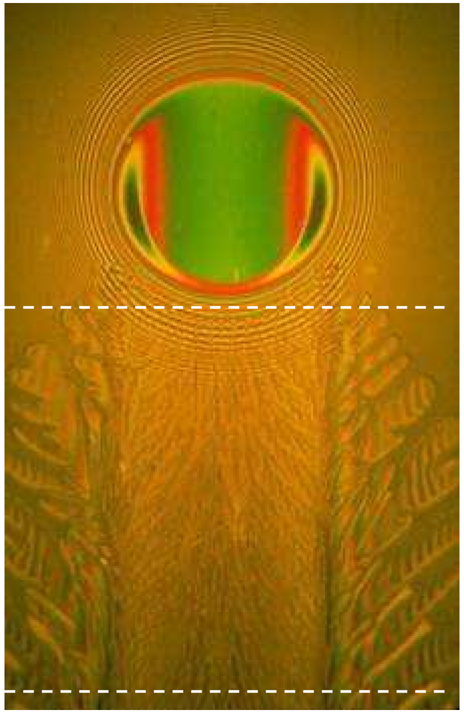
Traction Coefficient Measurement



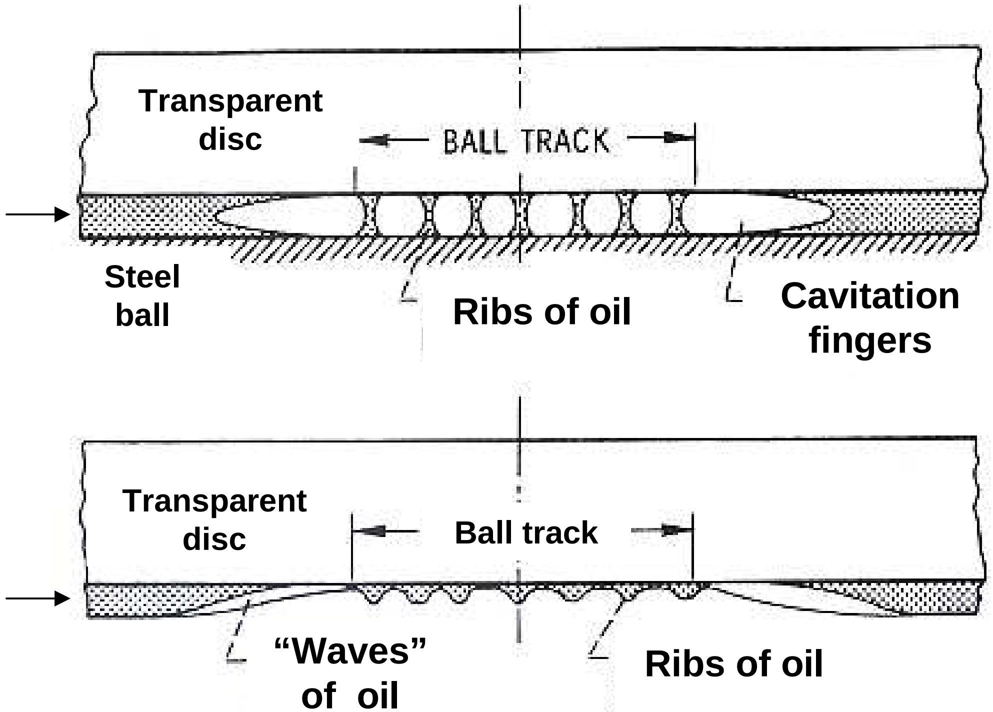
Oil/Air Separation at Divergent Exit Region



Oil/Air Separation at Divergent Exit Region

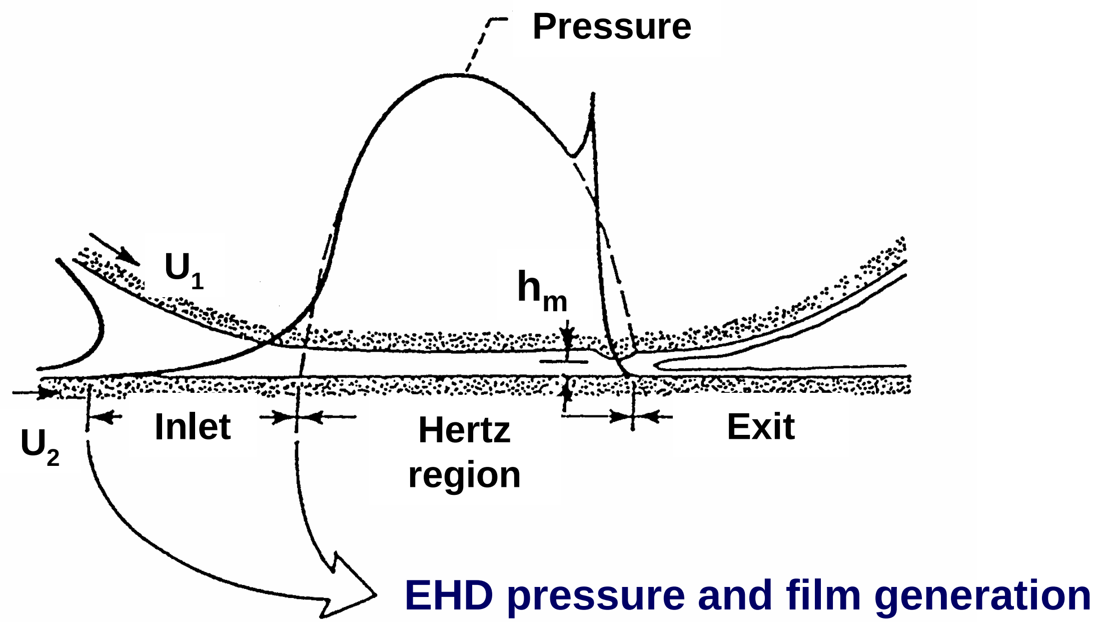


Schematic representation of cavitated region



E = <u>E</u>xit without trauma

EHD - the MIRACLE Mechanism



M– Molecular attachment

I – Inlet refueling

R – Radical viscosity increase with pressure

A – Accommodation of stress

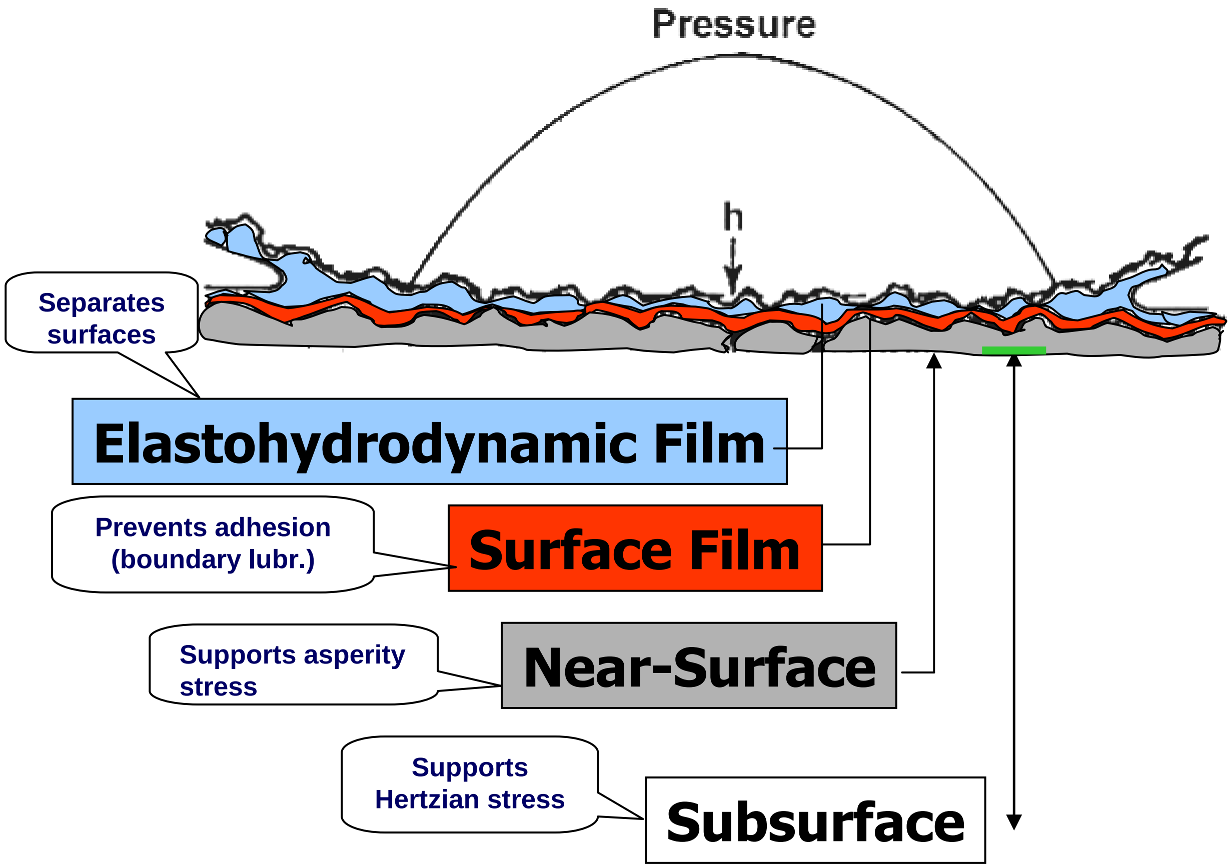
C – Cushioning of asperities

L – Limiting shear stress (traction)

E – Exit without trauma

Contact Structural Elements

Functions and technologies to prevent failures

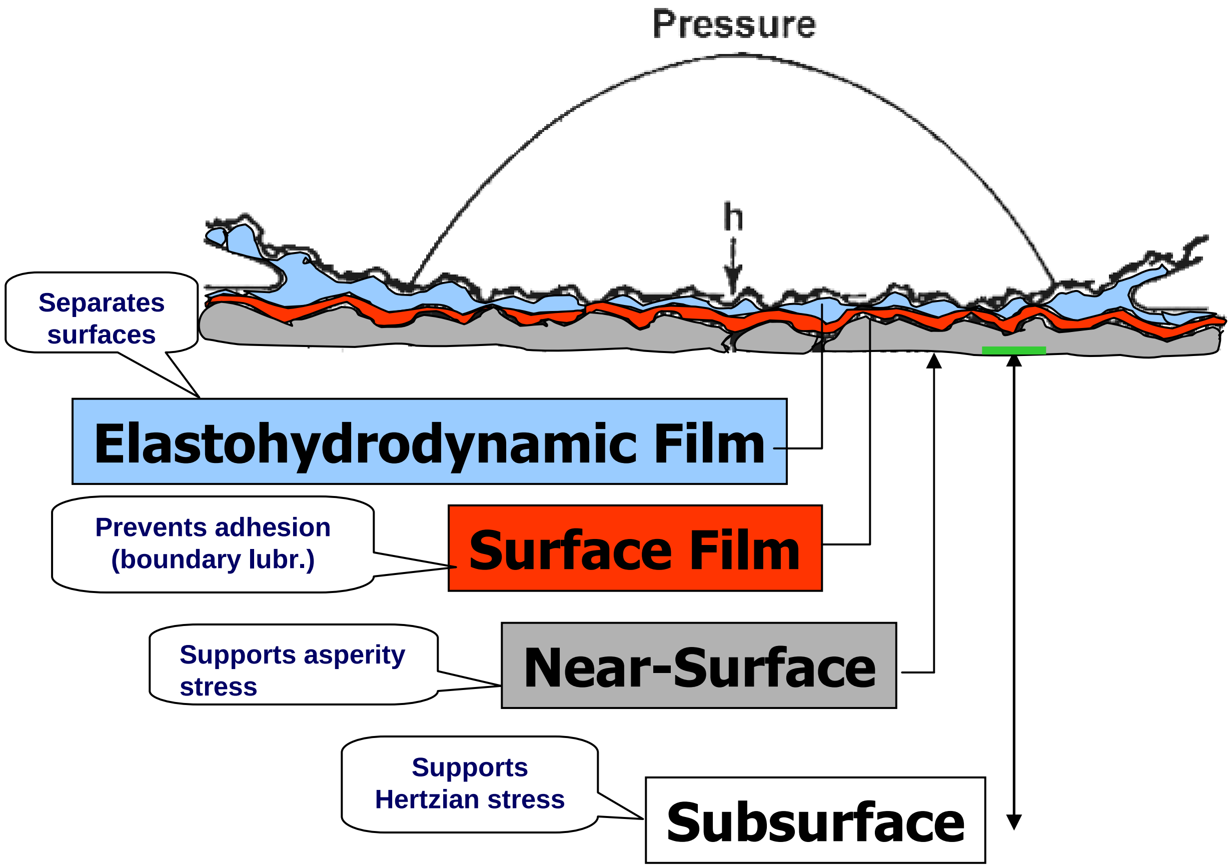


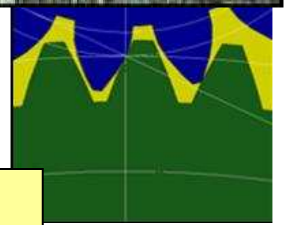
- **Wear**
- **Scuffing**
- **Fatigue**

Boundary lubrication creates & maintains integrity of surfaces to promote EHD mechanisms

Contact Structural Elements

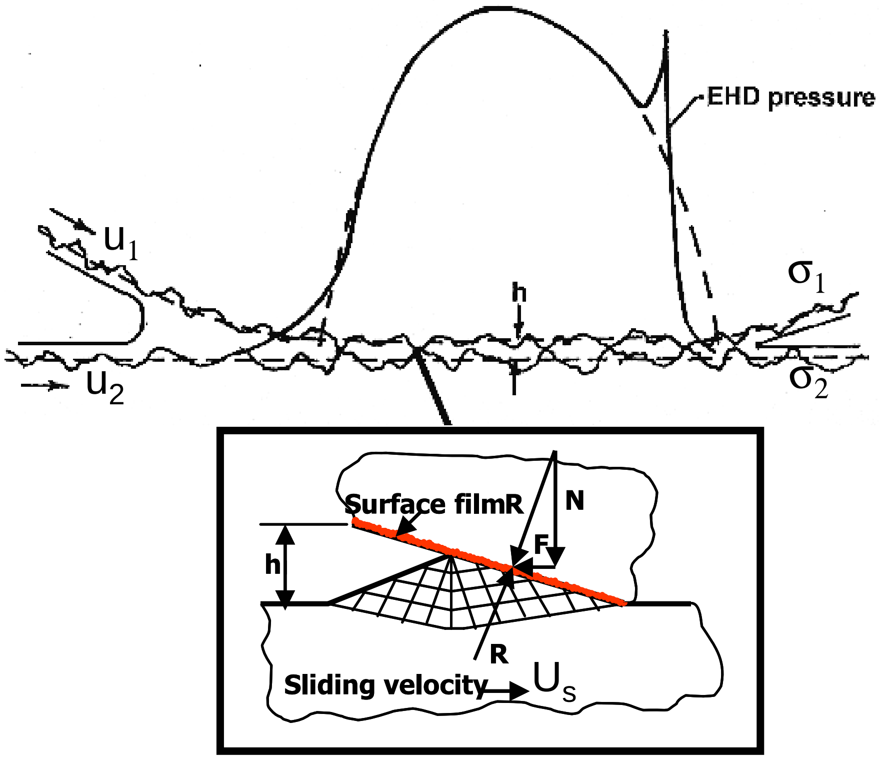
Functions and technologies to prevent wear scuffing and fatigue processes





Boundary lubrication creates & maintains integrity of surfaces to promote EHD mechanisms

Five Parameters Control Wear, Scuffing and Fatigue



Entraining velocity, $U_e = ½ (U_1 + U_2)$

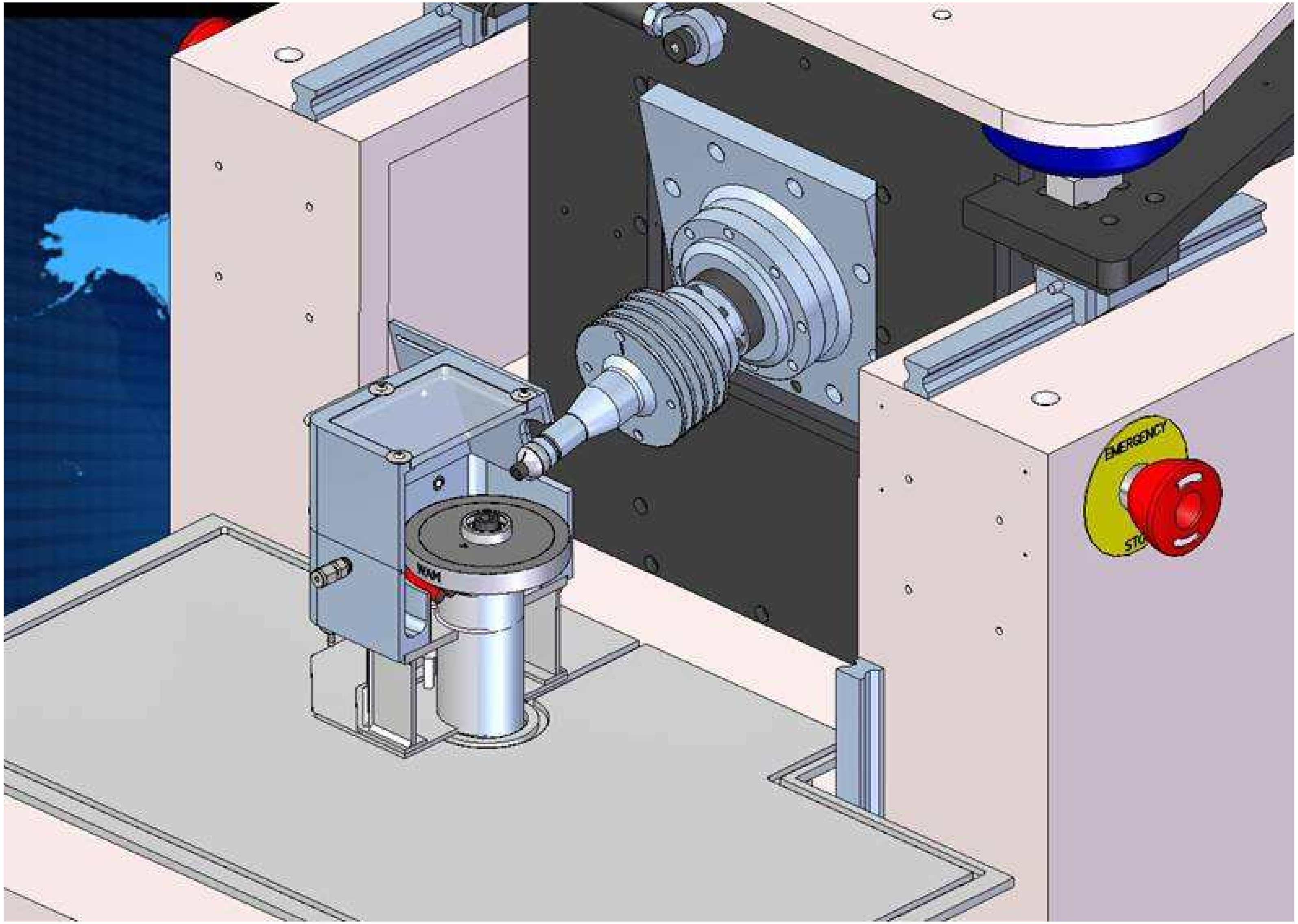
Degree of asperity penetration (h/σ)

Sliding velocity, $U_s = (U_1 - U_2)$

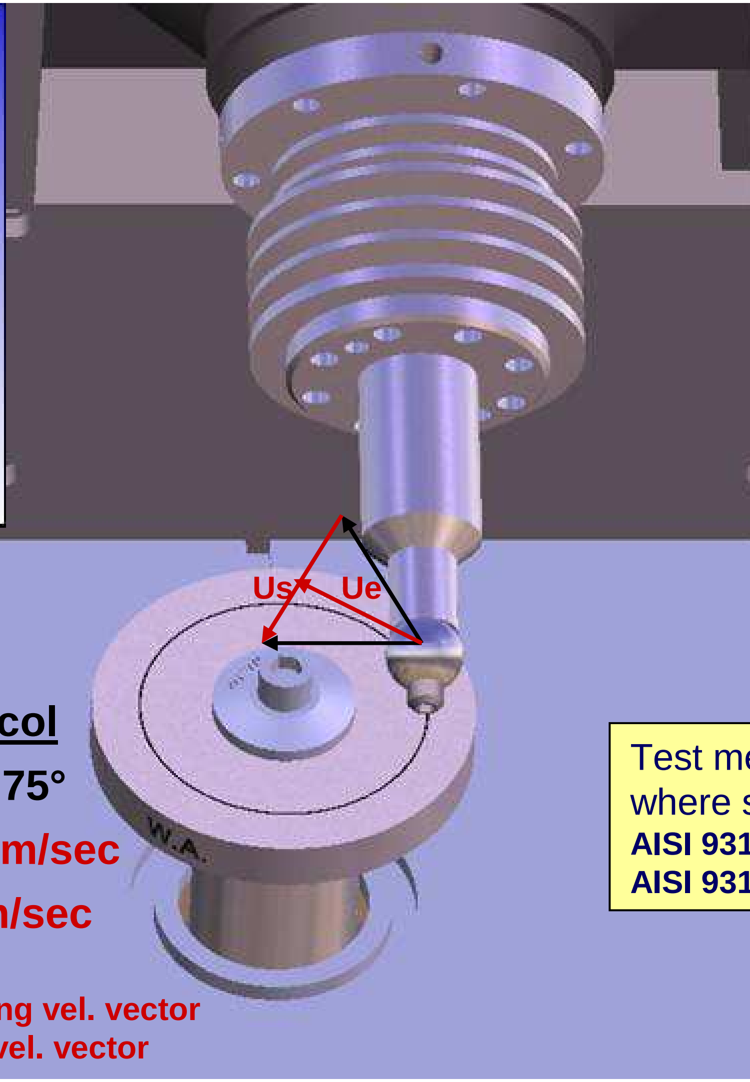
Contact temp ($T_c = T_{bulk} + T_{flash}$)

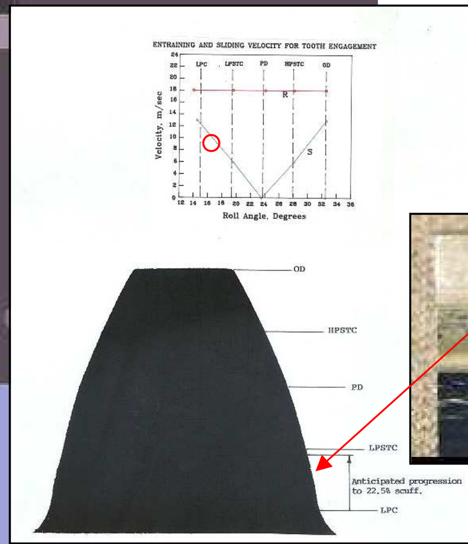
Contact Stress (asperity stress)

Wedeven Assoc. Machine (WAM)



Wear and Scuffing Tests – Gear Simulation





Test Protocol

Angle Z = 75°

Ue = 5.72 m/sec

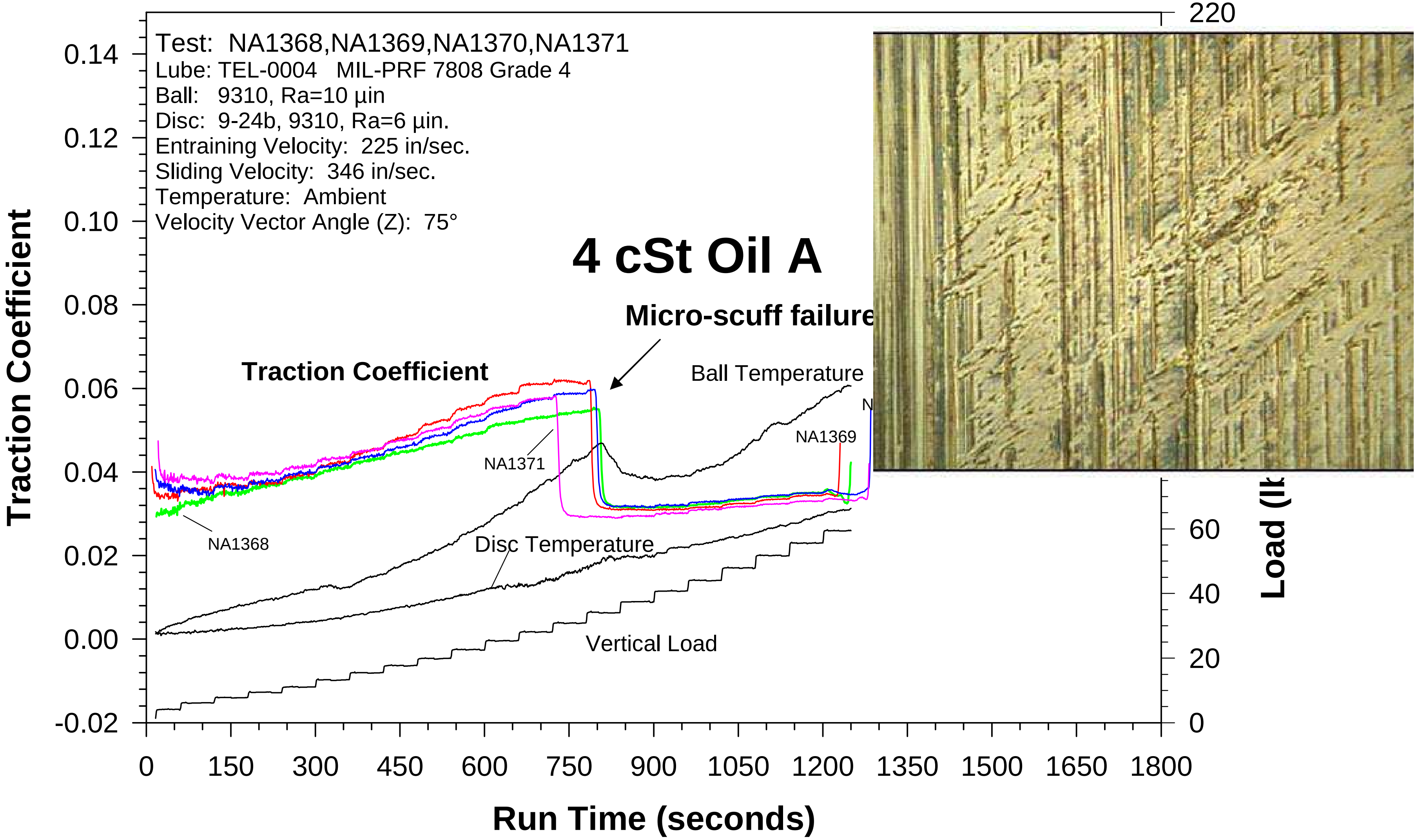
Us = 8.8 m/sec

Ue = Entraining vel. vector
Us = Sliding vel. vector

Test method simulates gear tooth mesh where scuffing is initiated.

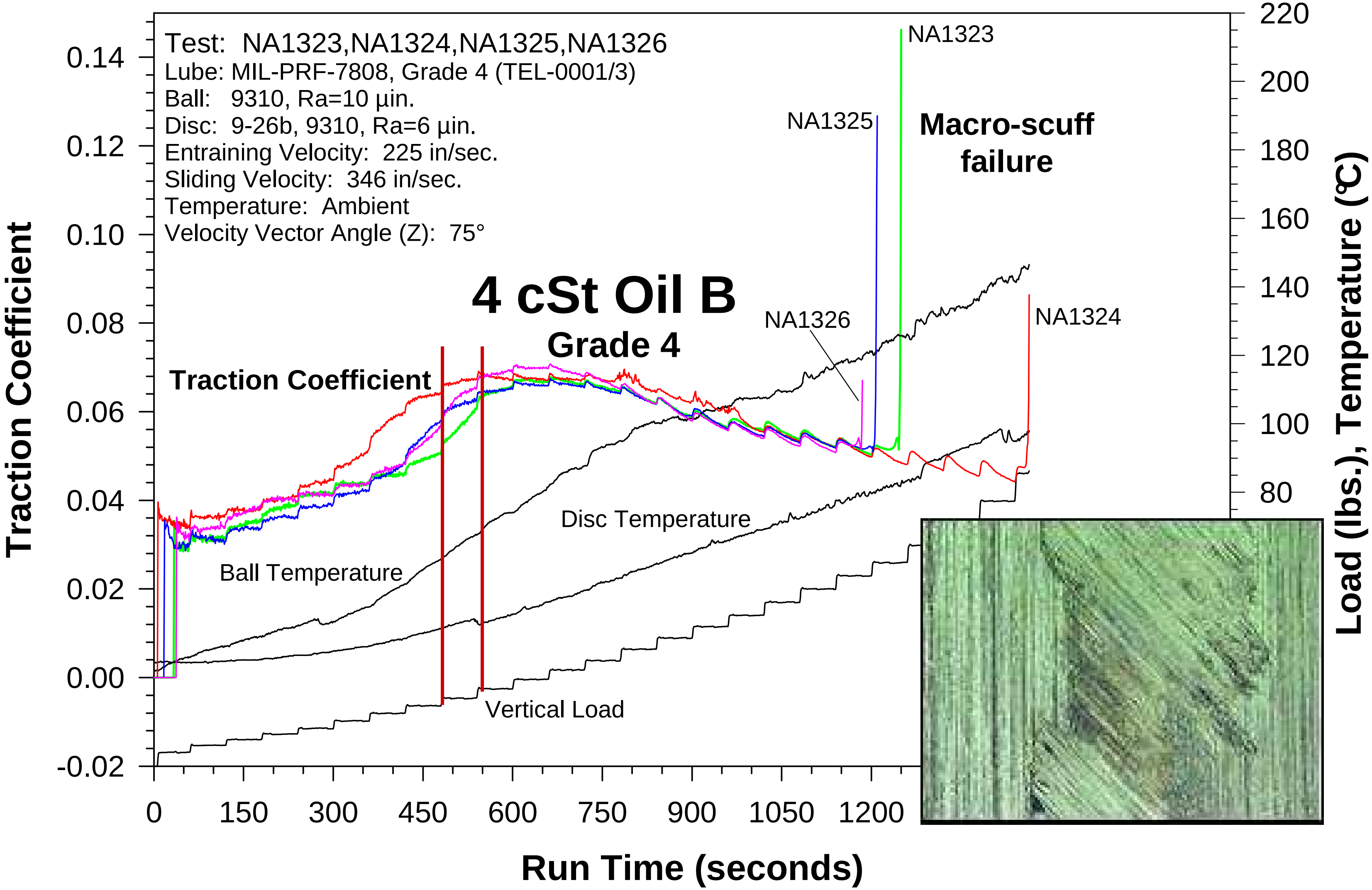
AISI 9310 ball, roughness = 11 μin (0.28 μm), Ra
AISI 9310 disc, roughness = 6 μin (0.15 μm), Ra

Wear and Micro-Scuffing

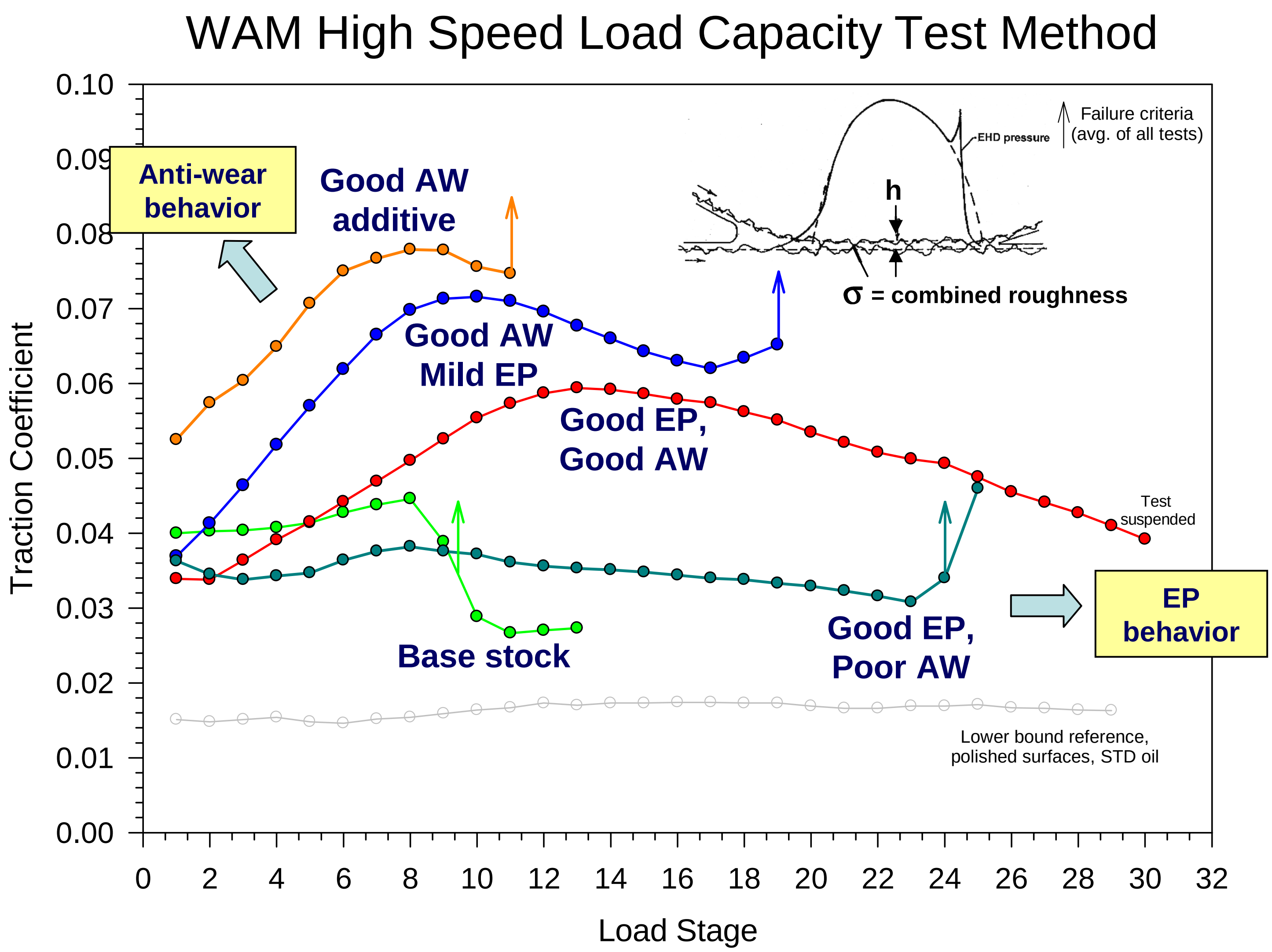


Wear and Scuffing

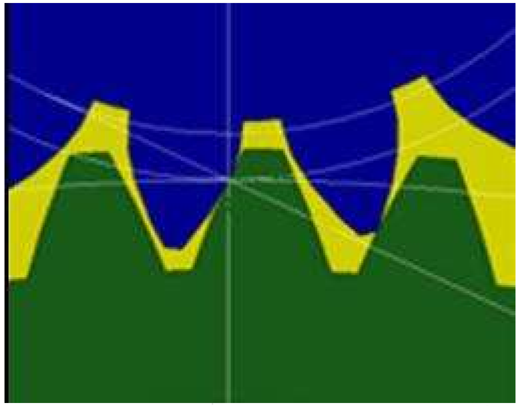
Average TC for each load stage

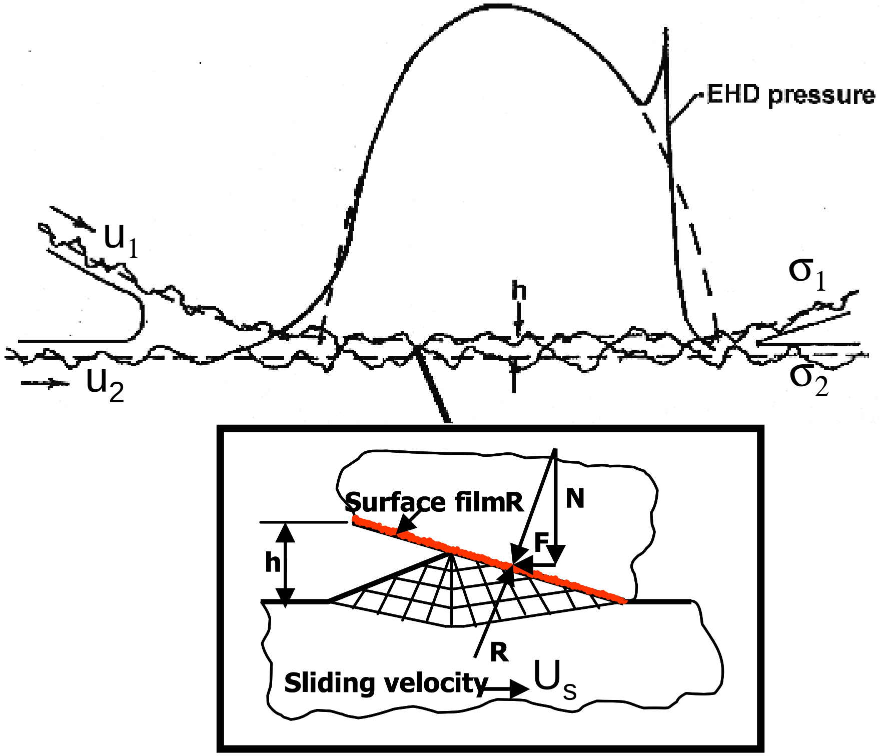


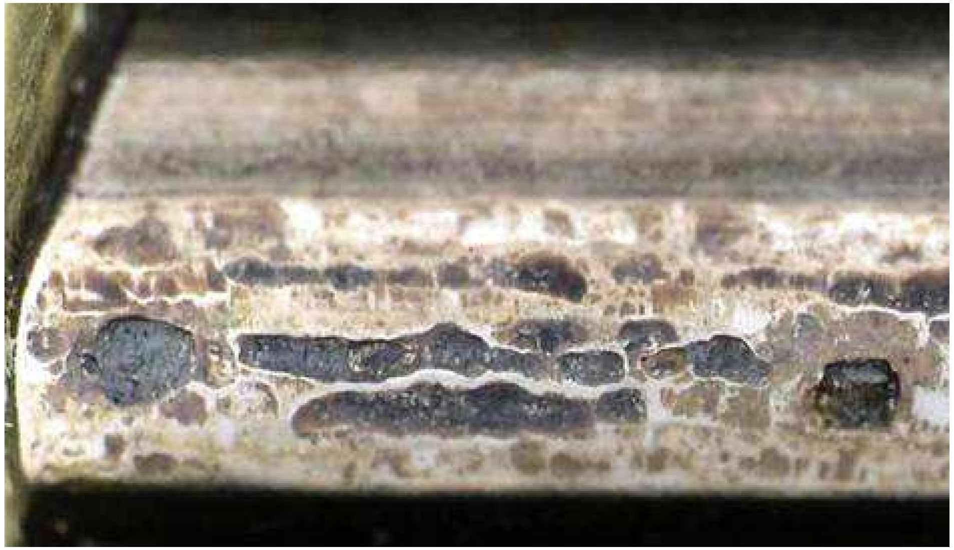
Wear and Scuffing Tests – Gear Simulation

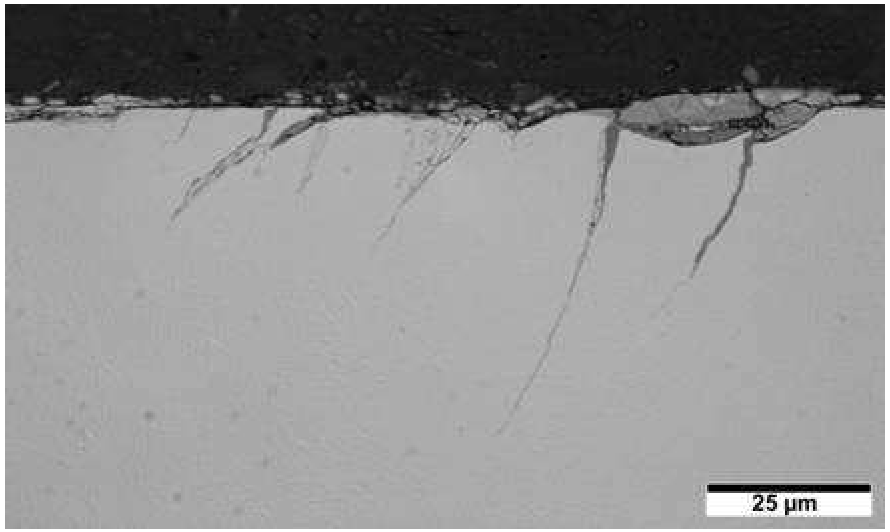


Dither Motion and Fretting









Thank you, Questions?