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 ($W$)
- $F = \mu W$ ($\mu$ 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 $\propto$ load / surface hardness

- Bonds form at contact points and must be broken to initiate movement

- Thus $\mu_s$ (static coefficient) $> \mu_d$ (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)

- $S \propto \text{viscosity} \times \text{velocity} / \text{stress}$
- Lambda value $\lambda = \frac{\text{fluid thickness}}{\text{surface roughness}}$
- Critical lambda value for reduced friction is $\approx 3$
• 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 = $\pi Pr^2$ (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:
  - \( V \propto \frac{LX}{H} \)
  - \( V = kLX \)
  - \( k = \) 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 \( \mu \text{m} \) diameter

• Phagocytosed by macrophages

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

• 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