Lecture 6. Mechanical Properties (Fracture)

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Failure of implant

- The failure of materials is always **an undesired event**. Hence, understanding the reasons behind a failure is always important.
- Fracture can be defined as —the separation or fragmentation of a solid body into two or more parts under the action of stress.
- The process of fracture can be considered to be made up of two components:

➢ Crack initiation.

➢ Crack propagation.

- The fracture can be **classified into two general** categories:

➢ Brittle fracture.

➢ Ductile fracture.

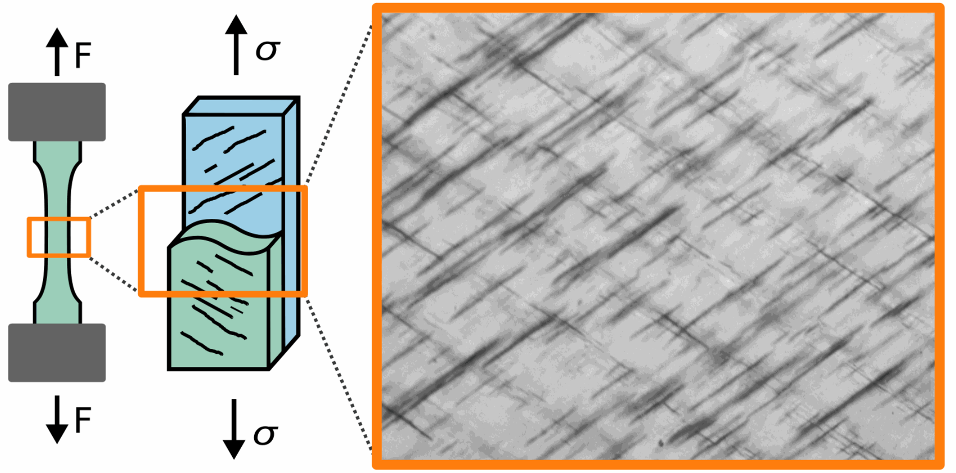
- Fracture occurs in characteristic ways, depending on the **following parameters**:

➢ State of stress.

➢ Rate of stress applications.

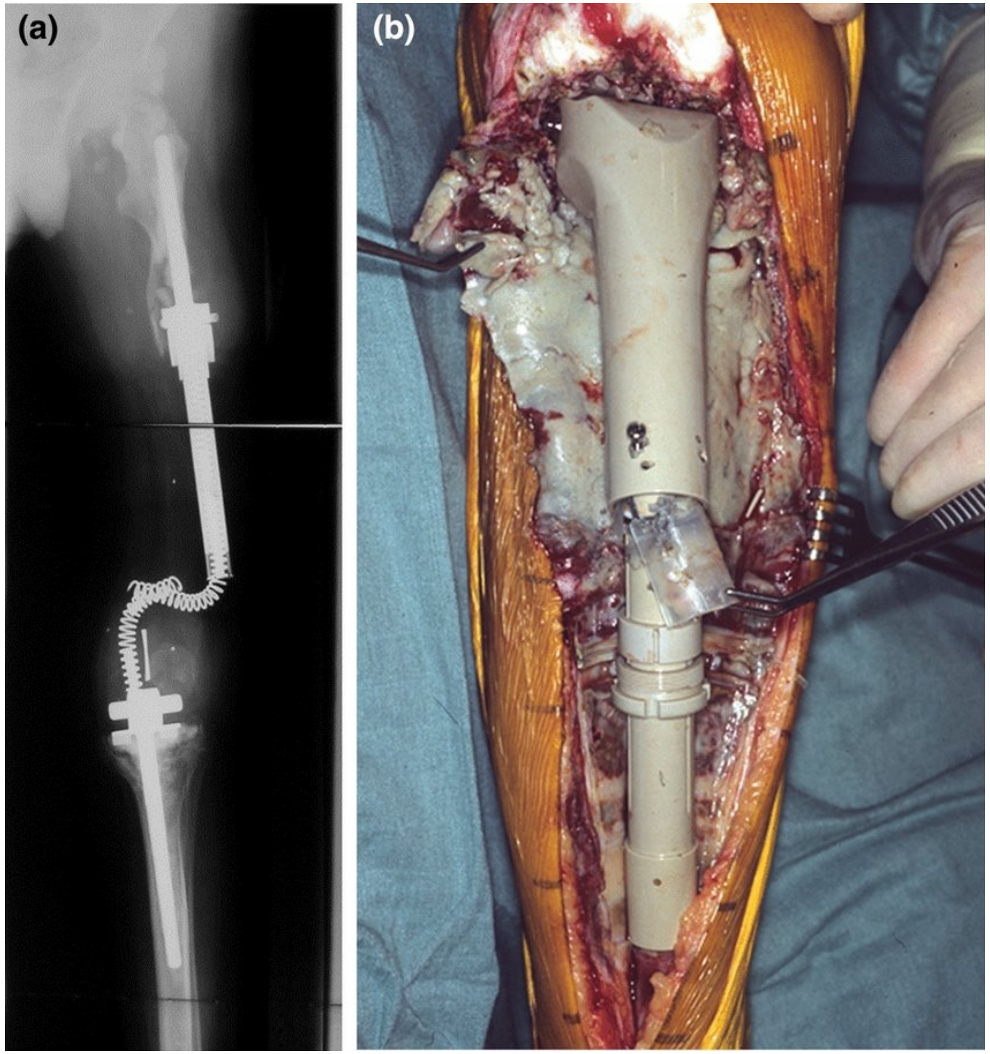
➢ Temperature.

Ductile fracture	Brittle fracture
Plastic deformation	Small/ no plastic deformation
High energy absorption before fracture	Low energy absorption before fracture
Characterized by slow crack propagation	Characterized by rapid crack propagation
Detectable failure	Unexpected failure
Stable crack	Unstable crack
Eg: Metals, polymers	Eg: Ceramics, polymers



Failure of implant

- The **fracture mechanism** of a material varies with its working conditions, based on which the fracture properties of materials are named, such as
- fatigue properties (cyclic loading),
- creep properties (at elevated temperature),
- stress corrosion cracking (SCC), and so on.
- Although these fractures appear **complicated and vastly different**, the fundamental **mechanism is the same**: **the breakage of chemical bonding between atoms or molecules.**
- Among these failure forms, **fatigue and SCC** frequently occur in medical implants.



an example of a mechanical failure

Fatigue failure

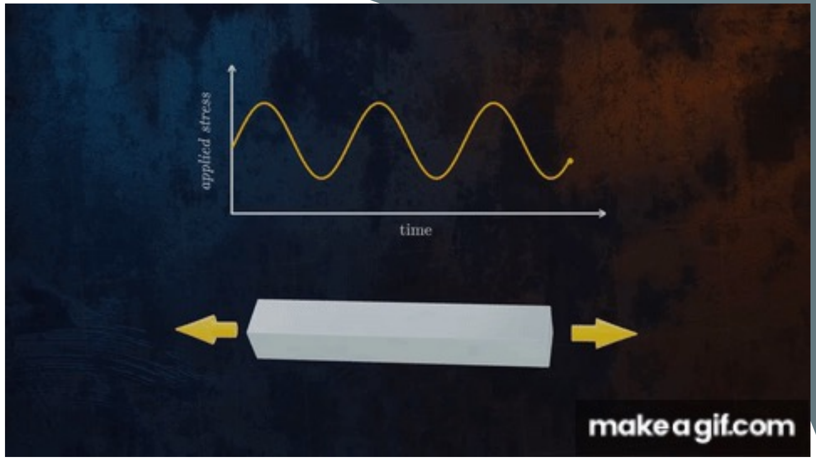
- Fatigue is the **progressive structural damage** that occurs when a material is subjected **to cyclic loading**.
- In general, **cyclic loading** will promote material damage more efficiently than static loading.
- Under static loading conditions, a material will only undergo permanent (plastic) deformation when the externally applied stress is higher than the yield stress limit (i.e., yield strength σy) of the material, and fracture can occur only when the applied stress reaches the tensile stress limit (i.e., UTS) of the material.
- However, when a material is subjected to a cyclic loading, it can fracture **far below its UTS**, and even below the yield strength of the material.
- As such, a fatigue failure is of **the brittle type**, which takes place with very little observable plastic deformation and minimal absorption of energy.
- Brittle fractures are more **dangerous than ductile fractures** because they occur abruptly under normal service conditions with little or no warning prior to rupture.
- Indeed, medical devices manufactured from any material expected to survive millions of cyclic deformations over their lifetime require testing of the fatigue and fracture resistance, with fatigue fracture being the major cause of premature failure in biomedical implants.

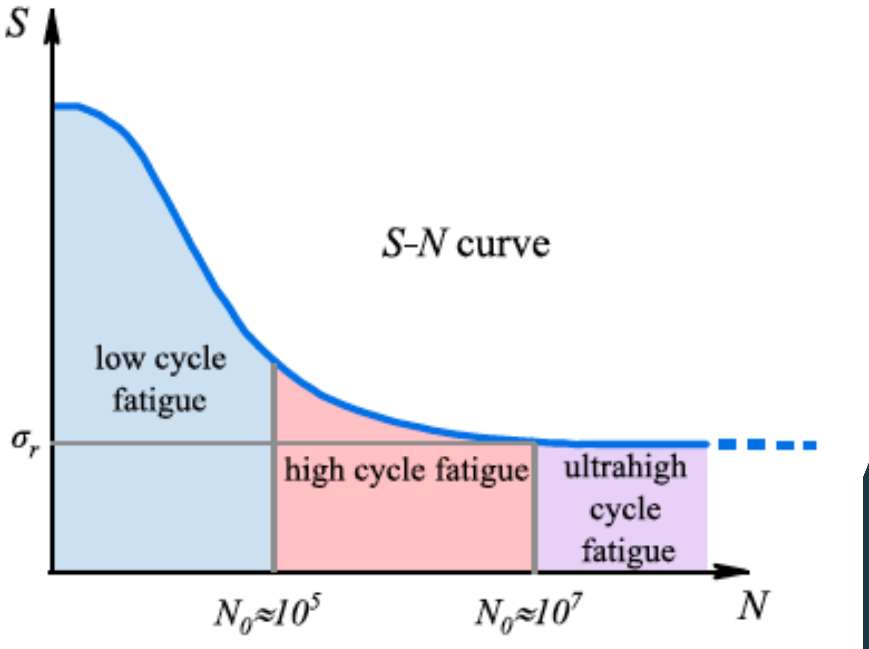
Fatigue failure

- Theoretically, a structurally perfect material (free of defects) would not suffer fatigue. In the real world, no materials are perfect, and fatigue usually initiates a defect that acts as a **stress concentration.**
- defects can arise from nonhomogeneity in microstructure (e.g., impurities, second phase particles, and grain boundaries), manufacturing defects of the metallic component (e.g., holes and welds), or surface defects (scratches, sharp fillets, notches, and pits) from machining operations.
- Stress concentrates locally on these defects sites when the material is subjected to external loading.
- The internal stress field always increases proportionally to the external load.
- When the external load **increases** to a certain level, stress concentration can escalate to permanent defects, such as dislocations and microcracks that cannot be removed by unloading.
- Among these defects, defects on surfaces are the most dangerous.
- The crack associated with fatigue failure almost always initiates (or nucleates) on the surface of a component at some point of stress concentration.

Fatigue failure

- Fatigue properties of a material are commonly characterized by an S-N curve.
- This is a graph of the magnitude of a cyclic stress (S) against the logarithmic scale of cycles to failure (N).
- When considering the figure, it makes sense that the higher the external stress (S) is, the more the dislocations produced by a single load would be, and thus a lower number (N) of cyclic loads would be needed to accumulate dislocations toward failure.
- Fatigue limit refers to the **range of cyclic stress that can be applied to a material without causing fatigue failure**, regardless of how many cycles it is loaded.
- Most nonferrous alloys do not have a fatigue limit, in that the S-N curve continues its downward trend at increasingly greater N values.





The S-N curve shows how many times you can bend it (number of cycles) before it breaks, depending on how hard you bend it each time (stress).

Fatigue failure

- The fatigue mechanisms described earlier explain why fatigue strength sensitively varies with the microstructure of materials, surface quality of products, and service conditions (e.g., load vectors, cyclic frequency, wearing, and corrosion environment).
- Nevertheless, generic relationships exist between the fatigue strength, UTS, yield strength, and Young's modulus of materials, which provide us with a very useful guide in the selection and design of materials for a good overall fatigue resistance.
- The fatigue strength is lineally proportional to UTS:

$$\sigma_{fatigue} \approx 0.5\, \sigma_{UTS}$$

- Since UTS is roughly proportional to the yield strength and Young's modulus, fatigue strength and UTS are also roughly proportional to the yield strength and Young's modulus.
- In principle, materials of UTS, Young's modulus, and high yield strength tend to have excellent fatigue resistance.

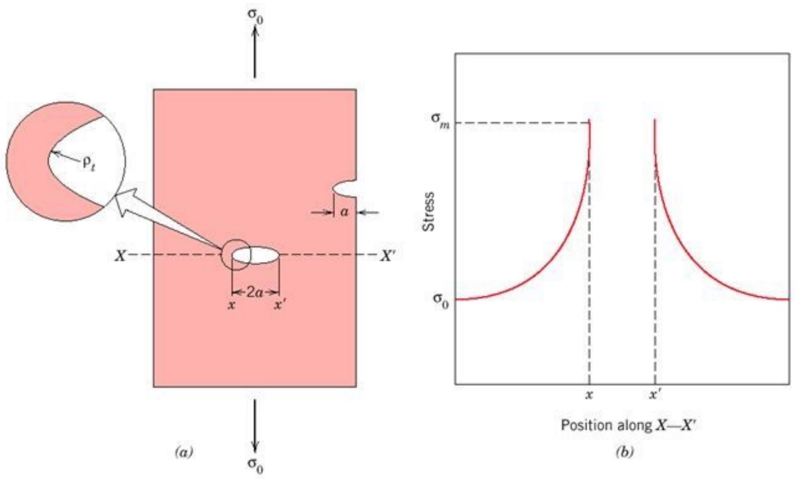
Stress corrosion cracking

- Stress corrosion cracking (SCC) is an unexpected sudden brittle failure of normally ductile or tough metals subjected to tensile stress in a mild corrosive environment.
- In other words, neither the stress nor the corrosion conditions alone can cause failure, but in **combination**, they are more likely to contribute to **SCC.**
- The fracture of a material is a process of breakage of chemical bonding between atoms.
- Chemical bonds can be broken mechanically (tensile stretch), chemically (corrosion), or jointly (i.e., SCC).
- With the assistance of chemical action (i.e., corrosion) on a metallic material, the mechanical stress needed to break a chemical bond can be well below the tensile stress limit (i.e., UTS).
- **In practice**, **cracking from stress corrosion** has been shown to occur under stress much lower than UTS, such as occurring in an implant with residual stresses.

Determination of the Maximum Stress at the Crack Tip

- if it is assumed that a crack is similar to an elliptical hole through a plate and is oriented perpendicular to the applied stress, the maximum stress, σ_m, occurs at the crack tip and may be approximated by

Stress Concentration



Crack perpendicular to applied stress:

maximum stress near crack tip →

$$\sigma_m \approx 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2}$$

σ_0 = applied stress; a = half-length of crack;

ρ_t = radius of curvature of crack tip.

Determination of Stress Concentration Factor

- The **stress concentration factor** is a simple measure of the degree to which an external stress is amplified at the tip of a small crack.
- The ratio of the maximum stress and the nominal applied tensile stress is denoted as the stress concentration factor, $\mathbf{K_t}$, where $\mathbf{K_t}$ can be calculated by Equation.

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

Using principles of fracture mechanics, it is possible to show that the **critical stress σ c** required for crack propagation in a brittle material is described by the expression

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

where **E** is modulus of elasticity, **γs** is the specific surface energy, and **a** is one-half the length of an internal crack. ρt is the radius of curvature of the crack tip

H.W

- A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

- An MgO component must not fail when a tensile stress of 13.5 MPa (1960 psi) is applied. Determine the maximum allowable surface crack length if the surface energy of MgO is 1.0 J/m2 , and E of MgO is 225 x 109 N/ m2 .

- Estimate the theoretical fracture strength of a brittle material if it is known that fracture occurs by the propagation of an elliptically-shaped surface crack of length 0.5 mm and having a tip radius of curvature of 5 x 10^{-3} mm when a stress of 1035 MPa is applied.

Essential Mechanical Properties of Orthopedic Implant Biomaterials

In order to serve safely and appropriately at load-bearing sites for a long period of time without rejection, a metallic implant should possess the following essential characteristics:

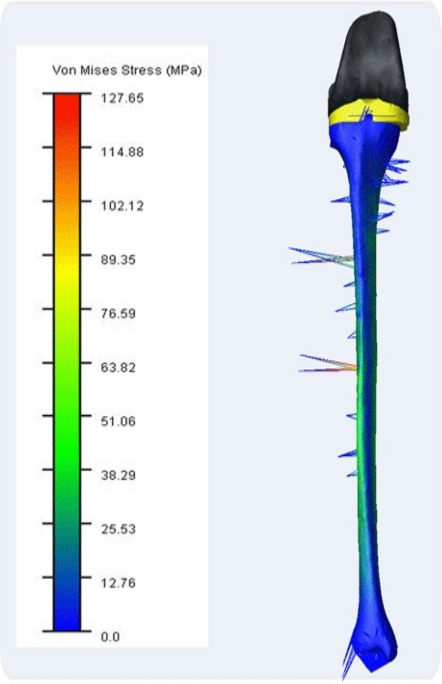
1. No toxicity (equivalent to excellent corrosion resistance)
2. Suitable mechanical strength
3. High wear resistance
4. Osseo-integration ability (including bone bonding)

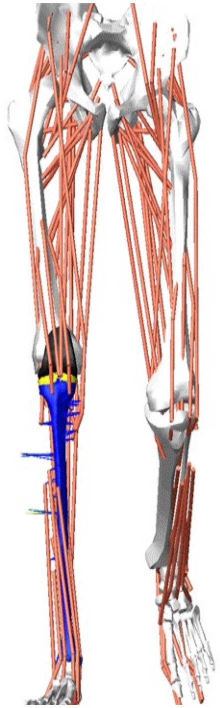
Mechanical Working Environments of Implants in the Body

- In the design of mechanical requirements of biomaterials, a first step may be to understand the mechanical working conditions of implants.
- The mechanical working conditions within the human body are complex.
- Human beings normally walk several thousand steps a day at a rate of 1 Hz.
- As such, skeletal bone implants such as artificial hip joints, knee joints, spinal fixations, plates, and wires suffer from fatigue due to cyclic loading.
- In the case of total hip replacements, the loading stress level is several times higher than that of the patient body weight. This is because when the hip joint is located out of the perpendicular alignment of the body weight, the balance between body weight and muscular strength pivots on only one leg.

Mechanical Working Environments of Implants in the Body

- Loading stress on the leg during this motion is estimated to be ~50 MPa on average, when a load of five times of the body weight is applied to the cross section of the stem of a total hip prosthesis.
- Under this average loading, according to finite element analysis, the maximal tensile stress in a total hip replacement in the body is around 200 MPa in the stem, and ~300 MPa in the neck .
- This is a conservative estimation, under the assumption that patients with hip implants would not jump or run.
- This value could be higher in practical situations, such as jumping, running, falling down, stepping down, carrying heavy loads on one side, so on.





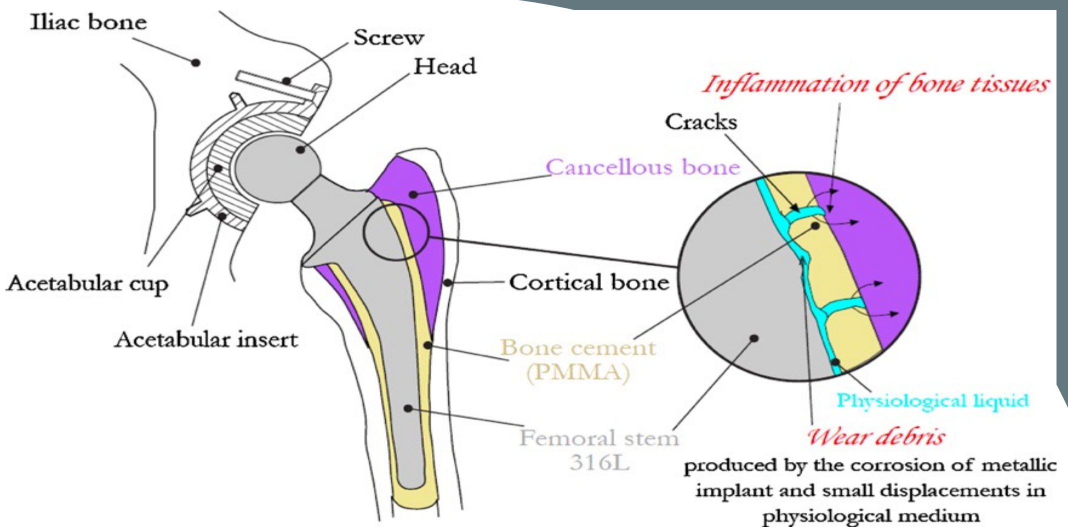
Mechanical Working Environments of Implants in the Body

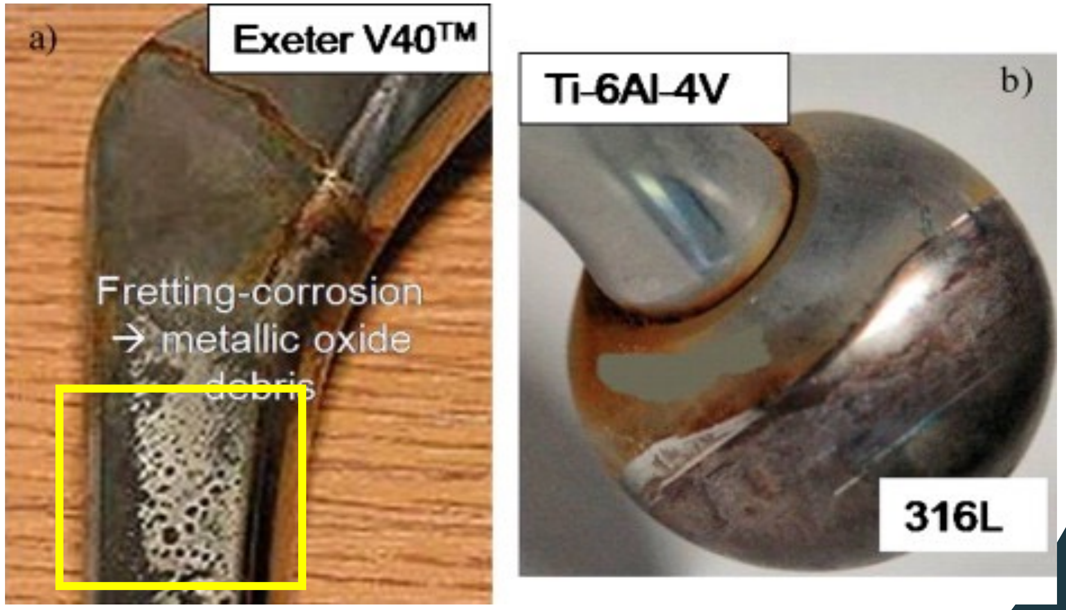
- With the increase of human life span, total hip replacements are expected to serve for 20 years.
- Assuming that a person walks 2×10^3 steps, the total number of steps over 20 years is estimated to be **2000 × 365 day × 20 years * 1 × 10' cycles** (as shown in the table). Cyclic stress also occurs in dental implants during chewing motion and in nonosseous tissue implants, such as pacemaker electrodes in response to myocardial activity.

Fatigue Mechanical Working Conditions of Some Implants			
Implants	Loading Strength	Loading Frequency (Hz)	Expected Total Number of Implants Loading Strength Loading Frequency (Hz) Loading over the Lifetime of a 65-Year-Old Patient (i.e., 20 Years Implantation)
Joints	Compression ~50 MPa Bending 200-300 MPa	1	10^7
Pacemaker	Not available	1	10^9
Tooth fillings	Not available	1	10^7

Fretting Fatigue and Corrosion
Fretting Fatigue

- The mechanical working conditions of orthopedic implants are frequently complicated by cyclic stress and friction called fretting fatigue.
- When fretting fatigue occurs, a foreign body is statically pressed to the surface of the specimen to which cyclic stress is applied.
- Fretting occurs due to slight relative movements between adjacent contacting surfaces of components. This leads to the production of oxide debris and fresh metal surfaces.
- Visible damage is found even when the slip amplitude is little as 10-4 mm.
- A crack starts at the contact site, quickly spreading before breaking.
- Artificial hip joints, bone plates, and wires will likely suffer from fretting fatigue.
- When fatigue occurs along with corrosion, it is known as corrosion fatigue. Fretting fatigue with corrosion is thus known as fretting corrosion fatigue.
- Metallic implant biomaterials tend to be damaged by corrosion fatigue or fretting corrosion fatigue in the human body.





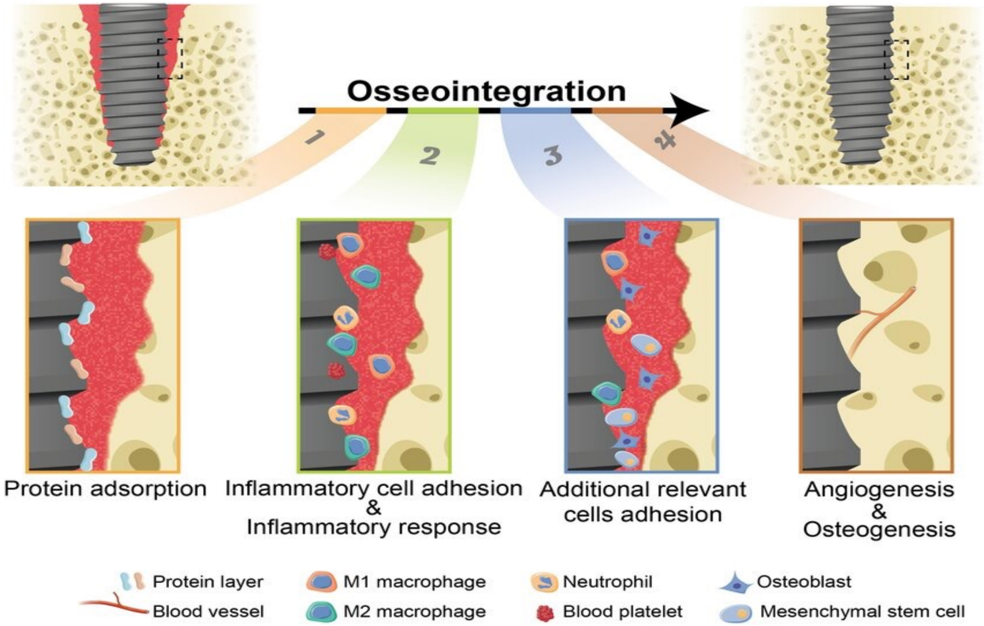
*Fretting-corrosion between femoral stem (Exeter V40TM) and bone cement [7] and (
b) fretting-corrosion between a head (316L) and a femoral neck (Ti–6Al–4V).*

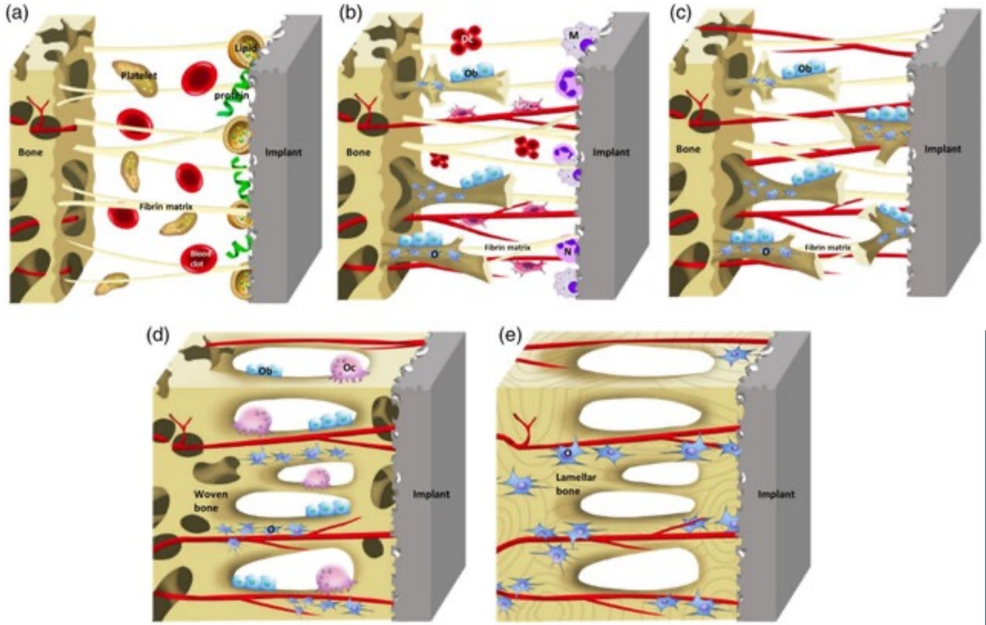
Wear of Joints

- Wear is an unavoidable issue in joint replacements, regardless of the materials used. The wear resistance of a material is primarily influenced by its hardness.
- The low wear resistance or high friction coefficient in a joint system can lead to implant loosening.
- Although not fully understood, aseptic loosening is a common issue caused by wear damage. This occurs when a large number of tiny microscale particles accumulate around a joint replacement.
- While a joint replacement performs its intended biomechanical function very well initially, a gradual increase in the amount of particles occurs over long-term wear, attracting cells of the immune system (called macrophages) that recognize and engulf the particles as foreign bodies, just as they do with bacteria. This is a natural defense mechanism (the foreign body response).
- However, the same particles tend to kill macrophages after ingestion. As a result, dying macrophages break down and release enzymes and metabolites which are acidic and cause severe acidification in the surrounding microenvironment.
- It is these enzymes, acidic chemicals, ions, and cellular debris that contribute to the erosion of both the implant and bone.
- There are also concerns over the adverse reactions to systemic distribution of metal wear particles and ions due to the toxicities of most alloying elements.
- In brief, wear debris causes severe adverse responses, whereby a revision surgery is likely to be required.
- Alternatively, wear resistance of an implant can also be improved by surface modification or treatment.

Osseo-Integration

- While high fatigue strength, excellent corrosion resistance, and wear resistance are the key properties that determine the longevity of permanent orthopedic implants in human bodies, the ability of an implant to bond with host bone is another fundamental requirement of permanent implants in orthopedics.
- Osseo-integration is a term that describes the bonding process of an implant with bone.
- The incapability of an implant surface to join with the adjacent bone and other tissues due to micromotions will cause the formation of fibrous tissue around the implant and promote loosening of the prosthesis.
- Therefore, it is essential for an implant to have an appropriate surface to integrate well with surrounding bone to prevent osteolysis.
- Materials (especially surface) chemistry, surface roughness, and surface topography are all factors that need to be considered for good osseo-integration.
- Nevertheless, the bone-bonding process is not desired in the applications of temporary devices, such as internal fixation or traction devices.
- In these applications, the devices are removed after healing has taken place, and any bonding of the device to the host bone would complicate the removal surgery and cause further damage to the attached bone.





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