Tribology and Bearing Surfaces

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Tribology

• Tribology, from the Greek *tribos* ‘to rub’

• The science of interacting surfaces in relative motion, including friction, lubrication and wear

• Biotribology is this science related to the body

• Primarily synovial joints and replacement joints
Outline

• Tribology
• Polyethylene
• Ceramics
• Metals
• Science and technology of interacting surfaces in relative motion.
• It includes the study and application of principles of:
  – Friction
  – Lubrication
  – Wear
Friction

• Resistance to sliding motion between two bodies in contact
• Frictional force = applied load x coefficient of friction
• CoF of best synthetic coupling is 10x larger than human synovial joint
Friction

- Friction force is a resistance to motion
- With no lubricant:
  - Friction force is proportional to normal force
    \[ F = \mu N \]
  - Friction is independent of velocity
  - Friction is independent of apparent contact area
  - Friction is dependent on real contact area
    (1 to 0.0001% of apparent contact area)
• “Real Area of Contact.” As stated by Frank Phillip Bowden, a pioneer in the field of tribology: “…putting two solids together is rather like turning Switzerland upside down and standing it on Austria – their area of intimate contact will be small” (1950).
Apparent contact area = 

True contact area =
More pressure
Same force/smaller apparent contact area

Less pressure
Same force/greater apparent contact area

Bigger true contact area
Smaller true contact area
Friction

Friction force \( (F) = F \text{ adhesion} + F \text{ ploughing} \)

Due to chemical bonding at the asperity contacts

Due to breaking and deforming of one asperity by another
Wear

• Adhesive wear
  – occurs by the transfer of material from one surface to another when two surfaces articulate against each other under load. The transferred material could break off and act as third-body particles resulting in abrasive wear.

• Abrasive wear
  – occurs when material is removed from a surface by hard asperities on the counterface and hard particles (third body) trapped between the two contact surfaces.

• Corrosive wear
  – occurs by the combination of mechanical wear and chemical reaction. Corrosion is the mechanism by which metal ions are released, and as this process is less understood than the other wear mechanisms
Wear

Adhesion + fracture

Abrasion + fracture

Fatigue + fracture
Adhesive wear
Abrasive wear

Two body abrasive wear

Three body abrasive wear
Fatigue Wear - Poly

- Non congruent - knees
**Backside Wear**

**TECHNOLOGY**

**MOTTO JEANS TECHNOLOGY:**
- lining with 100% original DuPont™ KEVLAR® for:
  - knees, backside, hips, outer thigh

Main features:
- strong abrasion resistance and protection for lined parts with DuPont™ Kevlar®
- double layer protection of jeans: *jeans denim / Kevlar®*
- great wearing comfort: *cotton layer lining over Kevlar®*
- optional KNOX® hip protectors

* SAS-TEC or KNOX® knee CE protector depending on model

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Backside wear

Articular PE surface

Backside PE surface
Backside Wear

New Poly
Wear

• Wear can be measured as a depth, but volume is much better.

• Generally wear volumes:
  ➢ Increase with load
  ➢ Increase with sliding distance
  ➢ Increase with surface roughness
  ➢ Decrease with surface hardness

• However, many other factors can be involved in the wear process.
Linear and volumetric wear

• Charnley 22mm
• Mayo clinic
  – Livermore Ilstrup Morrey 1990 JBJS
  – 385 THRs at 9.5 year follow-up
  – 22mm ; 28mm; 32mm head
  – Measured linear wear
  – Calculated volumetric wear
• Highest **linear** wear 22mm head
• Highest **volumetric** wear 32mm head
• Best wear 28mm head
Pin on plate wear
Tribology of wear

Osteolysis
Polymorphisms in IL-1 receptor antagonist and IL-6 genes affect risk of osteolysis in patients with total hip arthroplasty.
Macrophage attempting to absorb UHMWPE particle
Professor Richard Striebeck (1861-1950)

- Professor of Engineering Berlin
- Sliding and rolling bearings
- Railway wagon bearings
- Boundary and fluid film lubrication
- Tribology ‘termed’ 1966
STRIBECK CURVE

Coefficient of Friction ($\mu$)

Sommerfeld Number
(viscosity \times sliding speed \times radius/\text{load})

BL  ML  FFL
Boundary Lubrication

• High clearance between surfaces
• High surface roughness
• Boundary lubrication
• High coefficient of friction for bearing couple
• Asperities make contact
• Adhesive and abrasive wear
Surface roughness and lubrication

- Typical metal-on-polymer joint, polymer relatively rough
- Metal-on-metal joint under typical mixed lubrication
- Resurfacing metal-on-metal joint. Fluid film lubrication possible
Fluid film lubrication

• As radial clearance reduces ...
• Fluid film thickness increases
• 50mm articulation vs 28mm articulation
• Potential for fluid film lubrication
• Low coefficient of friction
• Low wear
Equatorial bearing
Polar bearing

Mid-polar bearing
Combination of boundary and fluid film
Radial clearance and Bearing
Wear

• Volumetric wear
• Linear wear
• Particle size
• Bio-compatibility
Wear Rate
(microns/year)

CoCr/Polyethylene
200 microns/year

CoCr/Crossfire Polyethylene
20 microns/year

Metal/Metal
4.2 microns/year

Alumina/Alumina
less than 1 micron/year
Main problem of THA

- Wear debris from articulating surfaces
- Host tissue reaction
- Periprosthetic osteolysis and loosening and failure
- >70% of failures
Solution of particulate debris

Eliminate periprosthetic osteolysis

Eliminate loosening

Improve the duration of implants
Fig. 3. Modular design of bearings currently used in total hip arthroplasty.
Polyethylene
UHMWPE

- Polymer chain
- Crystalline (strength) and amorphous (ductile) regions
- Sterilisation
- Oxidation
- Free radicals
- Processing - compression moulding and ram extrusion
- Cross-linking - reduces wear
  - Irradiation and annealing
Ultra high molecular weight Polyethylene (UHMWPE)

Sir John Charnley 1962
High level of particles
Highly-crosslinked UHMWPE

Crosslinking:
- Stabilizes the polymer
- Reduce surface reorientations

Eliminate free radicals

Peroxide chemistry
- Ionizing radiation
- Electron-beam irradiation

DECREASES WEAR
Highly-crosslinked UHMWPE

- Clinically introduced in 1998
- Now second generation cross-linked UHMWPE (e.g. X3)
Highly cross linked UHMWPE

• Lower linear wear rate in obese pts at 4.75 years compared to std UHMWPE. Stephani et al

• Reduced mechanical strength and toughness if 10MRad and above melting temp annealing
  – Tower et al (2007) showed 4 fractures in above type of liners with thin thickness and high abduction angles

• Below melting temp annealing associated with better mechanical properties but..
  – Currier et al (2007) showed oxidation and fatigue damage in in-vivo retrievals from up to 5 years
2nd Generation HC-UHMWPE - X3

• Registry and studies performing well at up to 10 years

• Match wear and failure rates of ceramic on ceramic
Highly-crosslinked UHMWPE

- Metal / HC-UHMWPE
- Ceramic / HC-UHMWPE
- Oxinium/HC-UHMWPE

Metallic alloy with a ceramic surface (Smith & Nephew)
Ceramics
Zirconia Dioxide (ZrO2)

• Crystalline structure
• Expands with heating to cubic then tetragonal then monoclinic crystal states
• High stresses that cause cracks as shrinks with cooling
• Stabilize with oxides (e.g. yttrium oxide)
• Transformation toughening
• Metastable tetragonal structure that expands to monoclinic under stress
• Thus compressing and stopping crack propagation
Zirconia failures

- Thermal tetragonal transformation
- Y-TZP (yttria-stabilised tetragonal zirconia polycrystal)
- Crack propagation at head neck stress-risers
- Critical failure
- Secondary metallic destruction
  - Maccauro et al 2004
Alumina (Al2O3)

- Aluminium (III) oxide
- Hexagonal crystalline structure
- Properties:
  - High thermal stability
  - Hard
  - Bio-inert
  - But...
  - Brittle
  - Difficult to manufacture
Ceramic/ceramic (alumina/alumina)

- Mittelmeier hip prosthesis 70’s and 80’s

- **PROBLEMS:**
  - Pain
  - Neck/socket impingement
  - Loosening
  - Isolated accelerated wear
  - Ceramic fracture
Failed because design issue:
- Ceramic alone
- Large grain size material
- Inclusions
- No standards for testing

Mittelmeier THA in a young woman with RA. Follow-up: 21 years
Alumina-zirconia composites

- Offer optimal thermal and mechanical properties
- Easier manufacturing
- Increased implant options
- CeramTec AG ™
- Biolox forte ™ and delta™
Ceramic - Biolox forte

During 80s: (CeramTec)
- Less grain boundaries
- Less inclusions
- Grain size < 2 microns
- More dense alumina
- Limited to 28 and 32mm head size
Ceramic – Biolox Delta
Forte™ to delta™

Microstructure of Biolox® forte

Microstructure of Biolox® delta

Alumina

Zirconia  Platelet  Alumina

1  2  3
Biolox Delta

• *Mixed* ceramic
  – Increased hardness
  – Increased wettability (hydrogen bonds)
  – Larger head sizes
  – 12 year follow up
Ceramic on ceramic

• Disadvantages:
  1. Past history (fractures)
  2. More expensive
  3. Noises in hip (Squeaking)
  4. More precise surgical technique
    1. Insertion of liners
    2. Version of cup
  5. More dislocations
Bevelled edge: means less than 180 degrees
Ceramic – no ‘lipped’ liners
Borgwardt et al Denmark 2005
Dislocation Rate

- Zr-UHMWPE: 14.3%
- CoCr-CoCr: 5.3%
- Zr-Asian: 3.6%
- Alu-Alu: 22.1%
Ceramic on ceramic

- Squeak in 0.7% of hips Walter et al (2007)
  - Associated with component position outside >25deg AV and >45deg inclination
- Lusty et al (2007) 99% seven year survival for aseptic loosening
- Koo et al (2008) 1.4% Ceramic head fracture rate associated with one design with suspect neck head junction
Metals
Metal on metal

- McKee-Farrar THR (60s)
  - Thompson stem
  - A chrome cobalt metal on metal articulation
  - Fixed with cement.
  - Outcome let down by manufacturing
Metal on metal

- METASUL (Zimmer) 80s
- Metasul System has a metal inlay inside the polyethylene insert
Metal on metal

- McMinn (1990s) - Birmingham
- Resurfacing Arthroplasty
- Initial success

“Magnum” heads
Fourth Generation Designs

- ASR; Durom etc
- Thinner cup
- Deformable
- Not hemispherical
- Poor positioning
- High wear rates
- High early failure rates
- ASR withdrawn
Then it got worse!
Large head MoM THR

- Even higher wear and associated failure rates
- New terms
- Adverse reaction to Metal Debris (ARMD)
- Trunnionosis
- British hip society 2011
Metal on metal

Pseudotumors

- 1% within 5 years
- Cystic mass lying posterolaterally to the joint
Metal on metal

Histology:
• Perivascular lymphocyte and plasma cell infiltrates
• ALVAL: atypical lymphocytic and vasculitic associated lesion
• Perivascular infiltrated.
A. Macrophages
B. B-lymphocytes
C. T-lymphocytes
D. Activated T-lymphocytes
Metal on metal

• Serum and urine metal ion levels
• Risk of cancer
• Immune response to metal
• Decrease in CD8 cells
• Placenta barrier
• Induction of cellular necrosis
• Chromosomal aberrations
Metal on metal pitfalls

• Small component sizes (women)
• Component alignment
  – Open inclination - edge loading
• Design problems (ASR)
• Metallurgy (Birmingham - carbon content)
• Bioactive wear products
MHRA guidance since April 2010

- Contact patients with MoM bearings
- Annual review
- Cobalt and Chromium serum levels
Not Allergy
Not Allergy
Distal Articulation
Black stuff – must be corrosion
Unique Occurrence?
Volumetric assessment of taper wear

4 mm$^3$
total wear

Enough to provoke ARMD

NOT enough for Co > 7
Cases
Case 1

- 55 Female
- R Birmingham THR 5 years
- 3/12 Right leg sciatica; past history of back problems
- Mild foot drop
Blood tests

- Cobalt 7.9 ppb
- Chromium 4.2 ppb
Case 1

- 55 Female
- R Birmingham THR 5 years
- 3/12 Right leg sciatica; past history of spine problems
- Mild foot drop
- SPR clinic - MRI spine; normal

- MRI hip
• Histology ALVAL
Post op

- Dislocation 2/52
Case 3

- Cemented hip revised 10 years ago
- Metal on metal bearing
- Sudden onset pain left hip