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Review Article

Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) as Desired Polymer Material for Biomedical

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ABSTRACT

It is very important that any materials used as implant material work in harmony with the body. There will be drawback with every material. No matter how good, as nothing can be 100% identical as the natural human tissue. The body operates in an environment at a constant temperature of 37°C and pH of 7.25, so choice of materials will have to withstand these conditions. Incorrect use of material can cause rejection by the body, infection and even cancer, leading to more pain and discomfort by the patient. In turn the possibility of even further damage to the joint. The implant must work in the same way as the body part it is replacing- clear understanding of how the joint works is needed. Ultrahigh molecular weight polyethylene is considered as the standard material for Artificial joints to decrease the total weight and the wear rate to make it more flexible. This is what makes Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) such an appropriate polymer. It is very widely used in total hip and knee joint replacements having the highest known impact strength of any thermoplastic presently made, can highly withstand abrasion, and has a very low coefficient of friction. Therefore, these properties, connected with extremely low moisture absorption, make UHMWPE especial material for the medical industry due to good industrial impact and wear resistance sliding applications. For moving joints, the friction would be damaging without the natural lubrication. In implant components this does not exist, however UHMWPE is self-lubricating, making it ideal for component such as an acetabular cup, which would wrap around a metallic femoral head in a hip joint. Also, UHMWPE has high impact strength, high toughness, and low elastic modulus, but it has disadvantages such as low tensile, transverse and compressive strengths with high creep rate. This review article deals with the history of UHMWPE, its material properties that make it an ideal candidate for total joints, implant-component fabrication procedures and provides insights as to why some of the implants eventually fail.

Keywords: UHMWPE, Artificial Joints, Material, Femoral Head, Fabrication.

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INTRODUCTION

Ultra-high molecular weight polyethylene (UHMWPE) has become the gold standard to fabricate one of the articulating surfaces of total hip, total knee and total shoulder prostheses. More than a million total hip replacements are performed every year and is a multi-billion-dollar industry. In-spite-of the overwhelming success of this medical procedure, aseptic loosening as a result of wear limits its longevity to 15-20 years [1, 2].

The advent of UHMWPE as a material to manufacture parts of artificial TJR's started approximately in the year 1962, when Sir John Charnley implanted the first hip prosthesis. Since then, it has been the material of choice for the fabrication of one of the articulating surfaces of total joints. Despite the overwhelming success of this restorative procedure, wear of the components and resulting aseptic loosening remains the preemptive problem that limits the lifespan of these implants from 15-20 years [3].

Many orthopedic joints are used in the human joint to give it more flexibility during movement, and to reduce pain, and restore the quality-of-life increase mobility. Such as hip, shoulder, knee, and fingers (Figures 1). Prostheses are usually composed of two main components articulating with one another, usually a component of polymer against a metal or ceramic, the damages in the human body joints caused by different reasons such as advancing age, diseases and calcium deficiency [2]. A typical hip implant consists of a long metallic stem and a metallic head (usually Co-Cr) articulating against a UHMWPE polymeric component [2,4].

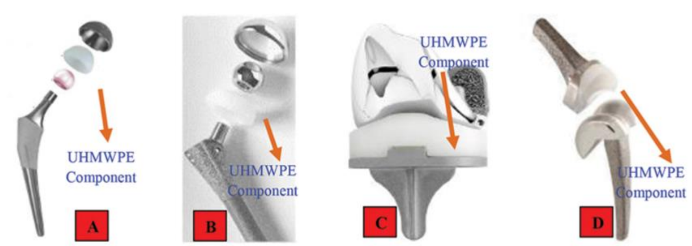

Figure 1. Artificial joint prosthesis system components fabricated from UHMWPE comprises the articulating surface for (A) hip, (B) shoulder, (C) knee, and (D) finger bearing joints [2].

Some Typical Metallic Alloys Used for Artificial Joints

There are five metallic alloys used for artificial joints cast cobalt chromium-molybdenum alloy, wrought cobalt-chromium-tungsten-nickel alloy, pure titanium and titanium-6Al-4V alloy, and stainless steel, 316 L [5].

Stainless Steels

Produced by casting and then hot / cold forged worked to strengthen the alloy from using sufficient chromium to provide corrosion resistance, balanced by adding sufficient austenite stabilizer, e.g., Nickel, to allow austenite to be retained at room temperature [6].

Prosperity of stainless steels contains; poor long term corrosion resistance, susceptible to crevice corrosion, geometry and design problems, high young's modulus, stress shielding, some patients allergic to nickel and chromium, good strength and fatigue resistance, and cheap and easy to fabricate [3].

Sensitization of stainless steels can be caused by precipitation of both carbides (Cr23C6) and nitrides (Cr2N), solubility of carbon and nitrogen decreases with temperature, austenitic steels are sensitized by slow cooling through or heating within 450 to 850°C range, sensitization leads to corrosive attack at grain boundaries, precipitation of carbides and nitrides causes denudation of chromium in solution either side of grain boundary, and preferential corrosion attack occurs at denuded zone. Moreover, decreasing sensitization can be due to; 1) Extra low carbon contents, 316L grade; 2) Solution treatment: quench from 1050°C, not successful in ferritic grades; and 3) Stabilize by adding titanium or niobium, to form TiC or NbC instead of Cr23 C61 or Cr2N.

Co- Based alloys

These materials are usually referred to as cobalt-chromium Mo alloys. There are two main types; Co Ni Cr Mo alloy and the Co Cr Mo alloy, first one normally is a cast product, and now used for making the stems of prostheses joints for both hip and knee joints. But the other one is wrought and produced by hot forging. It has been med for many years in dentistry but recently used also as artificial joints.

Types and Compositions of Co-Based Alloys

There are four types of Co-based alloys for surgical implant applications, cast Co Cr Mo alloy (F76), wrought Co Cr W Ni alloy (F90), wrought Co Ni Cr

Mo alloy (F562), and wrought Co Ni Cr Mo W Fe alloy (F563). The chemical compositions of the first three types are summarized in Table 1 below. But recently only two alloys are used extensively in implant fabrications, the castable Co Cr Mo and the wrought Co Ni Cr Mo alloy. As can be seen in Table 1, the compositions of the alloys are quite different [5,6].

Properties of Co-Based Alloys

The two basic elements of the Co-based alloys form a solid solution of up to 65 wt % Co and the remainder is Cr. The molybdenum is added to produce finer grains, which results in higher strengths after casting or forging.

Table 1: Chemical compositions of Co- Based Alloy [6]

Element	Co Cr Mo (F75)		Co Cr W Ni (F90)		Co Ni Cr Mo (F562)	
	Min	Max	Min	max	Min	max
Cr	27.0	30.0	19.0	21.0	19.0	21.0
Mo	5.0	7.0	----	-----	9.0	10.5
Ni	----	2.5	9.0	11.0	33.0	37.0
Fe	----	0.75	----	3.0	----	1.0
C	----	0.35	0.05	0.15	----	0.025
Si	----	1.00	----	1.00	----	0.15
M n	----	1.00	----	2.00	----	0.15
W	----	----	14.0	16.0	----	----
P	----	----	-----	----	----	0.015
S	----	----	----	----	----	0.010
Ti	----	----	----	----	----	1.0
co	----	----	Balance	----	----	

Femoral head design to reduce friction and wear

A metal or ceramic socket will be thinner than a plastic one, which means that a larger ball can be used. The advantage of this is that a larger ball gives a greater range of movement and reduces the risk of the ball coming out of the socket (dislocation), so the patient can take part in more vigorous sport or exercise. The harder materials also allow better lubrication of the joint which means that the components will wear more slowly.

It has been found that a remarkable reduction in the wear of joints can be achieved by simply increasing the diameter of the joint. In the lubrication study of a tribological evaluation of joints of 16, 22.225, 28 and 36 mm diameter was conducted in 25 per cent bovine serum using a hip joint simulator. The joints were subjected to dynamic motion loading cycles simulating walking for both lubrication and wear studies, for each of the joint in the lubrication study, the wear was measured. Joints of 16 and 22.225 mm diameter showed no surface separation, this suggested that wear would be proportional to the sliding distance and hence these joint sizes were in the boundary lubrication regime.

A 28 mm diameter joint showed only limited evidence of surface separation suggesting that these joints were operating in a mixed lubrication regime. The mean steady state wear rate of the 36 mm diameter joints was lower than those of all the other diameters. For a range of joints of various diameters, subjected to identical test conditions, mean wear rates differed by almost two orders of magnitude [7-10].

Overview on Ultra high molecular weight polyethylene (UHMWPE)

UHMWPE is a polymer of ethylene, its molecular formula is $(C_2H_4)_n$ and its molecular chain may contain as-many-as 400,000 carbon units. The molecular weight (MW) of Ultra high molecular weight polyethylene is the MW of ethylene multiplied by the number of ethylene groups [$(CH_2{=}CH_2 \rightarrow -(CH_2\text{-}CH_2)_n$] and may be between two and six million g/per mole. Figure 2 shows the structure of UHMWPE.

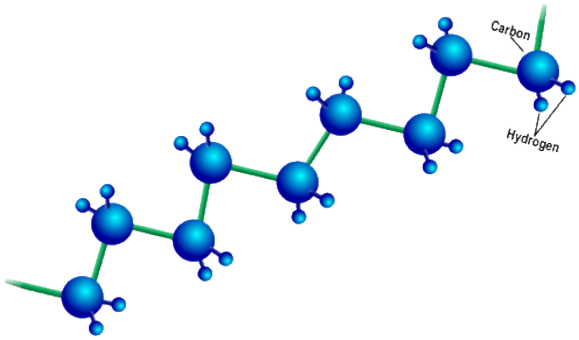

Figure 2. Chemical structure of UHMWPE [11]

Mechanical and Physical Properties of UHMWPE

UHMWPE had properties make it the preferred plastic for a variety of uses and applications, in particular medical applications. It is used in some circumstances as an improvement on the qualities that you will find in High Density Polyethylene.
UHMWPE has a higher molecular weight than its counterpart HDPE. CNC machines have an easier time machining with PE material that features a higher molecular weight. With all things considered, Ultra High Molecular Weight Polyethlyene is more durable, and usually, more chemically resistant than HDPE.
UHMWPE can be fabricated as sheets, rods, and tubes and different specifications that application requires [12]. Table 2 shows some mechanical and physical properties of UHMWPE (Fig. 3) [1]

Table 2. Some mechanical and physical properties of UHMWPE [1]

Property	Units	UHMWPE
Molecular Weight	(Million g/mole)	2.0 - 6.0
Melting Point	(° C)	125-135
Density	(g/cc)	0.926-0.945
Tensile Yield	(MPa)	19.3-23.0
Elongation at Break	(%)	200-350
Tensile Modulus	(G Pa)	0.8-1.5
Izod Impact	(J/m)	>1070 - No Break
Shore D-Hardness	——	60-65
Poisson's ratio	——	0.46
Degree of crystallinity (%)	——	39–75
Wear Rate	(mm3/106 cycles)	80–100
Poisson's ratio	——	0.46
Wear Rate	(mm3/106 cycles)	80–100

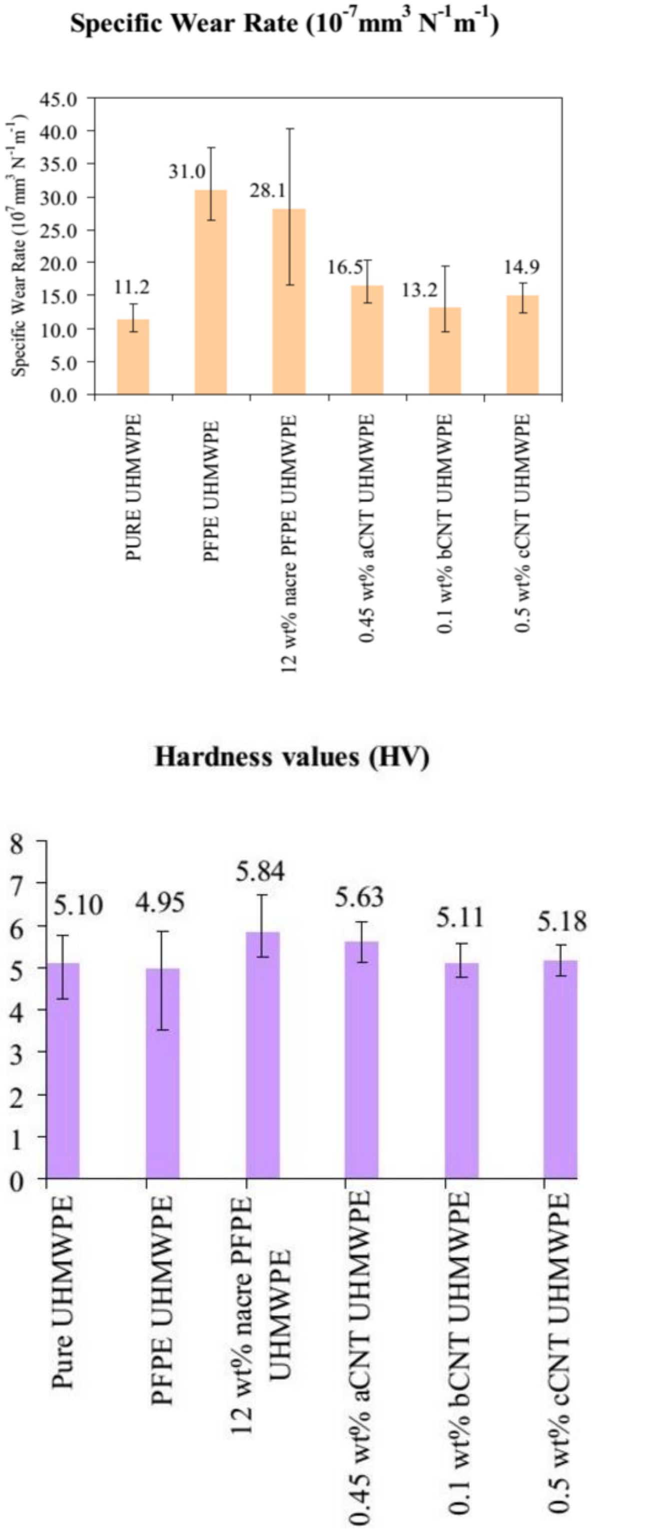

Figure 3. The hardness values for different UHMWPE composites and Wear rate for different UHMWPE composites [13].

Manufacturing of UHMWPE

The rheological properties of the UHMWPE are such that precise, complex shapes cannot be molded; items must be machined from blocks of polymer using techniques similar to those which would be applied to metals. The polymer processing is therefore the method whereby large blocks of solid polymer are produced.

If a large volume of molten polymer is allowed to cool and solidify, then the outer surfaces will cool first and solidify first. The polymer reduces in volume as it solidifies. Therefore, the inner core of melting polymer will be restrained from contracting as it freezes by the solid outer layers, and voids will form. To produce blocks of polymer which are free of voids, it is necessary to apply pressure during solidification.

UHMWPE is usually produced by Ziegler process involving ethylene, hydrogen and Ti-tetra chloride and is conducted at pressures between four and six bar at a temp of 66-80 ºC. This results in a thin white powder.

The molecular chain of UHMWPE can be visualized as an intertwined mass of spaghetti, which at temperature is lower than the melting temperature, the chain rotates and folds to form the crystalline region, but at higher temperature becomes mobile. By using SEM and TEM the crystalline and amorphous entities of UHMWPE can be visualized. At about 90-100ºC UHMWPE is beyond its glass transition temperature, then the amorphous regions become mobile and the crystalline regions begins to melt. The melting point of UHMWPE is about 134ºC. Virgin UHMWPE consists of spheroidal structures from 0.3μm to 2μm joined to each other by fibrils, as shown in Figure 4.

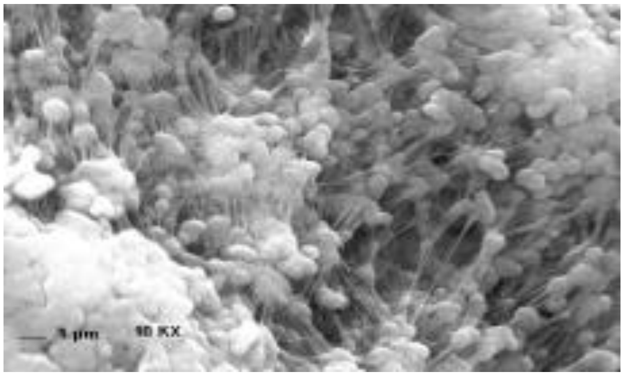

Figure 4. few tens thin of nanometers of UHMWPE [14].

To be used for medical purposes, the resin powder must meet the requirements as specified in ASTM standard F648 and ISO standard 5834-1 [14]. UHMWPE is initially produced as very fine a powder, as shown in Figure 4.

The powder is consolidated under high pressure and temperature into a single, solid piece of material, fusing the powder and includes optimization of pressure, temperature and time. One of the following methods to consolidate the powder is used: compression molding, ram extrusion, hot isostatic pressing, and direct compression molding.

Compression Molding

The powder is molded into large sheets, this includes: 1) Introduction of powder into mold cavity; 2) Heating of the cavity; 3) Compression of the plate, and 4) The sheets are sectioned and turned on a lathe.

Ram Extrusion

The UHMWPE powder is introduced into a heated cylindrical bar stock ranging from two to six inches barrel by a ram and as the ram retracts, the chamber is refilled with UHMWPE powder. Due to the heat and pressure the powder is consolidated into a continuous bar. This method usually includes the addition of Ca-stearate to the raw powder.

Direct Molding of the Implant

The powder is placed in a mold which is heated and compressed. The consolidated UHMWPE are further machined into the final implant component [14]. Commercial, medical grade UHMWPE is produced by two methods - compression molding or ram extrusion. In compression molding, heat and pressure are applied to polymer granules so that a molten polymer is formed, and the pressure is continually applied as the polymer is allowed to cool and solidify.

The advantages of UHMWPE

Biocompatibility HDPE. The toughness is proportional to the molecular mass and as such UHMWPE is tougher than HDPE. UHMWPE is presently used in total joint arthroplasty (TJA) only, of the many polyethylenes [14].

Dimensions

This is critical for example a femoral head cannot be made bigger than an acetabular cup. Surgery of the implant into the body must be made relatively easy-packaging of the implant is very important, with all types of surgery there is a big risk of infection. Also, the surface finish of the material must not be damaged during surgery, so implants should be designed to enable installation with minimal operating time, and for reducing damage to the surrounding area. A booklet of concise instructions must also be provided. If anything goes wrong the manufacturer will be responsible which is why so much care has to be taken when presenting the final product [2, 14-16].

Elastic Modulus

The balance needs to be correct; fractures can occur if the material is too flexible and surrounding tissue can be damaged if the material is too stiff. Ideally the elastic modulus of the implant should be the same as the bone needing replacement [2].

Resistance to fracture

The significant reasons for the failure of artificial joints are friction and / or wear. A high-quality

material combination for joint replacement should have small friction and wear. The friction is able to be divided into a start up friction and stable state friction. On the other hand, start up friction is more significant than the other because it is higher than the stable state friction also results in higher wear rate.
Most artificial joints are composed of UHMWPE (cup) due to good biocompatibility, good resistance to wear and stability in contact with a Co–Cr–Mo femoral head. However, as UHMWPE wears away in the body, wear debris may accumulate and cause biological response such as rsorption of bone and loosening of the implant. To decrease the influence of wear debris, therefore alumina has been used for hip replacement as the alternate for UMHWPE [3,10].
Wear rate is often substantial also the wear debris cause harmful tissue reactions that may cause osteolysis and destruction of bone around the implant which cause loosening of the component fixation. Therefore, the role of the lubricant is naturally crucial, but there is no practical and reliable lubricant available [2].

- The polyethylene (PE) does not transfer to the metallic surface.
- The wear particles should be microscopic - 1 mm in size.
- The surface finish of polyethylene is important.
- The wear should be of the order of 10-6 mm^3/ N. m.

The common lubrication was apparently of boundary or mixed type; if there is full fluid film polyethylene will not transfer. Totally separating of the surfaces, thus the number of particles did not correlate with the roughness of the counterface. This observation contradicts the general belief that heavy PE transfer always leads to high polyethylene wear. it appears that, a boundary lubricant is not capable to prevent the PE transfer can still refuse the actual wear of the PE component by lubricating the contact of polyethylene against itself, therefore polyethylene slides against a Co-Cr-Mo counterface with scattered protruding blocks of PE strongly adhering to the Co-Cr-Mo surface [14-18].

Radial clearance and spherecity

Spherecity rather than point contact reduce stress, and smaller radial clearance increases lubricant film thickness and helps establish full fluid lubricant.

Surface finish

Good surface finish improves lubrication and reduces abrasive wear of UHMWPE cup. Surface hardness, with high general hardness will provide more resistant to scratching and abrasive damage to UHMWPE cup.

Failure of artificial joints

The life limit of an implant is when movement becomes so painful that the quality of life of the patient is badly affected. It is essential that the root cause of mechanical failure in implants is properly understood. One of the major factors contributing to the failure of total joint replacements is the damage of articulating UHMWPE surfaces. Such damage not only affects implant performance, but more importantly results in release of particulate debris to the surrounding tissues and fluids. Damage can be also attributed to fatigue fractures of the metal components and adhesive wear of UHMWPE components. The main factors of failure are Friction, wear and lubrication of artificial joints, Mechanical damage, Cracks, Scratches, Plastic flow and Flaking.

Friction, wear and lubrication of artificial joints

Friction, wear and lubrication of artificial joints play important roles in its successful function. Research efforts are currently addressing the evaluation of the determinants affecting the overall wear rate of the artificial joint articulating surfaces, with the aim of reducing wear rate. The average diameter of the wear debris from joint simulator is 7.54 μm. The average diameter of the wear debris from artificial joint is 1.33 μm.
Wear is recognized as the main reason of implant failure, which can lead to implant loosening. The

fundamental wear mechanisms in artificial joint are adhesion, abrasion, creep and fatigue. However, pitting, scratching, burnishing and delamination on retrieved total condylar knee joint replacements are also detected. A technique for the classification and quantification of damage in retrieved total knee prostheses is presented and applied to the examination of 48 removed total condylar-type knee replacements. The technique involves inspection of all metallic and polyethylene components for evidence of gross deformation, fracture, and damage to articulating surfaces. Wear depends on many factors so it can be rather hard to predict which mechanism will affect the sliding bodies. For the 48 total condylar-type prostheses, significant positive correlations were found for the surface damage correlated with the patient's weight and the time the prosthesis was implanted [18,19].

In general, lubrication refers to the existence of a lubricant between two surfaces in contact to avoid or reduce the interaction between their asperities. In healthy natural joints, synovial fluid is generally present as a lubricant [18,20].

Cooper [21] studied the wear of UHMWPE sliding on metallic and ceramic counter faces under wide range of tribological conditions in order to investigate the influence of contact stresses on the macroscopic and microscopic wear mechanisms. In the body under cyclic loading, the macroscopic polymer asperity is cyclically deformed at the frequency of the loading cycle and this can produce crack propagation and surface fatigue within 10 µm of the surface under the polymer asperity. That main the cyclic loading is one of the main factors affecting failure of artificial joints. In addition, subsurface cracking was found in the highly strained region, which may cause the failure and removal of material from the highly strained polymer peaks, hence greatly increasing the macroscopic polymer asperity wear processes, these may also produce large wear particles which can cause adverse tissue reactions in the body [19,21].

In general, lubrication refers to the existence of a lubricant between two surfaces in contact to avoid or reduce the interaction between their asperities. In healthy natural joints, synovial fluid is generally present as a lubricant. After joint replacements, a pseudo-periprosthetic synovial fluid is found to be similar to those from patients with osteoarthritis [22,29].

The lubrication regime can be assessed either experimentally or theoretically. The theoretical assessment is based on the determination of the parameter λ defined as the ratio between the minimum film thickness hmin and the composite roughness of the two surfaces;

$$\lambda = \frac{h_{min}}{R_a} = \frac{h_{min}}{[(R_{a-head})^2 + (R_{a-cup})^2]1/2}$$

Where Ra is average roughness, the lambda ratio and the corresponding lubrication regimes can be determined accordingly;

- Boundary lubrication: $\lambda < 1$
- Mixed lubrication: $1 < \lambda < 3$
- Fluid film lubrication: $\lambda > 3$

In joint bearing types, metal on polymer is considered to be boundary lubricated as the relatively soft polymer surface has a high roughness.

Mechanical damage

Mechanical damage is resulted from an acetabular cup not properly aligned in vivo. This damage can also occur after severe wear, when the neck of the femoral component makes contact with the acetabular part. It usually results in pieces of polymer or cement being ripped from the edge of the cup. The pieces of material removed, therefore, will cause relatively large floating particles and possible loosening of the cup due to impact loading.

Scratches, Cracks and Plastic flow

Polymer wear surface appeared relatively smooth and shiny, indicating that the surface had been burnished or lapped. At the end of wear tests, measuring of surface roughness (Ra) of polymer surfaces were found in order of 0.2- 0.3 μm while roughness of the steel counterface were about 1.3-1.5 μm.

Surface and subsurface cracks are usually expected in the high stress areas or on the rim of the cup due to localized stress. Stress cycling and plastic strain accumulate and many surface, and subsurface, cracks are ultimately initiated. With further cycling, these cracks create one crack large enough to break from the bulk causing pitting and spalling. Figure 5 shows cracks that caused break to the UHMWPE hip joint artificial joint.

Optical examination of acetabular cups showed areas of plastic flow. The affected area normally occurs just outside the region of high contact stress. If the compressive stress on the bearing surface in the cup exceeded the maximum stress limits of the material, it will result in outward flow and/or creep [2, 30-34].

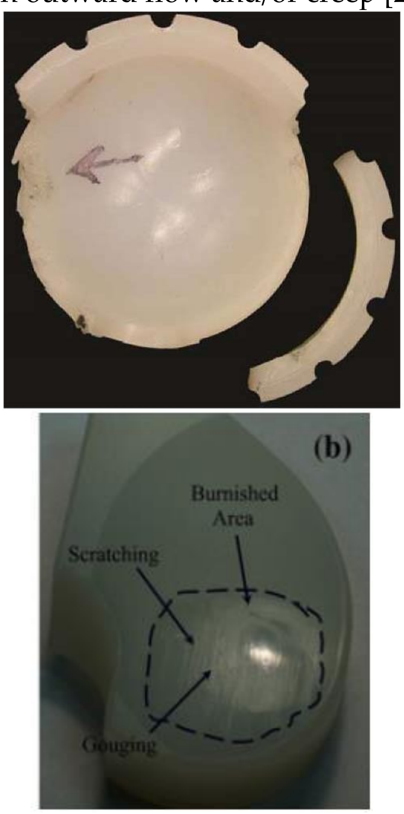

Figure 5. UHMWPE total hip replacement bearings that fractured in patients under ordinary service conditions [23], and (b) Some fine scratching in the direction of sliding [2].

Decreasing wear in UHMWPE

- Use of alternative sterilization methods to avoid chain scission and oxidation.
- Develop cross linking between tie chains to restrict / prevent chain alignment and chain splitting under shear.
- Promote unidirectional motion of bearing surfaces.
- Gama irradiation causes cross linking and can improve wear resistance but also reduces toughness and may increase third body abrasive wear.
- Irradiate under nitrogen, followed by removal of free radicals. Store under nitrogen or in vacuum packs.
- Femoral head design: By using smaller head the contact pressure with acetabular cup will increases, therefore linear wear rate increase, and the cup will suffer more creep deformation, but the small head reduces range of mobility.

CONCLUSIONS

UHMWPE has been a popular bearing material because it has a low coefficient of friction, wears relatively little over the long period, and is relatively inert in the body. While it has been placed in knee and hip joints since the 1960s, it has also been used in shoulder, elbow, wrist, ankle, and great toe replacements, and current techniques are also finding use for UHMWPE in the spine.

Highly cross-linked UHMWPE has recently become the alternative bearing material of choice in hip replacements, because it is relatively inexpensive and has biocompatible properties. It is an economical material alternative and offers design flexibility, including smaller sizes. Highly cross-linked–grade formulations are also good candidates for the creation of longer-wearing and safer joints than conventional UHMWPE for joint replacement. The most common metallic alloys used for artificial head joints are cast cobalt chromium-molybdenum alloy, or wrought cobalt-chromium-tungsten-nickel alloy. Issues like surface finish, radial clearance, head and cup size, sphericity, tolerances are important factors to consider for reducing wear in UHMWPE. Mechanical damage, scratches, cracks, plastic flow, wear and flaking are the common factors of failure in artificial joints.

Wear debris can cause adverse tissue reactions and the loosening of the prosthetic components. It is important to reduce the contact stresses in order to avoid failure of artificial joints, particularly for thin polymer cups. Effective lubrication, in terms of both boundary and fluid- film lubrication, is the key to reducing friction and wear in artificial joints.

Disclaimer

The article has not been previously presented or published and is not part of a thesis project.

Conflict of Interest

There are no financial, personal, or professional conflicts of interest to declare.

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