Wear tests in a multidirectional bio-tribometer of UHMWPE on CoCrMo and Ti_6Al_4V

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Abstract

This bachelor thesis presents a relative new method for testing wear of ultra high molecular weight polyethylene used for joint replacements. The method proposed by Ducom fills the gap between pin-on-disk (PoD) and hip-joint simulator testing in the sense that the testing conditions are physiologically more realistic than PoD but the focus is on material testing instead of testing a conventional hip-joint prostheses. Four situations have been simulated to test the wear performance of a UHMWPE Pin. Linear sliding, with a frequency of 0.54 Hz and 5 mm stroke length, of at 1 Hz rotating polymer pins on two different counterpart materials, a CoCrMo disk and a Ti_6Al_4V disk, has been simulated where each material combination was subjected to a fixed load of 225 N and a dynamic walking gait cycle load with a maximum of 400 N. The test had been running for a total of around 1250000 sliding cycles.

Wear rates of 9.23 ± 1.69, 7.42 ± 0.68, 6.22 ± 0.55, 7.11 ± 0.69 mm^3 per million cycles were found for UHMWPE on CoCrMO with a fixed load, Ti_6Al_4V with a fixed load, CoCrMo with a dynamic load and Ti_6Al_4V with a dynamic load respectively. These experimental wear rates can be supported with the aid of measured surface roughness of the disks, friction forces of each material and load combination, and optical and scanning electron microscopy images for wear analysis.

Contents

1 Introduction

The number of hip-joint replacements is increasing and also the age of the patients getting an hip-joint replacement is getting lower, so there is a need to produce artificial hip-joints that last longer than the current life-time of 15 years in order to avoid revision surgery. The hip-joints replacements, and also other artificial joints such as for the knee, are commonly made out of an UHMWPE (ultra high molecular weight polyethylene) head, because of its excelent mechanical properties in the body. As a counterpart a metal cup, usually a cobalt-chrome alloy or a titanium alloy, is used. Together they form an artificial hip-joint. These kinds of joints are also referred to as soft(UHMWPE)-on-hard(metal) joint replacements.

During normal life activities such as walking the joint replacement is subjected to all kinds of stresses, where shear stress caused by sliding of the head over the cup is the most critical one. Due to this shear stress, wear of UHMWPE is generated by different types of wear mechanisms, which consists of microscopically pieces of wear debris. This material loss of the joint replacement does not degrade the functionality of it, nevertheless it is fatal for the implant. These wear debris are triggers for bone resorption cells around the prostheses and so causes aseptic loosening of the joint replacement attached to the bone, which eventually leads to a need for revision surgery [1]. There is also a risk of infection or tumor growth due to the wear debris particles. So the need for low wear materials in hip arthroplasty is there in order to reduce wear and postpone aseptic loosening of the implants and so increase the life time of the joint replacements.

Currently there are two basic test methods for testing wear of hip joint replacement materials, the pin-on-disk instrument and the hip joint simulator. Certain international standards exists that describe laboratory methods for the evaluation of wear properties of combinations of materials used as bearing surfaces of human total joint prostheses and methods of assessment of wear of the acetabular component of total hip-joint prostheses using gravimetric techniques [2] [3]. The test method is used for pin-on-disk machines, or simular instruments. It uses a fixed load of 225 N, corresponding to a contact stress of 3.54 MPa. However daily activities, such as walking or stair climbing, will result in loads and contact pressures in a hip prostheses that are not constant during a walking gait cycle [4].

The goal of this research is setting up a bio-tribological system that is able to simulate realistic physiological conditions as motion and forces to obtain wear rates similar to the clinical wear rate. The aim of the research is to investigate the difference in wear behaviour of a pin-on-disk test between a fixed contact pressure and a dynamic walking gait cycle contact pressure for two different material combinations, UHMWPE on CoCrMo and UHMWPE on Ti_6Al_4V. The analysis of wear will be done by several quantities, (i) volume loss of UHMWPE pin, (ii) coefficient of friction of each system for the pin sliding over the disk, and (iii) surface roughness analysis of the metal disk, each after around 140000 sliding cycles. Additionally, optical microscopy and electron scanning microscopy is performed on the test specimen in order to support and explain the obtained wear data visually.

The outline of this thesis is as follows. First some background information will be given concerning hip joint replacements, tribology, and aseptic loosening of implants. Then the experimental setup is explained, including the testing instrument, procedure, and post analysis. Then the results will be displayed followed by an conclusion including scanning electron microscope images to support the obtained data in the results. Finally there is a discussion with future research possibilities.

2 Background

In this section some basic information is given to give the reader some insight in the history of hip joint replacements, some properties of ultra high molecular weight polyethylene, tribology aspects and the osteolysis problem encountered hip joint replacements.

2.1 Hip joint Replacement

Total hip arthroplasty (THA) reported to performed already in the late 19th century. These first joint replacements were made out of ivory and some decades later they used glass. Around 1950 the first metal-on-metal hip implant, made of cobalt-chrome, was used as an hip joint replacement. However the lifetime of these prosthesis were good, they produced toxic metal particles in the body. It was around 1960 when Sir John Charnley introduced the use of polyethylene, in combination with metal, in total hip arthroplasty giving rise to so called the low friction arthroplasty[5]. Since then, polyethylene, or more precise ultra high molecular weight polyethylene (UHMWPE) is a basic ingredient in hip prostheses.

The most widely used kind nowadays are the metal-on-polyethylene (MoPE) bearing prostheses. Metal-on-Metal (MoM) bearings are also still used, especially for younger patients because of the low wear performence. A preference for younger patients is also the ceramic-on-ceramic (CoC) prostheses.

2.1.1 UHMWPE

As its name suggests, UHMWPE is a polymer consisting of a very large amount of ethylene (C_2H) monomers. This number can exceed over 400000, giving the polymer a molecular weight up to millions g/mol and creating very long chains of polymer molecules. These chains can allign in various ways, which can be roughly divided into two structures: crystalline lamella and amorphous regions. These crystalline lamella are visible under a transmission electron microscopy.

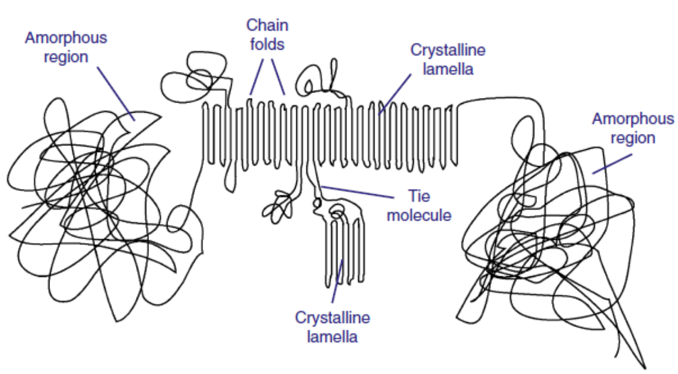


Figure 1: Allignment of UHMWPE polymers

Wear of UHMWPE appeared to occur mostly through the break-up of fibrils formed by large-strain plastic deformation and orientation of the surface. The orientation of these fibrils is important since orientation increases the strength of the fibrils in the direction of the motion and weakens them in the transverse direction. When producing UHMWPE, its properties can be altered by some treatments. One of those treatments is crosslinking by ionizing radiation. When the polymer is subjected to ionizing radiation, the C-H bonds can break, and create so called free radicals, and new C-C bonds can be formed between two different polymers molecules. With this method the free radicals caused by the radiation do not all form new bonds, and can cause some sort of oxidation which reduces the strength of the material. To counter this anti-oxidants can be added. An often used anti-oxidant is Vitamin E.

2.2 Tribology

The study of material surfaces in relative motion, and especially the wear, friction and lubrication phenomena, is called tribology. Tribology is known as a broad study combining a number of basic engineering subjects from material science, solid mechanics, fluid mechanics, lubricant chemistry etc. The main concepts of tribology that can be analyzed and characterized at the interface of surfaces in motion are surface characterization, friction, wear and lubrication. All these properties depend on the system as a whole instead of the type of material.

The term bio-tribology is referred to as the study of all aspects of tribology occurring in and related to biological systems, such as a hip joint or a knee joint. The most important and crucial aspect of bio-tribology in a hip-joint replacement is wear, but also friction and lubrication are important aspects. These three concepts will be discussed in this section, starting with the surface characterization in order to support them, since they are all present in the millions cycle lifetime of a hip-joint replacement and so it is important to understand these tribology concepts.

First the surface characterization of materials will be discussed with the main emphasis on surface roughness, second some basic theory of friction will be given, then the lubrication will be discussed including the different regimes of lubrication and last wear will be discussed including all kinds of different types of wear.

2.2.1 Surface Characterization

No solid material surface is completely flat but they are all rough on the microscopic scale. A material surface is complex and depends on composition, manufacture process and of course the interaction with other surface, either fluids or solids. The surface texture or topography is characterized by lay, waviness and roughness, where lay is due to the production process, roughness is on the micrometer-nanometer scale and waviness is on the millimeter scale. Asperities are referred to as peaks in a profile (two dimensions) and summits in a surface map (three dimensions).

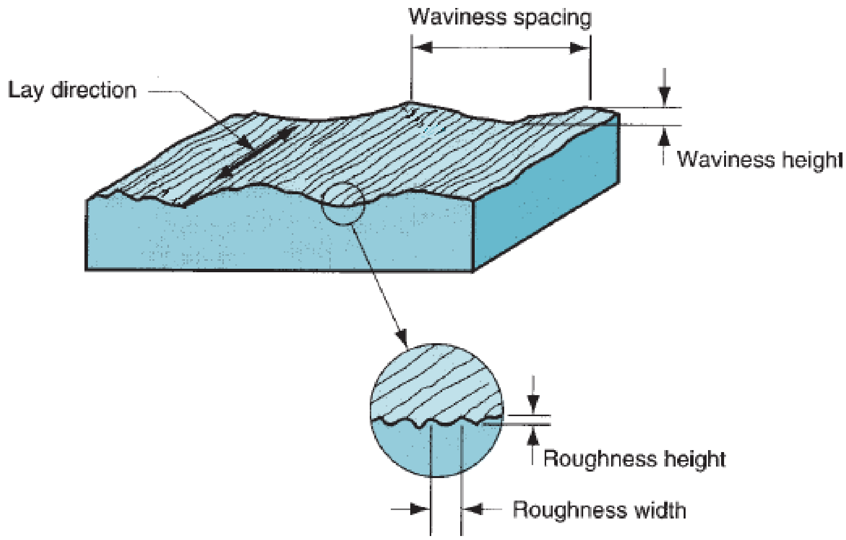


Figure 2: Caption

The most important component of surface texture in tribology is surface roughness, or just roughness. The roughness can be seen as the variations in the height profile with respect to a certain reference frame and can be quantified by different parameters. The most common parameter is the arithmetic average $\mathrm{R_a}$, defined as

$$R_a = \frac{1}{L}\int_0^L |y(x)|dx, \tag{1}$$

where L is the length of the profile being analyzed and y(x) is the height profile. From this equation it is clear that a higher $\mathrm{R_a}$ corresponds to a rougher surface. When two rough surfaces are in contact, only the asperities of the surface will touch and we speak of a real contact area. A smaller real area of contact results in a lower degree of interaction, leading generally to lower wear. The problem of relating friction and wear to the surface texture and material properties generally involves the determination of the real area of contact. Therefore, understanding of friction and wear requires understanding of the mechanics of contact of solid bodies.

2.2.2 Friction

Friction is known as the resistance to relative motion of two surfaces sliding against each other. The direction of the friction force is opposite to the motion and tangential to to normal of the two surfaces in contact. Friction generally converts kintetic energy into thermal energy at the surface contact interface. Friction is not a property of a material but it depends on various parameters of a certain system, such as load and lubrication.

There are two basic rules concerning friction. First is the well known law that the friction force is proportional to the applied load

$$F_f = \mu_f W, \tag{2}$$

where W is the applied load and μ_f is a proportionality constant known as the coefficient of friction (CoF). It is clear that a higher coefficient of friction means a higher friction force. The second basic rule is that the friction force is independent of contact area of the two surfaces in contact.

2.2.3 Lubrication

The most general factor to decrease friction is to lubricate the system. Lubrication affects the way asperities touch and interact. There are several different types, or regimes, of lubrication: Fluid (full) film lubrication, Mixed Elastohydrodynamic lubrication and Boundary lubrication. The type of lubrication of a certain tribological system with two surfaces in contact depends on the applied load, the viscosity of the lubricant and the sliding speed of the two surfaces. Figure 3 shows the different regimes along as a graph of friction coefficient vs. sliding speed × viscosity divided by the applied load.

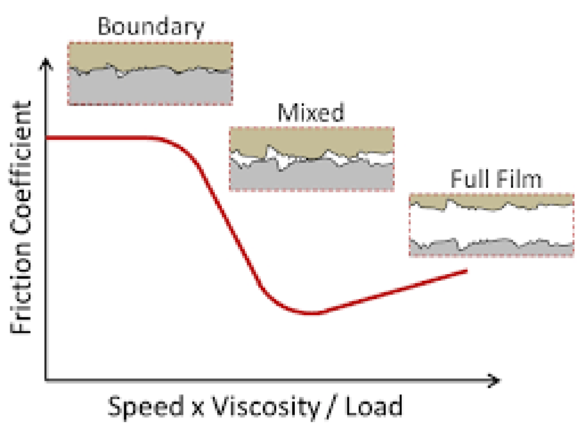


Figure 3: Lubrication regimes

2.2.4 Wear

Adhesive Wear. The transfer of material from one surface to the other during sliding described as adhesive wear. Upon further sliding the transferred material may come of the surface and transfer back to the its original surface and eventually leading to loose wear particles. These loose wear particles may be formed by chemical changes in the transferred fragments lowering its adhesive strength or due to residual elastic energy of the adherent fragments due to residual elastic stresses resulting after stressed heavily by loading. In the case of UHMWPE in joint metal on polyethylene joint prostheses, microscopically pieces of polyethylene sticks to the metal surfaces and debris gets pulled off under further sliding. There are several well known proposed mechanisms for the detachment of a fragment of a material. A quantitative expression in the form of Archard's equation can be deduced to determine the volume of wear. [6]

Consider two surfaces in a sliding contact under applied load W and assume that during an asperity interaction the asperities undergo plastic deformation under the applied load and that at each contact cycle there is a definite probability that a wear particle will be produced. Another assumption to make is that the contact of the two surfaces is made up of hemispherical shaped asperities with an average radius of a.

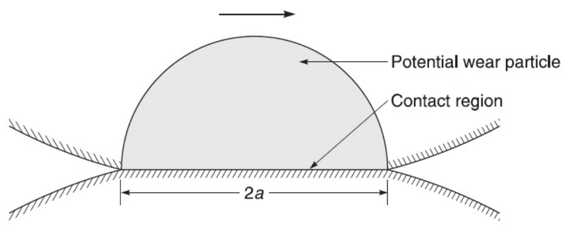


Figure 4: The generation of a hypothetical hemispherical wear particle under sliding motion.

We now define dW as the maximum normal load under which the material has yielded as

$$dW = \pi a^2 H \tag{3}$$

where H is the mean contact pressure under the condition of full plasticity, flow pressure, or hardness of the softer material. We now assume that this asperity contact results in a worn particle of volume dv. It is found that the wear particles generally are of roughly equal lengths in three dimensions, so we can state that dv is proportional do a^3

$$dv = \frac{2}{3}\pi a^3. \tag{4}$$

Now at last assume that contact remains in existence for a sliding distance dx equal to the diameter of the particle, $2a$ after which it is broken and the load is taken up by a new contact. We can now state with the previous equations

$$\frac{dv}{dx} = \frac{1}{3}\frac{dW}{H}. \tag{5}$$

Not all encounters produce wear particles but only a fraction α, which will be set equal to $3k$, will produce wear particles. Now by integration we can come to the final Archard's equation of adhesive wear stated as

$$v = \frac{kWx}{H} \tag{6}$$

and can be used to give the amount of wear removed from the softer of the two surfaces. The quantity k is usually interpreted as the probability that transfer of a material fragment occurs or a wear particle is fomred to a given asperity encounter and is called the wear coefficient. So the lower the wear coefficient of a material in a certain tribology system, the lower the wear of that material.

Abrasive wear. Asperities of a rough, hard surface or hard particles slide on a softer surface and damage the interface by plastic deformation or fracture. Hard asperities or hard particles result in the plastic flow of the softer material. Three modes of abrasive wear by plastic deformation are possible which include plowing, wedge formation and cutting. Also abrasive wear by fracture is possible which occurs above a certain threshold load.

Fatigue wear. The repeated loading and unloading cycles to which the materials are exposed may induce the formation of surface cracks, which eventually, after a critical number of cycles, will result in the breakup of the surface with the formation of large fragments.

The above mentioned types of wear are all mechanically driven. There are however more wear mechanisms that can or do occur. Especially chemical wear in the form of corrosion will play a role since often metal materials are used in joint replacements.

2.3 Osteolysis

As mentioned before, aseptic loosening due to osteolysis is the main cause for a limited life time of a hip prostheses. Osteolysis is a type of bone resorption that is mainly associated with joint replacements. There are several biological mechanisms which may lead to osteolysis. In total hip replacement, osteolysis is best explained by the worn off wear particles of the contact surface of the prostheses. As the body attempts to clean up these wear particles (typically consisting of plastic or metal), it triggers an autoimmune reaction which causes resorption of living bone tissue. Osteolysis has been reported to occur as early as 12 months after implantation and is usually progressive. This may require a revision surgery.

3 Current testing methods

Since this research project is about a relative new tribological wear test method, the test methods that already exists should be discussed. The first wear test methods wear pin on disk instruments, were simply a pin is sliding over a disk under loading in simple motion. The geometry and loading and motion profiles are relative simple in the pin on disk test and not very physiological realistic. On the other hand there are the hip joint simulators, in which an actual final hip prostehes is being tested for wear. In such a hip joint simulator the motion and loading profiles are set to be as realistic as possible. So here the geometry of the instrument and loading and motion profiles are very complex. There are many variables that play a role in hip simulation, and the precise way these variables are addressed can affect the clinical relevance of the data. Over the world there are a lot of these hip joint simulators, all varying slightly in geometry and motion settings, so there is not really a worldwide standard.

The test method discussed in this research project thesis is somewhere between the pin on disk and the hip joint simulator. The purpose of the test method is actual to test the wear of biomaterials, and not of actual final hip prostheses. But the physiological conditions are more complex than the pin on disk instruments. Figure 5 gives a clear view on the differences between the three test methods, the one used in this research, and the pin on disk and hip joint simulator.

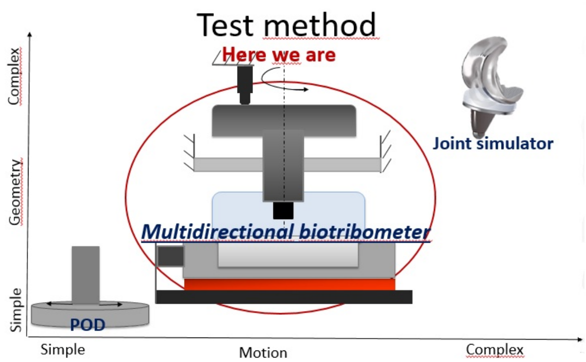


Figure 5: Graph comparing three wear test methods for motion and geometry.

In hip joint simulator tests done by several different scientists wear rates ranging from 22.5 to 51.7 mm^3 per million cycles are found. These wear rates correspond to a UHMWPE cup in combination with a CoCrMo femoral head of 28 mm in diameter. The clinical wear rates in mm^3 per million cycles for a 28 mm CoCrMo femoral head on a UHMWPE cup are ranging from 43 to 86, with extreme values of 27 and 144 [8].

4 Experimental Setup

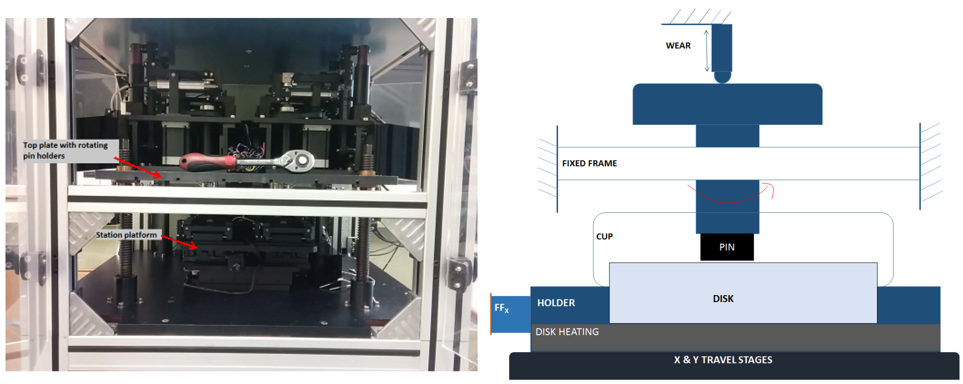
4.1 Ducom Biotribometer

The testing instrument used in this research project is the Ducom Biotribometer [1]. The instrument is used for tribology experiments of materials that are used in the replacement of natural joint interfaces. It follows the international standards for wear

[1]TR-BIO 20, Ducom Instruments, Pvt. Ltd., India.

testing ASTM-F732 and ISO 14242-2 mentioned before. The instrument is controlled via a computer together with the sofware Winducom 2010

The instrument consists of six testing stations and is divided into two main parts. At the bottom there is the moving station platform that can move in the x-y direction and is fixed in the z-direction. Several motion profiles are possible, such as linear, circular and figure 8. On the station platform there are six installations for disk holders. The second main part is the top plate, that can be set up in a certain vertical position but stays fixed in the planar x-y direction. The top plate contains 6 six pin holders, each positioned above one of the installations for the disk holders, together forming the six stations. All the stations are expanded with friction force sensors in the x- and y-direction, a linear variable differential transformer (LVDT) and a standard loading module such that the load can be applied individually to each station. Additionally to the sliding motion of the station platform, the pin holders have the possibility to rotate about their vertical (cylindrical) axes. A schematic and picture of the stations is shown in figure 6.

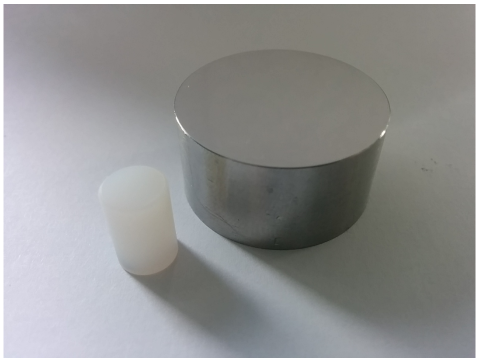


(a) (b)

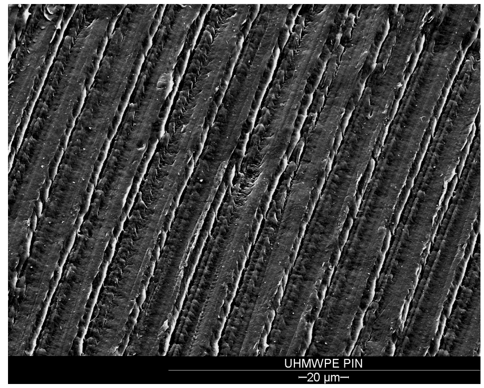
Figure 6: (a) Shows a picture taken of the two plates with stations. The picture is taken in front of the station. There are two stations next to each other and three behind each other. (b) Shows a schematic of one single station.

4.2 Test Specimen

The materials investigated in this research project are UHMPWE used for the pins with metal counterparts as disks. CoCrMo and Ti_6Al_4V are used for the disks. In total eight test specimen were used in this experiment, 4 UHMWPE pins, two cobalt-chrome disks and two titanium alloy disks. Beside the test specimen, control specimen were used. The control polymer pin has been coated with a thin layer of gold in order to perform confocal microscopy and scanning electron microscopy. These SEM images will be discussed later together with the SEM images of the polymer pins at the end of the experiment.



(a)



(b)

Figure 7: (a) Picture of the pins and disks used in the test. (b) A SEM image of the control UHMWPE pin.

Figure 7 shows a picture of one of the pins and disks. The polymer pins are 8.00 $\pm$ 0.03 mm in diameter and their height is 12.00 $\pm$ 0.03 mm. The diameter of the disks is 29.00 $\pm$ 0.03 mm and the height of the disks is 14.70 $\pm$ 0.03 mm. All the test specimen, both the disks and the pins have a clear distinction between testing surface and non-testing surface because of the clear distinction between manufacturing finishes visible with naked of the top and the bottom of the pins and disks. The top side of all specimen is referred to as the test surface. However, as can be seen later on the SEM image of the control pin, there are still manufacturing finish lines present but they are not visible with the naked eye.

4.3 Experimental method

There are two disks of each type of metal alloy, one for a test involving a constant fixed load of 225N in accordance with ASTM-F732, and the other for a test where the load is changing periodically in accordance with a parameter set generated by the evaluation of in vivo walking motion [4]. So in total four situations are tested:

- UHMWPE Pin on CoCrMo Disk with Fixed Load
- UHMWPE Pin on Ti_6Al_4V Disk with Fixed Load
- UHMWPE Pin on CoCrMo Disk with Dynamic Load
- UHMWPE Pin on Ti_6Al_4V Disk with Dynamic Load

Figure 8 shows the profiles of the applied load for the fixed load, constant at 225 N and the dynamic load profile over time.

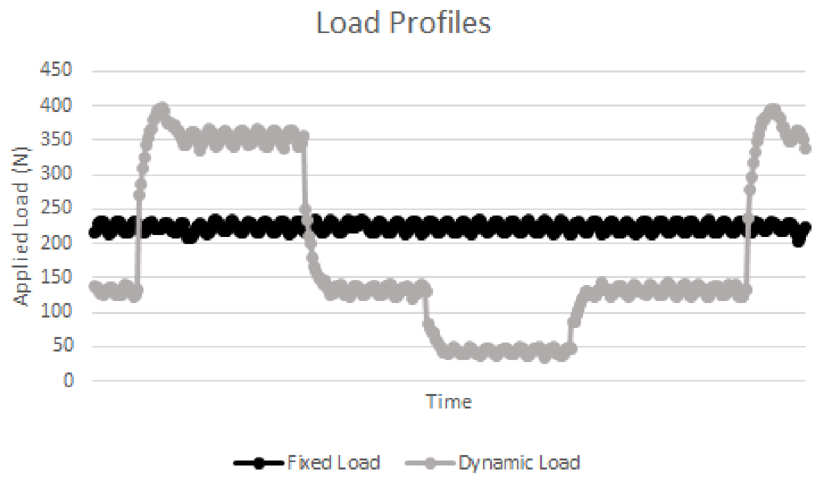


Figure 8: The load profiles for fixed load and dynamic load

The station platform was set to slide a stroke length of 5 mm, so 10 mm per cycle, at a frequency of 0.54 Hz. This is not in accordance with the standard due to limitations and possible re-alignment of the instrument, but as will be discussed later is a point for future research. The pins are all rotating in clockwise direction at a frequency of 1 Hz, which corresponds to the walking frequency. The disks are installed using disk holders, which fit in the stations on the station platform. The pins can be installed in the pin holders.

At all stations, the system was lubricated with bovine serum albumin (BSA) solution. BSA is is often used as a protein concentration standard in lab experiments. The BSA was dissolved in phosphate buffered saline, which consists of 8.67 g of NaCl, 20 ml of 43.5 M KH_2PO_4, and 980 ml of deionized water. The concentration of BSA solution is 5 g/L.

Initially the goal was to run the test for about 2.5 million cycles, which corresponds to the 1 Hz sliding frequency described in ASTM-F732 and a testing time of 29 days. But due to limitations and possible re-alignment because of frequent use of the instrument the total number of cycles is changed to about 1.26 million. Also in first instance data collection and test specimen cleaning would be performed after every 0.25 million cycles, but that has become 0.14 million cycles. This obtained data consists of the following properties per station or system:

- Weight loss of the pins which can be converted to wear as volume loss.
- Wear from the linear variable differential transformers (LVDT).
- Friction force of the system in the x and y direction. This will be converted to a friction coefficient.
- Surface roughness of the generated wear track on the metal disks with the aid of a confocal microscope.

- Scanning electron microscopy (SEM) images of the disks and optical microscopy images of both the pins and disks.

Before the execution of the weighing of the pins and the three types of microscopy, all the test specimen are cleaned in accordance with the standard ISO-14242-2. For a complete plan of action of this test method the reader can consult appendix A.

5 Results

The outline of this results section will be as follows. The emphasis will be on the difference between the load profiles, so first are the results shown for the UHMWPE pins against the CoCrMo disk, for both applied load profiles. These results will be divided into the data, thus the volume loss, friction coefficient and surface roughness, and the visual data, thus the optical microscopy and scanning electron microscopy images. Then the same outline will be depicted for the UHMPE pins against the Ti_6Al_4V disks.

5.1 UHMWPE against CoCrMo

5.1.1 Volumetric wear rate, Coefficient of Friction, Surface Roughness

Figure 9 shows the volume loss as a function of number of cycles for the UHMWPE pins subjected to a fixed load and a dynamic load on a CoCrMo disk. The overall volumetric wear rate for the fixed load case and the dynamic load case is 9.23 $mm^3/millioncycles$ and 6.22 $mm^3/millioncycles$. From the graph it can be seen that the volume loss in the case of the dynamic load shows a linear trend over the number of cycles. In case of a dynamic load however the rate of volume loss, or the volumetric wear rate, is not constant during the test. The R^2 value of the linear fit for the fixed load data is thus much lower, 0.81, than for the dynamic load date, 0.97.

Focusing on the data for fixed load in figure 9, the data can roughly be divided into three regions, (i) from 0 to 0.3 million cycles, (ii) from 0.3 to 1 million cycles, and (iii) from 1 million cycles to the end of the test. The volumetric wear rates in regions (i) and (ii) are 4.1 and 3.4 respectively but they are separated by a sudden big increase in the volume loss after 0.3 million cycles. Also at the end, region (iii), there is a sudden increase, but it is only one data point so it could also be a measurement error.

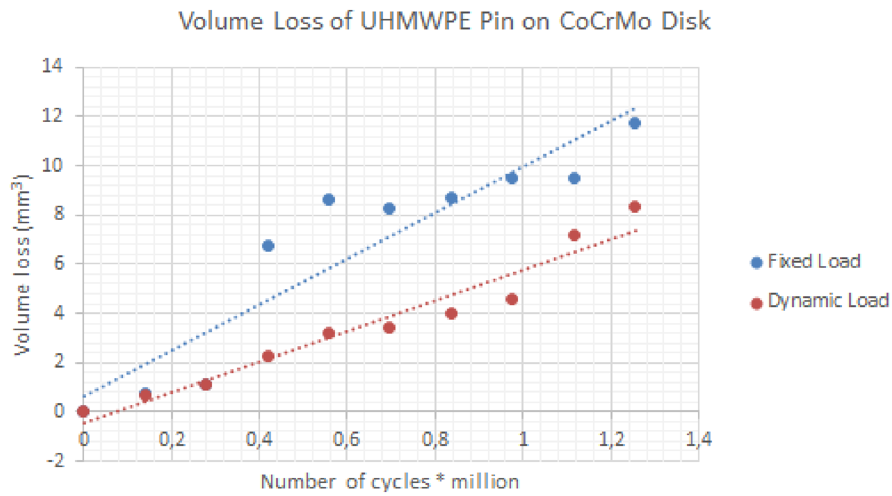


Figure 9: Volume loss as a function of cycle number. The red line shows the data for the pin with an applied fixed load and the blue line shows the data for the pin with an applied dynamic load. Both the pins were sliding over a CoCrMo disk.

The testing instrument was able to measure the friction force F_{fx} and F_{fy} in the x-direction and in the y-direction respectively and recorded their values every 0.5 seconds. From those values the coefficient of friction for two directional motion was calculated by adapting equation 2 into

$$\mu_f = \frac{\sqrt{F_{fx}^2 + F_{fy}^2}}{L} = \frac{F_f}{L}, \tag{7}$$

and then out of all the data points recorded during a period of 14000 cycles the maximum value for μ_f was taken as the representative value for the coefficient of friction after the corresponding amount of cycles.

Figure 10 shows the friction coefficient evolution data for the test with UHMWPE pins on CoCrMo disks for both applied load profiles, fixed and dynamic. The coefficient of friction for the system with the dynamic load profile is more or less constant during the test, with an average value of 0.17 ± 0.02 during the test. In the case of an applied fixed load, the friction coefficient is in the beginning of the test, region (i), quite high, about 0.23, then it decreases radically to a value of about 0.04 in region (ii) and at the end, region (iii) it increases again to 0.13.

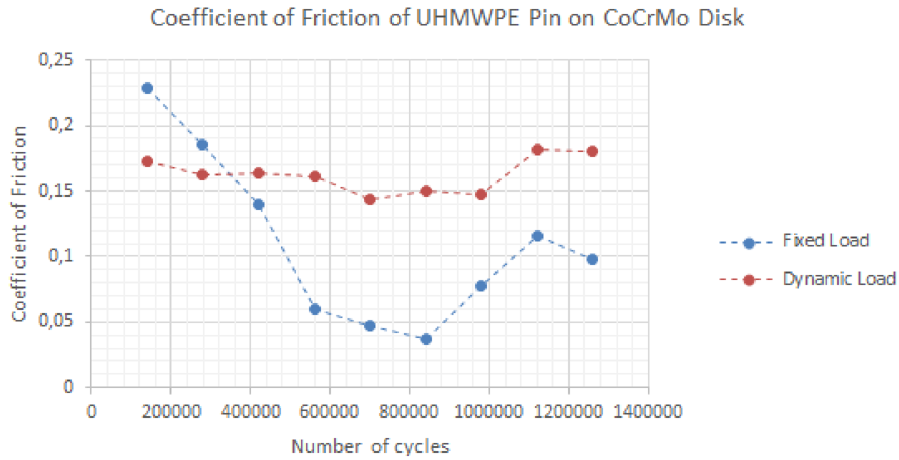


Figure 10: Coefficient of friction as a function of number of sliding cycles

As mentioned before, the surface roughness is determined with the aid of a confocal microscope. Due to the poor reflectance of the UHMWPE pins for white light, only the metal disks could be examined under the confocal microscope. However, since the wear track was too large too examine as a whole, only certain points were analyzed and averaged.

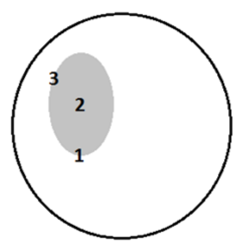


Figure 11: Evaluated points on the weart track for determining the surface roughness.

Figure 11 shows a schematic representation of the wear track generated on the disks. On all the disks the wear track positioned the same way on the disk, somewhat to the left when standing in front of the instrument. Figure 11 shows three points which were evaluated for surface roughness, and in the end the measured R_a values of these three points were averaged to get a mean surface roughness of the wear track. Due to symmetry of the wear track the choice was made to only evaluate these points, so not the whole wear track has been evaluated, but this method gives more or less a accurate insight in the surface roughness of the whole wear track.

Figure 12 shows the averaged surface roughness of the wear track on the CoCrMo disks as a function of cycle number for both fixed load and dynamic load. Generally the surface roughness of the CoCrMo disk subjected to a fixed load profile is lower than the disk subjected to a dynamic load profile during the whole test except in the beginning of the test when they are more or less equal. Also both CoCrMo disks experience a abrupt increase in the average surface roughness at the point of 1 million cycles.

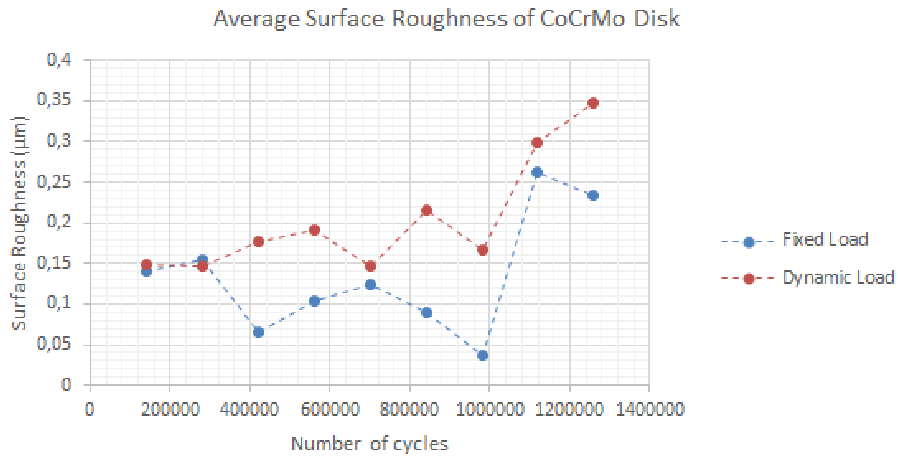
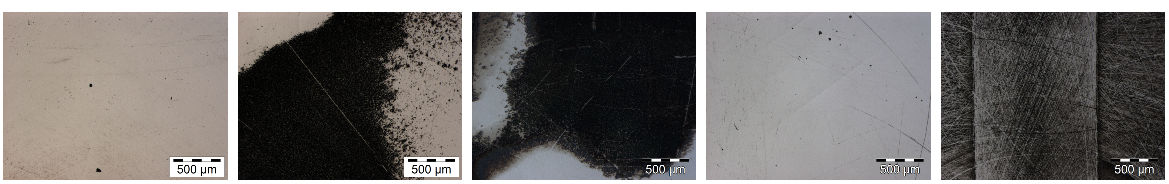


Figure 12: Average surface roughness as a function of number of sliding cycles

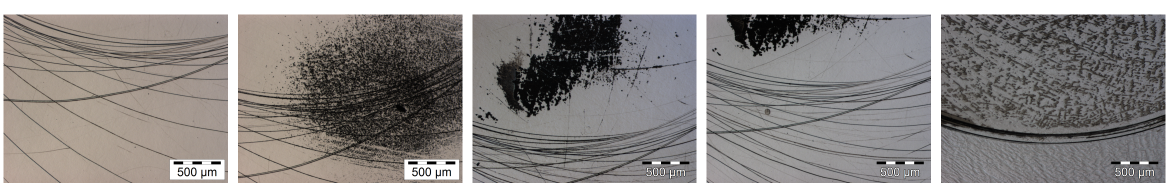
5.1.2 Optical Microscopy and SEM images

Figure 13 and 14 shows optical microscopy images of the wear tracks on the CoCrMo disks for both the fixed load and the dynamic load profile case. Looking at figure 13a and 13b, suddenly a big black spot is visible, which occurs at the transition from region (i) to region (ii). Then in figure 13d, at the end of region (ii), this spot has disappeared and only a few minor scratches are visible at the wear track. At the end, the transition from region (ii) to region (iii), the wear track changes abruptly with a lot of scratches visible.



(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

Figure 13: Optical microscopy images of the CoCrMo disk subjected to fixed load

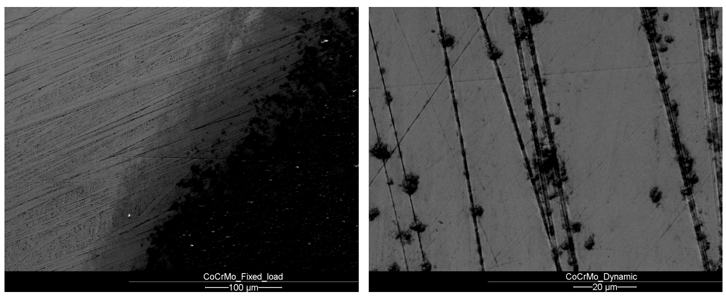


(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

Figure 14: Optical microscopy images of the CoCrMo disk subjected to dynamic load

In figure 14a, which shows the optical microscopy image of the wear track on the CoCrMo disk subjected to the dynamic load profile, there are clear distinct curved scratches visible. Then from figure 14b to 14d there have become more scratches but the profile looks more or less the same. Also on these images a small black spot is visible. Then at 1.12 million cycles, figure 14e the wear track has changed completely.

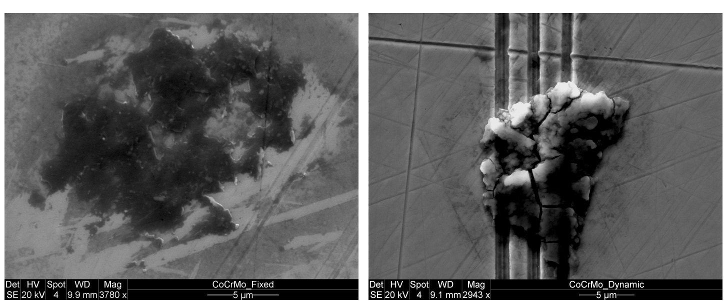
Also on the SEM images the there is a big dark spot visible on the CoCrMo disk of the fixed load case, as can be seen in figure 15a. When comparing with the CoCrMo disk subjected to a dynamic load, clear distinct scratches are visible with a lot of microscopically wear debris particles on the scratches.



(a) Fixed load (b) Dynamic load

Figure 15: SEM images of the wear track on the CoCrMo disks at the point of 0.56 million cycles

After 0.98 million cycles, the dark spot on the CoCrMo disk of fixed load was gone. Looking at figure 16a it can be seen that there is still something on the surface of the disk but it is way less dense and smaller than before. Figure 16b shows that at the point of 0.98 million cycles there are still wear debris particles on the scratches and cracks are forming on these wear debris.



(a) Fixed load (b) Dynamic load

Figure 16: SEM images of the wear track on the CoCrMo disks at the point of 0.98 million cycles

5.2 UHMWPE against Ti_6Al_4V

5.2.1 Volumetric wear rate, Coefficient of Friction, Surface Roughness

Figure 17 shows the progression of volume loss of the UHMWPE pins on the titanium alloy disks over sliding cycle number for both the fixed load and dynamic load profile. The overall volumetric wear rates calculated by linear regressions is 7.42 ± 0.68 $mm^3/millioncycles$ and 7.11 ± 0.69 $mm^3/millioncycles$ for the fixed load and dynamic load case respectively. Here the wear rates are more or less equal within their error margins. However, having a look at the graph in figure 17, one can observe that the volume loss with a dynamic load profile starts somewhat higher, whereas in case of a fixed load the volume loss is even negative after the first measurement, because of the fact that the pin has gained more weight by soaking than it has lost by mechanical wear. The difference in volume loss of the pins, and thus volumetric wear rate, between the two load profiles is the highest at the point of about 0.4 million cycles. After that the volume losses are growing more and more together.

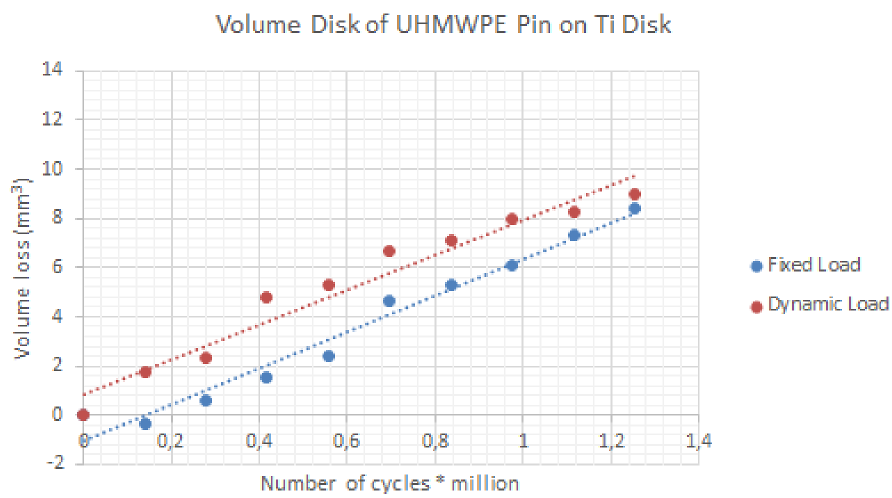


Figure 17: Volume loss as a function of cycle number. The red line shows the data for the pin with an applied fixed load and the blue line shows the data for the pin with an applied dynamic load.

Figure 18 shows the evaloution of the coefficient of frictions for the UHMWPE pins on the Ti_6Al_4V disks for both the fixed load and the dynamic load profile. It is interesting to see that the coefficient of friction of the dynamic load profile is in the beginning of the test about three times higher than the friction coefficient of the fixed load profile. During the test, after about 0.4 million cycles, the values for the friction coefficient for both load profiles are getting more and more the same.

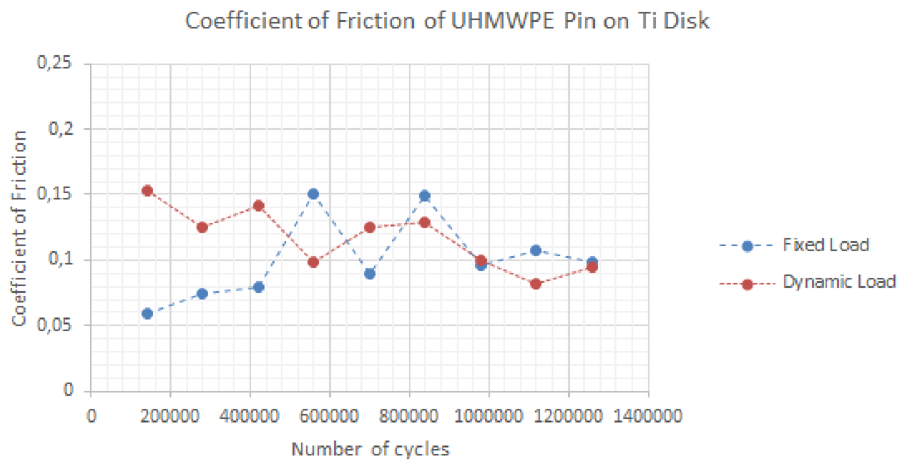


Figure 18: Graph of the coefficient of friction as a function of number of cycles.

Figure 19 shows the graphs of the average surface roughness of the wear track on the titanium alloy disks for both load profiles as a function of number of cycles. In the beginning of the test the values for the surface roughness of both load profiles are the same. Then, after about 0.3 million cycles, the surface roughness of the titanium alloy disk subjected to a dynamic load is about a factor of 1.5 higher than for a fixed load profile.

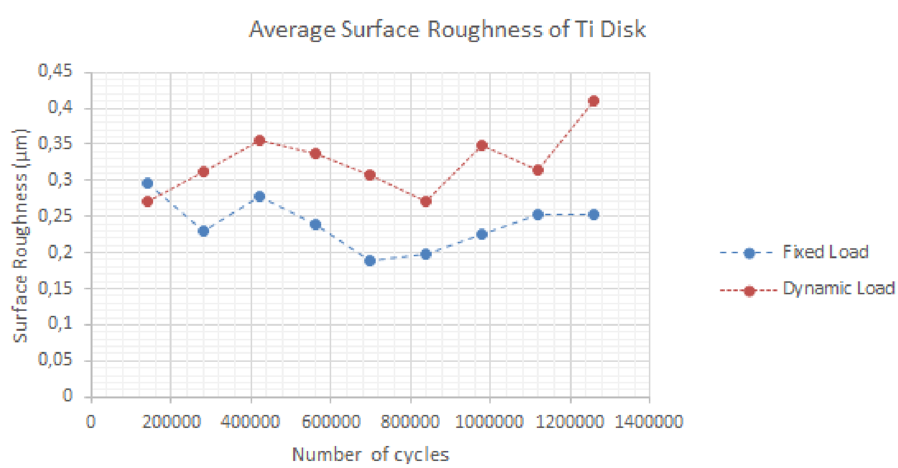
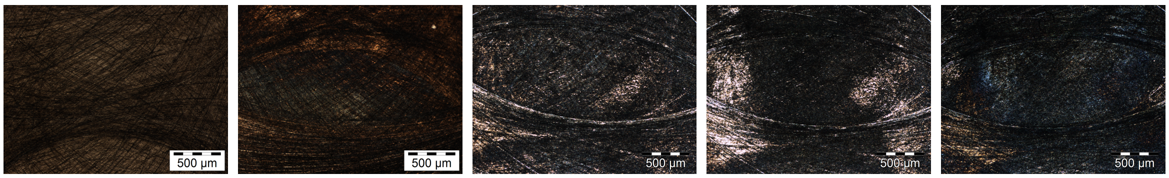


Figure 19: Average surface roughness, Ra, as a function of cycle number.

5.2.2 Optical Microscopy and SEM images

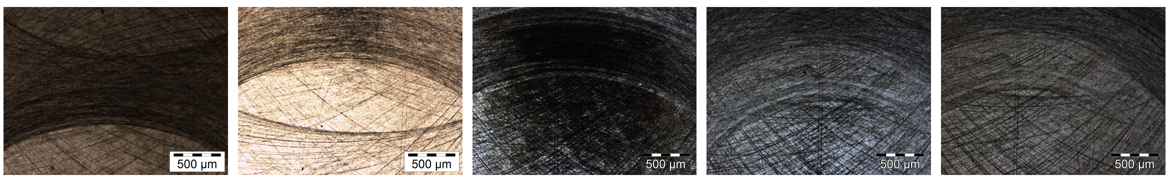
Figures 20 and 21 shows the optical microscopy of the center of the wear track on the titanium alloy disks for both the fixed load and dynamic load profile. On both disks there are a lot of dense scratches visible and they stay there during the whole test.

Not much difference can be observed in these images, except for the brightness of the images but that is an measurement error.



(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

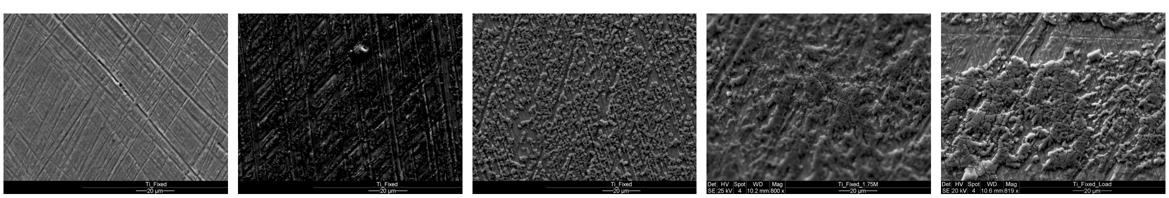
Figure 20: Optical microscopy images of the Ti_6Al_4V disk subjected to fixed load



(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

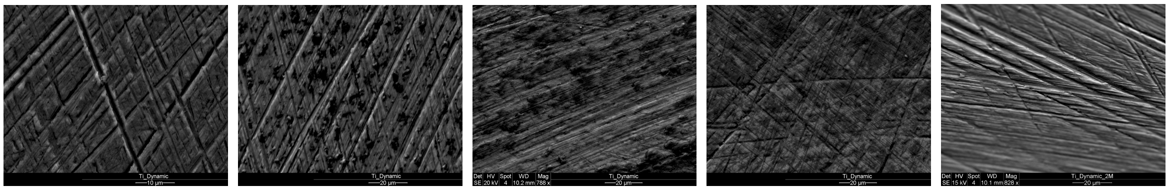
Figure 21: Optical microscopy images of the Ti_6Al_4V disk subjected to dynamic load

Figures 22 and 23 shows the scanning electron microscopy images of the wear track on the titanium alloy disks for increasing cycle number. Here the scratches seen on the optical microscopy images are also clearly visible. There is, especcially at the second half of the test, a clear difference visible in the SEM images of the two titanium alloy disks. This difference is in the wear debris attached on the wear track. In case of the fixed load there is a lot of wear debris visible, whereas with a dynamic load almost only the scratches can be seen.



(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

Figure 22: Scanning electron microscopy images of the Ti_6Al_4V disk subjected to fixed load



(a) 0.28 M cycles (b) 0.42 M cycles (c) 0.84 M cycles (d) 0.98 M cycles (e) 1.12 M cycles

Figure 23: Scanning electron microscopy images of the Ti_6Al_4V disk subjected to dynamic load

6 Discussion and Conclusion

In this section the results will be discussed and especially the most striking difference between the results will be highlighted. Also the various quantities measured will be interconnected to support each other, with additional visual support by the optical microscopy and SEM images.

6.1 Fixed load vs. Dynamic Load - UHWMPE against CoCrMo

First the differences in obtained data between the fixed load profile and the dynamic load profile will be discussed for the UHMWPE pins on CoCrMo disk. Beginning with the volume loss it is clear from the graphs in figure 9 that the volumetric wear rate for the dynamic load case is much more linear than in case of the fixed load profile. This difference is supported by the plots of the friction coefficients in figure 10. As said before, the coefficient of friction for the dynamic load case is more or less constant during the test, except that at the end a small increase is observed, while the rate of volume loss is also constant during the test, with a small increase at the end.

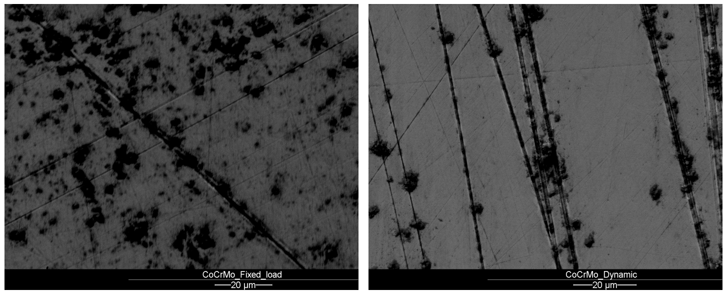
In case of the fixed load profile, the coefficients starts quite high, corresponding to a big increase in the volume loss. Then in region (ii) the coefficient of friction has dropped to a very low value, while in that region the volume loss does almost not change with increasing cycle number. In region (iii) the friction coefficient increases again, resulting in a increase in the volume loss. So one can conclude that the volume loss of the UHMWPE pin is related to the friction coefficient of the pin sliding over the CoCrMo disk: a high friction coefficient corresponds to a high volume loss, whereas a low friction coefficient corresponds to almost no volume loss with increasing sliding distance.

Looking at figure 12, for both the fixed load and the dynamic load profile there is a sudden increase in the surface roughness of the wear track on the CoCrMo disk at about 1 million cycles. This can be connected to the increases in the plots of the coefficient of friction in figure 10. One can conclude from it that the surface roughness of the disk affects the friction of the system. However, the two quantities are not directly proportional since an increase with a factor of 5 of the surface roughness in case of the fixed load corresponds only to an increase with a factor of 2 of the friction coefficient. Since the friction is a system property, it depends on more factors than only the roughness of the disk. So one also needs the surface roughness data of the UHMWPE pin to say more about the connection between surface roughness and friction force.

When comparing the data with the optical microscopy images of the CoCrMo disks in figure 13 and 14, some interesting features can be observed. Beginning with the fixed load profile case, in the beginning of the test there is hardly anything visible on the microscopy image, figure 13a. Then suddenly a big black spot appears to be visible on the wear track on the disk, where at that same point, the transition from region (i) to (ii), a abrupt increase in the volume loss is observed. So one can conclude that the black spot is adhesive wear from the polyethylene pin, since polyethylene is way less reflective than metal it should appear dark on the microscope, that is stuck on the disk, which is called an organometallic layer. However to be sure that it is actually polyethylene, EDS analysis should have been performed with a scanning electron microscope.

As can be seen in figure 13c, the organometallic layer is still present on the wear track of the CoCrMo disk, and has not changed much in size. This observation is in line with the volume loss plot, where in region (ii) the volume loss is almost not increasing. Since in this same region, as said before, the coefficient of friction for the fixed load case is very low, one can state that this organometallic layer acts as an lubricant layer that lowers the friction. This assumption is supported by the observation that when at around 1 million cycles the organometallic layer is gone, the friction coefficient increases again.

Now comparing the optical microscopy images of the CoCrMo disks for the fixed load and the dynamic load profile in figure 13 and 14 there is only a very small and not very dense organometallic layer formed on the wear track of the disk with the dynamic load profile. Because there is constantly loading and unloading in this case, the polyethylene that attaches on the disk due to adhesive wear is able to get loose and escape during the low-load intervals of the dynamic load cycle, whereas in case of an constant fixed load, this is, especially in the center of the wear track, not possible. This assumption can be supported by SEM images and with the results of the test with the Ti_6Al_4V disks.



(a) Fixed load (b) Dynamic load

Figure 24: SEM images of the distribution of the wear debris on the wear track

Figure 24 shows for both the fixed load disk and the dynamic load disk the distribution of polyethylene wear debris on the wear track. Here a clear difference is visible between the two load profiles. In the dynamic load case, the wear debris are almost all stuck on or in the scratches, whereas the wear debris on the wear track from a fixed load are much more evenly distributed and not only appear on scratches. So it looks like that during the high load stage of the dynamic load cycle the wear debris are pushed into the scratches and during the low load stage the wear debris that are not on the scratches are able to escape.

As mentioned before, figure 22 and 23 in the results section of UHMWPE against Ti_6Al_4V shows clearly a difference in the amount of attached polyethylene wear debris particles on the wear track of the disk between the fixed load case and the dynamic load case. In case of a fixed load there is a lot of wear debris on the wear track but in case of a dynamic load is it significantly less.

Also when applying a constant fixed load, oxide can not reach the wear track to create and/or restore a protective chromium oxide layer. This is again more possible when during the dynamic load cycle the applied load is quiet low.

An interesting observation from the optical microscopy images in figure 13e and 14e is that the wear tracks on both CoCrMo disks completely change at the point of 1.12 million cycles. This could be coincidence but it could also say something about some sort of fatigue of the material after this amount of cycles. More tests should be performed to investigate this. These sudden changes in the wear track topography is also visible in the data of the surface roughness of the disk in figure 12. Here after 1 million cycles the surface roughness of the wear track for both disks increase radically.

Types of wear on the UHMWPE pins

Since this study is about the wear behavior of UHMWPE against a metal counterpart, it is interesting to investigate what types of wear do occur on the surface of the polyethylene pins. This will be done with both optical microscopy and SEM images. The optical microscopy images show how the surface of the pins changes with increasing number of cycles. However, to really see what types of wear do occur, SEM images are needed, but this could only be performed at the end of the whole test when the pins are coated with a thin layer of gold. So the types of wear are visible but there is no indication on when a certain type of wear started to form.

Figure 25 shows a table with all the types of wear on the surface of the UHMWPE pins observed during an scanning electron microscope analysis.

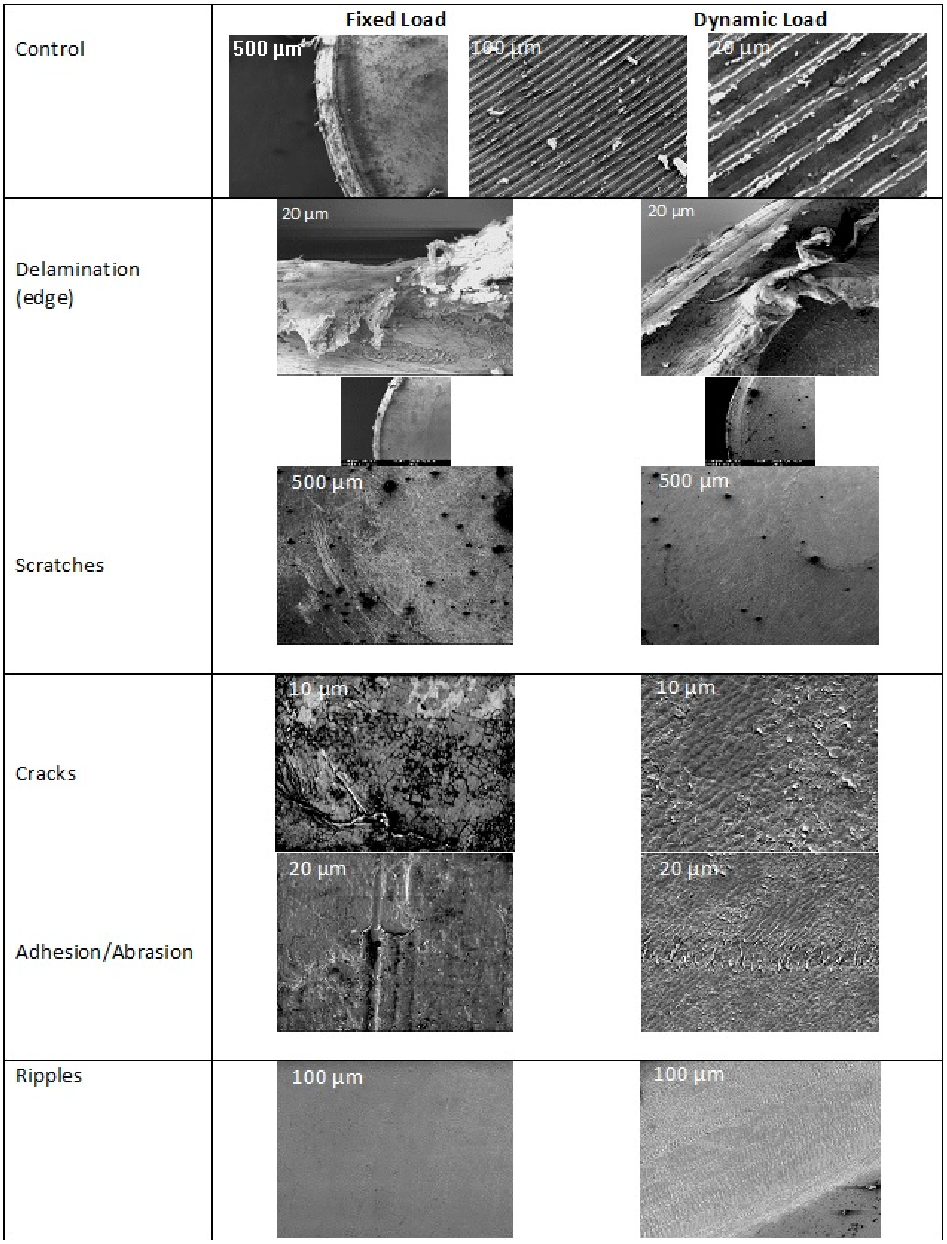


Figure 25: Types of wear on the UHMWPE pins that were tested on CoCrMo disks

At both pins there are the same types of wear visible. There is both delamination on the edges of the pin. Also scratches and cracks occur on the surface, but more on the pin subjected to a fixed load. On the pin of the dynamic load profile however there are much more ripples formed on the surface.

6.2 Fixed load vs. Dynamic Load - UHWMPE against Ti_6Al_4V

As mentioned before, the values of the overall volumetric wear rate of the UHMWPE pins against Ti_6Al_4V are very close to each other for the fixed load and the dynamic load case. However, the volume loss in the beginning of the test is much higher in case of a dynamic load, and only after about one million sliding cycles the values are converging, as can be seen in figure 17. This difference can be explained by looking at the friction of both systems. In figure 18 it is obvious that the friction coefficient is much higher for the dynamic load profile at the beginning of the test than in case of an applied fixed load. This corresponds to the higher start in volume loss of the polymer pins when subjected to a dynamic load. Then, at the second half of the test the coefficient of friction values for both systems are converging to about the same value, as is also the case with the volume loss. So the above discussed observations support the conclusion mentioned in the previous section that a high coefficient of friction corresponds to a high volume loss and vice versa.

7 Future research possibilities

Since we are talking about a relative new test method for testing wear of biomaterials used for joint replacements, future research is necessary to obtain more information on how these tests can be interpreted to eventually producing better joint prostheses.

As mentioned before, the sliding frequency and sliding distance, and thus also the average sliding velocity, is not in accordance with the standard ASTM-F732 due to limitations or alignment of the instrument. It would be interesting to compare the results of this research with a future research in which the sliding frequency is actual 1 Hz and 10 mm of stroke length. Increasing the frequency and stroke length would inevitably increase the sliding velocity, and under the same load conditions, this would mean more energy transfer between the two sliding surfaces.

In this research project the tribology test was performed under lubrication with bovine serum albumin, since the ASTM-F732 standard is followed as much as possible. However, in a real hip joint replacement, the cartilage of the natural hip joint is removed and no lubrication is present. So it is debatable whether lubrication should be included in these wear tests. Therefore repeating the test without lubrication and compare results would give information on how the wear progresses without lubrication, so in real hip joint replacements.

This research only concentrated on tribology of biomaterials used for hip joint replacements. However, since the tests were performed in a liquid lubricant and the test specimen where metals, also corrosion would occur. The combined study of corrosion and tribology is called tribocorrosion and is gaining interest in the last few years among researchers [9]. So to fully understand the wear behavior of the biomaterials, one should perform both tribology and corrosion analysis during the tests. The current test apparatus can be expanded with a corrosion control cell to make this possible.

In the experimental setup section it was mentioned that the instrument includes a LVDT sensor in each station. This sensor can be used to measure linear wear, thus the length of material that will wear off from the pin and how deep it will penetrate into the disk. However, since the pin is made of UHMWPE, the pin will be compressed while applying a force on them. This will be measured by the LVDT sensor and so an incorrect value for the linear wear will be depicted. Thus to use the LVDT sensors one would have to perform some compressibility and creep test on the pins to correct for the linear wear.

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