Tribology In Orthopaedics

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History

- David Tabor (23 October 1913 - 26 November 2005)
- A British Physicist
- Coined the term *Tribology*
- First recipient of the Tribology Gold Medal

Introduction

- Science of interacting surfaces in relative motion
- *Tribos* (Greek) meaning rubbing
- Encompasses Friction, Lubrication, Wear

Friction

- Resistance to sliding motion between two bodies in contact
- Friction Force (F) $\propto$ Applied Load (W)
- $F = \mu W$ (μ is the coefficient of friction)
- F is independent of the apparent contact area

Contact Area

- True contact area is between asperities (1% of the apparent contact area)
- Asperities deformation ∝ load / surface hardness
- Bonds form at contact points and must be broken to initiate movement
- Thus μ_s (static coefficient) > μ_d (dynamic coefficient)

Lubrication

Synovial fluid:

- produced by Type B fibroblast-like cells (Type A cells help phagocytosis)
- clear viscous liquid
- made up of proteinase, collagenase, hyaluronic acid, lubricin and prostaglandins

Synovial fluid (cont.):

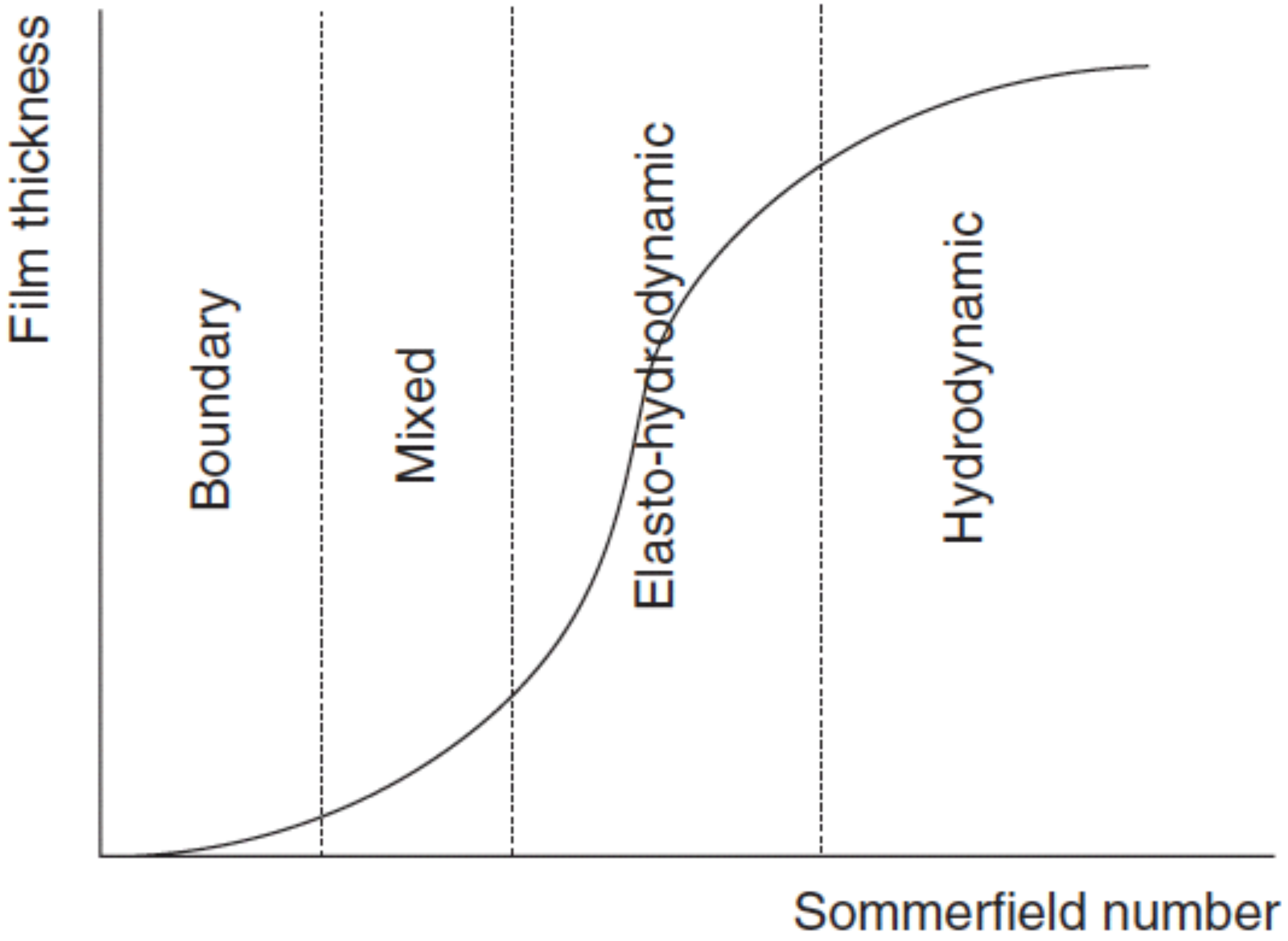
- is a dialysate of blood plasma without clotting factors or erythrocytes
- Exhibits non-newtonian flow properties
- Pseudoplasticity = fall in viscosity as shear rate increases
- Thixotropy = time-dependent decrease in viscosity under constant shearing

Synovial fluid (cont.):

- Functions
    - Lubrication
    - Cartilage nutrition

Sommerfeld Number (S)

- S ∝ viscosity × velocity / stress
- Lambda value λ = fluid thickness / surface roughness
- Critical lambda value for reduced friction is ≈3



- Rougher surface with higher asperities requires a thicker fluid film
- Artificial joints have a lambda value of < 3
- Metal-on-metal and ceramic-on-ceramic approach this value
- As lambda value exceeds 3 the friction starts to increase again

Types of Lubrication

- 1. Boundary
- 2. Fluid film
- 2.1 Hydrodynamic
- 2.2 Elastohydrodynamic

Boundary Lubrication

- Contact-bearing surfaces separated only by lubricant of molecular thickness
- Occurs when fluid film has been depleted
- Involves single monolayer of lubricant adsorption on each surface
- Glycoprotein lubricin, found in synovial fluid, is the adsorbed molecule
- Friction is independent of the sommerfeld number

Fluid film Lubrication

- Separation of surfaces by a fluid film
- minimum thickness exceeds the surface roughness of the bearing surface
- prevents asperity contact

Hydrodynamic

- Non parallel rigid bearing surfaces
- Separated by a fluid film slide tangentially
- Converging wedge fluid forms
- Viscosity within this wedge produces a lifting pressure
- No contact between surfaces and hence no wear
- May occur during the swing phase of gait

- This model assumes that:
- Surfaces are rigid and non-porous
- The lubricant velocity is constant (newtonian)
- The relative sliding speed is high
- Loads are light

Elastohydrodynamic Lubrication

- Occurs in non rigid bearing surfaces
- Macroscopic deformation serves to trap pressurized fluid
- This increase surface area which decreases the shear rate
- This increases the viscosity of synovial fluid

Microelastohydrodynamic Lubrication

- Assumes asperities of articular cartilage are deformed under high loads
- This smoothens out the bearing surface
- Which creates a film thickness of 0.5–1 μm, sufficient for fluid film lubrication

Squeeze film

- Occurs when there is no relative sliding motion
- Pressure builds up as viscous fluid offers resistance to being squeezed
- Lubricant layer becomes thinner and the joint surfaces come into contact
- This mechanism is capable of carrying high loads for short lengths of time

Boosted Lubrication

- Under squeeze film conditions
- Water and synovial fluid are pressurized into cartilage
- Leaving behind a concentrated pool of hyaluronic acid protein
- This lubricates the surfaces

Weeping Lubrication

- Articular cartilage is fluid filled, porous and permeable
- It is capable of exuding and imbibing lubrication fluid
- Cartilage generates tears of lubricant fluid by compression of the bearing surface
- The process is thought to contribute to nutrition of the chondrocytes

Wettability

- Relative affinity of lubricant for another material
- Measured by the angle of contact

Hydrostatic

- An unnatural system
- Fluid is pumped in and pressure is maintained to reduce surface contact

Lubrication Mechanisms - Synovial Joints

- No one knows exactly when each type of lubrication comes into play
- Intact synovial joints have a very low coefficient of friction (~0.02)
- Articular cartilage surface is not flat and has numerous asperities
- Kind of lubrication occurring at one time in a synovial joint varies according to the loading conditions

Wear

- Progressive loss of material from the surface due to relative motion
- Generates further “third body” wear particles
- Softest material is worn first

Wear Mechanisms

- Wear is either chemical (usually corrosive) or mechanical
- Types of mechanical wear include:
  - Adhesive
  - Abrasive
  - Fatigue

Adhesive Wear

- Occurs when junction is formed between two opposing surfaces
- Junction is held by inter-molecular bonds
- This force is responsible for friction
- This junction is responsible for spot welding / transfer
- Steady low wear rate

Abrasive wear (ploughing)

- Occurs when softer material comes into contact with significantly harder material
- Microscopic counterface aspirates on the harder surface cut and plough through the softer material
- This produces grooves and detaches material to form wear debris
- This is the main mechanism in metal / polymer prostheses

- Abrasive wear (cont.):

- Third body abrasive wear occurs when extraneous material enters the interfacial region

- Trapped wear debris produces a very high local stress

- This quickly leads to localized fatigue failure and a rapid, varying wear rate.

- Thought to be responsible in part for “backside wear” at “rigid” metal / polymer couplings and other modular interfaces

Fatigue Wear

- Caused by accumulation of microscopic damage within the bearing material
- Depends on the frequency and magnitude of the applied loads and on the intrinsic properties of the bulk material
- Also dependent on contact stress

Fatigue wear (cont.):

- Decreased by:
  - Conformity of surfaces
  - Thicker bearing surface
- Increased by:
  - Higher stiffness of material
  - Misaligned or unbalanced implants

Fatigue wear (cont.):

- In TKA the joint is less conforming and the polyethylene more highly stressed

- Delamination: repeated loading causes subsurface fatigue failure

Corrosive wear

- Mechanical wear may remove the passivation layer
- This allows chemical corrosion to occur

Fretting wear

- Localized wear from relative motion
- Over a very small range
- Can produce a large amount of debris

Wear sources in Joint Arthroplasty

- Primary articulation surface
- Secondary articulation surface
  - backside of modular poly insert with metal
  - screw fretting with the metal shell of acetabular liners
- Cement / prosthesis micromotion
- Cement / bone or prosthesis / bone micromotion
- Third body wear

Linear wear

- Loss of height of the bearing surface
- Expressed in mm / year

Volumetric wear

- Total volume of material that has been worn away
- Expressed in mm3 / year

Wear rate

- Debris volume; highest in the first year – “wearing in”
- Steady state then achieved (debris volume related to load and sliding distance)
- Accelerated wear occurs at the end of a prosthesis’ life
- Knee Joint, rectilinear sliding generates alignment of the linear polymeric molecules, reduces wear
- Cross-links increase the strength but also increase the brittleness of the polymer

Head size

- Larger the femoral head the greater the sliding distance and volumetric wear

- Volume of wear debris = $\pi Pr2$ (P is penetration and r is radius of femoral head)

- Smaller head size decreases the sliding distance and reduces volumetric wear

- Smaller the femoral head the greater the penetration

Laws of wear

- The volume of material (V) removed by wear increases with load (L) and sliding distance (X) but decreases as the hardness of the softer material (H) increases:
    - $V \propto LX / H$
    - $V = kLX$
    - k = a wear factor for a given combination of materials

Factors that determine wear

Patient factors

- Weight (applied load)
- Age and activity level (rate of applied rate load)

Factors that determine wear (cont.):

Implant factors

- Coefficient of friction (lubrication)
- Roughness (surface finish)
- Toughness (abrasive wear)
- Hardness (scratch resistance, adhesive wear)
- Surface damage
- Presence of third bodies (abrasive wear)

Wear in prosthetic hips

- There is a combination of wear and creep
- Creep usually dominates the initial penetration rate
- Majority of the linear penetration after the first year is due to wear
- Direction of creep is superomedial
- Direction of wear is superolateral

Wear in prosthetic hips:

- Cup penetration can be measured in the following ways:
- By comparison between initial and follow-up radiographs, corrected for magnification
- Shadowgraph technique
- Computer software scan imaging

Biological effects of wear particles

- Large (micron sized) particles have localized effects at the bone / implant / cement interfaces
- Small (nanometre sized) particles are thought to have the potential for systemic effects

Local

- Particles 0.1–10 μm diameter

- Phagocytosed by macrophages

- Stimulate the release of soluble pro-inflammatory mediators (tumour necrosis factor (TNF), interleukin (IL)-1, IL-6, PGE2, matrix metaloproteinases)

- Mediators released stimulate bone resorption by osteoclasts and impair the function of osteoblasts

Local (cont.):

Major factors that affect extent of osteolysis are:

- Volume of wear debris >150 mm3 per annum is thought to be the “critical” level
- Total number of wear particles
- Morphology of particles
- Size of particles
- Immune response to the particles

Systemic

- Metal ion release is increased five-fold by metal-on-metal bearing surfaces
- Metal ions are not phagocytosed
- Controversy surrounds the long-term effects
- Immune sensitization and neoplastic transformation are concerns
- Pseudotumours and metal hypersensitivity leads to early hip revision

Corrosion

Corrosion is reaction of a metal with its environment

- resulting in continuous degradation to
- oxides, hydroxides or other compounds

Passivation

- Oxide layer forms on the alloy surface
- Strongly adherent
- Acts as a barrier to prevent corrosion
- Can be jeopardized by mechanical wear

Types of corrosion

- Uniform attack
- Galvanic
- Crevice
- Pitting
- Fretting (combination of wear and crevice corrosion)
- Intergranular
- Inclusion corrosion
- Leaching corrosion
- Stress corrosion

Uniform attack

- Most common type of corrosion
- Occurs with all metals in electrolyte solution
- Uniformly affects the entire surface of the implant

Galvanic

- Two dissimilar metals are electrically coupled together
- An anode and cathode form – in essence a small battery develops as ions are exchanged

Crevice

- Occurs in a crevice or crack
- Characterized by oxygen depletion
- Tip of the crack cannot passivate due to lack of oxygen
- Accelerated by high concentrations of H^+ and Cl^-

Pitting

- Similar to crevice
- Corrosive attacks are more isolated and insidious
- A localized form of corrosion in which small pits or holes form
- Dissolution occurs within the pit

Fretting corrosion

- Synergistic combination of wear and crevice corrosion
- Relative micro movement forms where the passive layer is removed
- Can cause permanent damage to the oxide layer,
- Particles of metal and oxide can be released from fretting

Intergranular

- Metals have a granular structure
- Intergranular corrosion occurs at grain boundaries due to impurities

Inclusion corrosion

- Occurs due to impurities left on the surface of materials
- e.g. metal fragments from a screwdriver
- Similar to galvanic

Leaching corrosion

- Similar to intergranular corrosion
- Results from electrochemical differences within the grains themselves

Stress corrosion (fatigue)

- Metals repeatedly deformed and stressed
- In a corrosive environment
- Show accelerated corrosion and fatigue damage

Ideal implant

- Biocompatibility: inert, non-immunogenic, nontoxic, non-carcinogenic
- Strength: sufficient tensile, compressive and torsional strength, stiffness and fatigue resistance
- Workability: easy to manufacture and implant
- Inexpensive
- No effect on radiological imaging
- Corrosion free

Thank You

Source: Postgraduate Orthopaedics, Paul A. Banaszkiewicz, FRCS Queen Elizabeth Hospital and North East Surgery Centre, Gateshead, UK