Tribological applications of biomaterials: an overview

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Abstract  Tribological research is the study of lubrication, friction, and wear. Tribology of biomaterials is to study how the materials work and fail. This will help us to produce better biomaterials. Tribology plays a very important role in improving the design and making successful biomaterials for medical purposes. Joints of human body, such as hip, knee, jaw, dental parts etc., all need to consider the wear and lubrication problem. In this paper, we give a general introduction of biomaterial research in tribological applications. Materials, the synthetic characterization, and their failure are introduced.

Keywords: Biomaterials, Tribological Materials.

The earliest successful implants were bone plates, introduced in the early 1900s to stabilize bone fractures and accelerate their healing. As early as in the late 1950s, the first total hip replacement was introduced using polytetraflouroethylene (PTFE) as the cup bearing surface[1]. However, the PTFE undergoes aseptic loosening.

Early in late 1960s, tribology was introduced into the living and artificial human joints[2]. The development has been seen in many areas. For examples, the tribological behavior of synovial joints and their replacement, wear of human dental tissues, the lubrication by plasma of red blood cells in narrow capillaries, the wear of replacement heart valves, the wear of screws and plates in and on bone in fracture repair, the tribology of skin and the friction of hair, biosensors, artificial fingers, etc., are all the topics of study.

In the late 1970s, a temporomandibular joint (TMJ) replacement using PTFE as the bearing counterface was invented. In 1983, the PTFE implant, which was called the Interpositional Implant (IPI), was approved to the market. Because PTFE exhibits a low coefficient of friction and has been used extensively as a bearing surface in other engineering applications, it would seem an appropriate choice for an implant material in theory, However, of the more than 25,000 PTFE TMJ implants received by patients, most failed. With the development of the research on IPI, evidence did exist that PTFE was not an appropriate implant material[1].

It is estimated that 85 to 95% of approximately 600,000 total joints are performed each year in the United States (More than 120,000 artificial hip joints are being implanted annually) will still be functioning after ten years, based on research reported in orthopedic medical journals[3, 4]. Artificial joint replacement is performed when the cartilage that lines the joint deteriorates, resulting in bones grinding against each other (shown in Fig. 1)[5]. If non-surgical treatments, such as anti-inflammatory drugs, walking aids, and support braces do not offer relief.
Joint replacement surgery is most commonly performed for hips, knees, and shoulders (See the joint replacements in Fig. 2) \([5]\), although toes, fingers, and elbows have been successfully replaced. Most artificial joint replacements are designed to remove the diseased areas of the joint and replace them with metal- and-plastic implants designed specifically to restore that joint's function and stability.

For biomaterial design, engineers must consider the physiologic loads to be placed on the implants sufficient structural integrity. Material choices also must take into account biocompatibility with surrounding tissues, the environment and corrosion issues, friction and wear of the articulating surfaces, and implant fixation either through osseointegration (the degree to which bone will grow next to or integrate into the implant) or bone cement. One of the major problems plaguing these devices is purely materials-related: wear of the polymer cup in total joint replacements. A summary of tribo-biomaterials was introduced in Table 1.

![Knee joint deteriorate.](Image)

**Fig. 1.** Knee joint deteriorate.

![Joint replacements.](Image)

**Fig. 2.** Joint replacements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Application</th>
<th>Major Properties Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy: Titanium Alloys(^6), Titanium Aluminum Vanadium Alloy(^7), Cobalt Chromium Alloy(^8), Cobalt Chromium Molybdenum Alloy(^9)</td>
<td>Total joint replacement</td>
<td>Wear and corrosion resistance</td>
</tr>
<tr>
<td>Inorganic: diamond-like carbon, Biocompatible coatings,</td>
<td>Biocompatible coatings,</td>
<td>Reduced friction and increased wear resistance</td>
</tr>
<tr>
<td>Ceramics(^10): Al2O3, ZrO2, Si3N4, SiC, B4C, quartz, bioglass(Na2O-CaO-SiO2-P2O5), sintered hydroxyapatite (Ca10(PO4)6(OH)2)</td>
<td>Bone joint coating</td>
<td>Wear and corrosion resistance</td>
</tr>
<tr>
<td>Polymers: Ultrahigh molecular weight polyethylene, Polytetrafluoroethylene (PTFE), Poly(glycolic acid)</td>
<td>Joint socket</td>
<td>Low coefficient of friction</td>
</tr>
<tr>
<td>Composites: Specialized silicone polymers</td>
<td>Interpositional Implant temporomandibular joint(Jaw), Joint bone, Bone joint</td>
<td>Wear and corrosion, and fatigue resistance</td>
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</table>

**Table 1** Summary of Tribo-biomaterials
As advances have been made in the medical sciences, aging population has become important. More organs, joints, and other critical body parts will wear out and must be replaced if people are to maintain a good quality of life. Biomaterials now play a major role in replacing or improving the function of every major body system (skeletal, circulatory, nervous, etc.). Some common implants include orthopedic devices such as total knee and hip joint replacements, spinal implants, and bone fixators; cardiac implants such as artificial heart valves and pacemakers; soft tissue implants such as breast implants and injectable collagen for soft tissue augmentation; and dental implants to replace teeth/root systems and bony tissue in the oral cavity.

1 Synthesis and characterization

Biomaterials used to date, as mentioned earlier, are metals, ceramics, polymers, composites, and biopolymers. The first four classes are conventional methods adapted from traditional materials processing. The biopolymers, on the other hand, involve materials synthesis and bioengineering. There are three basic approaches: DNA linked material building, tissue culture, and biopolymerization.

Recently, scientists developed a method to link DNA to gold, a noble metal\(^{[11]}\). There are biochemical approaches to molecular structures of precisely defined dimensions ranging from 1 nm to 10 cm in length. Conversely, the synthesis of precisely defined unnatural molecular architectures beyond 25 nm in length is often unattainable due to solubility, material throughput, and characterization constraints\(^{[12]}\). Therefore, as nanotechnological needs advance, syntheses could rely upon self-assembling strategies using natural scaffolds as templates for the construction of synthetic nanostructures\(^{[13]}\). Most studies involving DNA self-assembly have focused on the duplex interactions between complementary DNA strands, the insertion of synthetic units through covalent tethering to specific nucleotides involving the assembly of materials through electrostatic interactions on the phosphate groups along a DNA backbone\(^{[14]}\).

The goal of tissue culture is to develop a synthetic alternative to orthopedic tissues such as bone, ligament, and cartilage. Once implanted, the presence of cells and growth factors will initiate bone regeneration throughout the 3-D pore network. As regeneration continues, the matrix is slowly resorbed by the body. Upon complete degradation, the implant site is filled with newly regenerated bone and free of any residual polymer. Examples are given about tissue engineered bone (shown in Fig. 3), tissue engineered ligament (shown in Fig. 4), tissue engineered cartilage (shown in Fig. 5), and Cell Culture (shown in Fig. 6)\(^{[15]}\). In studies examining cell growth on these matrices, osteoblast cell lines have been utilized as...
well as bone cells isolated from rat calvaria to create model systems for cell growth on bio-
 erodable materials. This image shows osteoblasts growing on the surface of the 3-D microsphere matrix. It is interesting to note that the cells are growing in a circumferential pattern due to the structure of the matrix.

Biopolymerization has been used to generate intelligent and smart materials. Very often one can find them in sensing and electronic devices.

Fig. 5. Tissue engineered cartilage. Fig. 6. Cell culture.

Materials characterization methods are mechanical testing, chemical analysis, microstructural characterization, explant analysis, coatings evaluation, development of special test techniques and component design and analysis include structural analysis, reliability and probabilistic modeling, engineering design optimization, failure analysis. Characterization is particularly difficult when the materials are used for human body that needs in vivo test conditions.

An atomic force microscope (AFM) image is widely used in materials analysis at nanometer scale\textsuperscript{16, 17}. It is also used in biomaterial research. Fig. 7 is an AFM image, which shows the surface structure of a hydrated Staphlococcus epidermis biofilm formed on an implant surface\textsuperscript{18}. The channels observed are believed to provide nourishment that sustains the biomaterials-associated infection. Using an AFM, cortical bone is imaged at ultrahigh magnification (shown in Fig. 8)\textsuperscript{19}. Advanced in situ microscopy testing devices allow biomaterials and biological materials to be observed at high magnification with the AFM while being subjected to controlled levels of stress or deformation.

Scanning electrochemical microscopy (SEM) is used to characterize the reaction rate and ion release imaging modes of metallic biomaterials\textsuperscript{20}. The scanning potential microscope (SPM) can
also be used in measuring the micro-corrosion processes on metallic biomaterial surfaces. The SPM has imaged localized preferential corrosion areas on the samples. Localized corrosion potential is clearly associated with topographic features[21].

Confocal laser-scanning microscopy (CLSM) is a rapidly advancing technique used to produce crisp and precise images of thick specimens in fluorescent and reflective light modes by rejection of out-of-focus light via a confocal pinhole. This feature of confocal microscopes, known as optical sectioning, makes it possible to scan a sample at various x-y planes corresponding to different depths, and, by ordering these planes into a vertical stack, reconstruct a three-dimensional image of the specimen. Because it does not require physical sectioning of thick samples, and precludes the need for extensive specimen processing, CLSM is one of the most efficient methods available to gain three-dimensional information on living biological specimens and biomaterials.

Auger electron spectroscopy (AES) is then used to identify and quantify calcium and phosphate, the major inorganic components of bone. The deposited mass depends on the surface chemistry and a clear correlation between surface pretreatment and calcium/phosphate ratios is observed. This can in some cases also be correlated to macroscopic properties such as the surface wetability[22].

Materials Scientists continue to develop novel surface modifications to enhance textile performance. Wettability is one important characteristic of a surface. Wettability of textile fibers can be enhanced to assist the dyeing operation during processing; and the fibers can be made to be wettable for application in, for example, materials of tissue culture.

Wear test is a basic method to evaluate the durability of biomaterials. Pin-on-disc experiments are carried out on different material combinations using systematically varied tribological conditions (lubrication, loading, contact geometry, sliding speed). Novel candidate materials will be investigated, as well as current materials (UHMWPE) that have been modifies by different methods (e.g. plasma technology, microfabrication, and polymer processing). The chemical and
structural properties of the tested materials and wear products are characterized by spectroscopic and microscopic analysis techniques. Results from multi-axial joint simulator experiments, as well as analysis of components from retrieved clinical implants constitutes references for the in vitro simulation studies.

The material properties and the mechanical and electrochemical processes were observed to control the corrosion attack to the hip replacement. Some electrochemical tests methods list as following, Short term tests: the effect of cyclic load magnitude on fretting corrosion currents; Long term tests: rest tests, cyclic mechanical loading, scratch test, etc [7, 8, 9].

Artificial mechanical heart valves are made of pyrolytic carbon to prevent complications associated with blood clotting, but this material can be subject to cyclic fatigue. An acoustic emission-based system is developed for detecting crack initiation and the growth of existing flaws during controlled stress testing of artificial heart valves.

2 Tribological applications and failure

The properties of biomaterials to date still do not meet the application requirements. The part of many potential causes of failure for the total hip arthroplasty, for example, is deficiencies in design (size and shape) of the device for a particular patient (e.g., an undersized noncemented stem); surgical problems (e.g., problematic orientation or problems in wound healing); host abnormalities or diseases (e.g., osteopenia); infection; and material fracture, wear, and corrosion [11].

Synovial joints, including the knee joints, are typically found at the ends of long bones and permit a wide range of motion [24]. This type of joint is surrounded by a fibrous articular capsule, which is lined by a thin synovial membrane. It is important to note that the surfaces of each bone are not in direct contact, but are covered by special articular cartilages, which resemble the hyaline cartilages found elsewhere in the body.

The synthetic biomaterials, such as stainless steel, titanium alloy, polymers, and ceramic composite, undergo degradation through fatigue and corrosive wear due to load-bearing and the salty environment of the human body. At the same time, deposits of inorganic salts can scratch weight-bearing surfaces, making artificial joints stiff and awkward. The lifetime of an implant is, at most, 10 to 15 years.

Using the methods previously mentioned, the failure mechanisms reported are discussed with a few examples.

Fracture happens often in bone and orthopedic implants when load-bearing ability is important. Once fractured, biomaterials cannot be regenerated as nature bones. Therefore, structure and properties are particularly important here. It is also very important to induce lubricants to improve the biomaterial properties in the same time. The inducing of the lubricants could reduce the wear, which is one of the main problems that could lead to fracture of the materials. Some research works have been done in investigating the lubricant thin film’s failure [25, 26].

Wear of the articulating surfaces in artificial hip and knee joints gives rise production of wear
particles of sizes of submicrons and larger. The negative biological effects of these wear particles are considered to be one important factor that limits the long term clinical performance of this type of devices. There is therefore an immediate need for development of novel and improved material combinations for the articulating surfaces in artificial joints. Such development is in turn dependent on an improved understanding of the wear processes involved and how these are influenced by different material properties and conditions. Equally important is it to develop reliable and predictive methods for stimulating the wear processes under in vitro conditions, preferentially in an accelerated way.

In order to provide a basis for systematic development of novel material combinations and surfaces with improved wear properties and to develop reliable in vitro screening methods for assessing the wear of different candidate combinations, the wear research is done to obtain an increased understanding of the mechanisms underlying wear in artificial joint prostheses. The long term engineering goal is to develop a material (surface) combination which does not produce biologically harmful wear particles under the physiological conditions that prevail in artificial hip and knee joints.

A total hip replacement is clinically successful with most designs that utilize an ultrahigh molecular weight polyethylene (UHMWPE) acetabular surface articulating with either a metallic or ceramic femoral head component\cite{27}. However, aseptic loosening, often accompanied by osteolysis, continues to be a source of long-term clinical failure. It was suggested that the macrophage response to phagocytosis of particulate wear debris, occurring in interaction between the cement and bone, was an important causative factor in osteolysis, leading to eventual loosening\cite{28}. The particulate debris has emerged as a major factor in the long-term performance of joint replacement prostheses\cite{29}. When present in sufficient amounts, particulates generated by wear, fretting, or fragmentation induce formation of an inflammatory, foreign-body granulation tissue that has the ability to invade the bone-implant interface\cite{30-37}. This may result in progressive periprosthetic loss of bone, a loss that threatens the fixation of prostheses inserted with or without cement\cite{12, 38, 39}.

Studies of wear debris extracted from actual tissue samples of patients whose implants failed as a result of aseptic loosening have generated significant information regarding wear particle size, shape, and surface morphology. AFM was used to produce detailed, high resolution images of wear particles, few hundred nanometers in size. Wear debris studied sometimes exhibits a cauliflower-like surface morphology. By combining wear debris and cellular response studies, engineers and biologists will be able to better understand implant failure and to re-engineer implants to prevent future problems.

The wear problem that occurs with an artificial joint implant component (socket) constructed of UHMWPE is illustrated in Fig. 9. At left is unworn UHMWPE. The sample at right has undergone a friction and wear test versus cobalt chromium (artificial joint ball material). The fibrillation and small particles are characteristic of an adhesive wear mechanism, which can result in sur-
rounding bone loss and the need for implant replacement[1].

Corrosive attack in the taper crevice of modular implants made of similar metals or mixed-metals combinations[40-44]. The corrosive attack results in metal release and mechanical failure of the component[45]. Corrosive fatigue, on the other hand, is expected due to cyclic loading and the corrosive environment of human body. The fractures occurred at the grain boundaries of the microstructure and appeared to be the result of three factors: porosity at the grain boundaries; intergranular corrosive attack, initiated both at the head-ceck taper and at free surface; and cyclic fatigue-loading of stem[46].

3 Summary

Biomaterials are the future of the medicine. From tissue removal, replacement, to future regeneration, biomaterials will take part the most advancement in the near future. Biomaterials and implant research will continue to concentrate on serving the needs of medical device manufacturers and recipients, as well as medical professionals. Development of technologies will meet those needs by designing the materials in strength, shape, function, and behavior. Future biomaterials will incorporate biological factors (such as bone growth) directly into an implant’s surface to improve biocompatibility and bioactivity. New projects will be directed at materials development for improved mechanical integrity, corrosion resistance, and biocompatibility. The understanding of the nature of the human body parts like knee, jaw, dental parts, and hip, etc., will lead to the applying of these techniques in future materials design.

References

15. http://laurencin.coe.drexel.edu/