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The Adhesive Wear Behaviour of UHMWPE for Knee Replacement Applications

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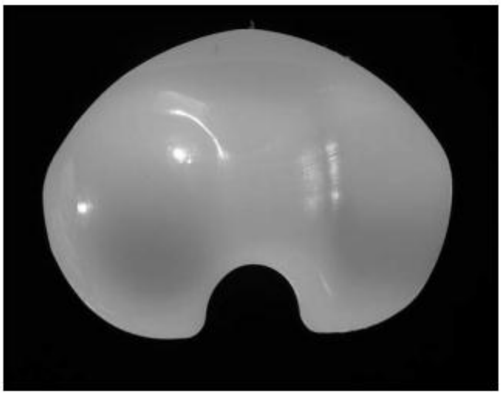
Abstract

In this article, the adhesive wear behaviour of ultra-high molecular weight polyethylene will be tested under dry and wet contact conditions. The influence of the applied load, sliding distance, sliding velocity and contact conditions (wet/dry) will be considered in the project. Scanning electron microscopy and roughness profile devices will be used to examine the worn and counterface surfaces. Block on ring technique will be used in the tribological experiments. Different solutions in the interface will be considered in the tests. Comparison with the previous published work will be established.

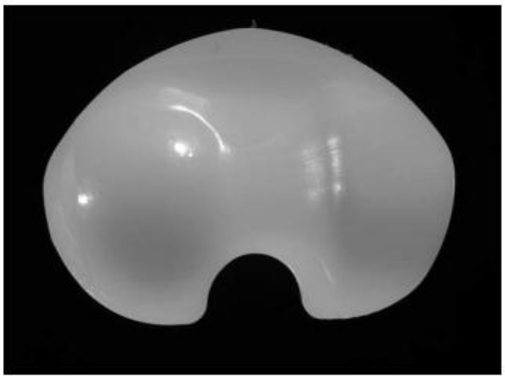
Keywords: UHMWPE; adhesive wear; wet condition, operating parameters.

INTRODUCTION

Nowadays, engineering materials have their path in many sectors due to their good performance compared to metals. The main advantages of the engineering materials (polymers) over the metals are the light weight, no-corrosion, low friction coefficient. Those advantages made the engineering materials good alternative candidate over the metals in several applications. The advance in technology attempts to use such materials in human body as replacement to the damaged parts such as knee, hips, disk…etc. The most common damaged part in human due to the aging is the knee. According to the annual report of the Australian orthopaedic association (2015) 54,277 knee replacements undertaken in 2014, i.e. an increase of 4.7% compared to the previous year. Australian Government: Australian Institute of Health & Welfare. Australian Hospital Statistics 2011-12. According to [1], 373,613 hip and 428,936 total knee replacement (TKR) patients have been reported in England. The first hip and knee surgery were took place as early as the late 1960s, [2]. Currently, biomaterials as alternative materials to the human joint evolved significantly. In the recent academic press. Gohil, Suhail [3] reported that there is a great need to develop a novel and effective biomaterial-based for orthopedic applications. Ultrahigh molecular weight polyethylene (UHMWPE) is found to be one of the most attractive candidate for human parts especially for knee and hip replacement due to its characteristics such as "*ultra-low water absorption, excellent chemical stability, and high impact strength, advantages that make it potentially suitable for application in wet lubrication*", [4]. In previous study by Blunn, del Preva [5], the quality of the UHMWPE found to be the key of the artificial knee life. Figure 1.1 a&b shows the wear damaged on two types of UHMWPE after five years in real life knee experience. The authors of that work emphases on the further works to be done on UHMWPE manufactured using different compacting methods. A comprehensive information on the UHMWPE is given in modern book published by Kurtz [6]; in that book, further understanding on the wear behaviour of such material is recommended especially on the dry contact condition since most of the work has been done on the wet condition.



(a)



(b)

Figure 1.1: Two identical prostheses retrieved after use in vivo for about five years: (a) was made from poorly compacted UHMWPE (b) was made from well-compacted UHMWPE, [5].

Besides, according to news.com.au (21 Oct. 2013, Australian Orthopaedic Association research shows best artificial joints) "more than 800,000 Australians have a joint replacement and each year another 90,000 devices are inserted at a cost of around $1 billion". This motivates me to work on the UHMWPE and further understand the wear and the frictional behaviour of such materials under dry contact condition since there are no much works have been published and there is a need for it.

From the literature, most of the reported works on UHMWPE for knee replacement have been carried out from tribological perspective since the main loading condition on the knee is adhesive wear condition. There are many devices have been used to evaluate the adhesive wear behaviour of UHMWPE such as knee device, pin on disk, block on ring, …. etc. In the current project, I used pin on disk setup to evaluate new type of UHMWPE under dry and wet contact conditions considering the different operating parameters. Scanning electron microscopy (SEM) and roughness machines will be used to examine the surfaces of both worn and counter face track.

The main objective of this study is to evaluate the adhesive wear behaviour of UHMWPE under wet and dry contact conditions

Material Selection

Worland plastic provided the UHMWPE for this study. The standard specification can be found in deferent resources which are based on ASTM D4020. The general mechanical properties of the UHMWPE can be found in www.velmex.com. UHMWPE has higher tensile strength than the LDPE and HDPE which give it better advantages than others in term of high tensile strength. This allows such thermoplastic to be used at high pressure and loading conditions. The provided UHMWPE is cut into tribological samples of 20 mm x 20 mm x 50 mm to be tested under block on ring tribology machine under wet and dry contact conditions.

TRIBOLOGY MACHINE AND EXPERIMENTAL DETAILS

At university of southern Queensland, there is a multi-purpose tribology machine which can be operated under dry and wet contact conditions, Figure 1. the tribology machine is made of 1.5 hp motor, block on ring arm, pin on disk arm, load cells to capture the frictional force, and control panel. The machine is integrated with a computer and data acquisition system to directly capture the frictional force with the time. Both configuration is placed in a container to allow both dry and wet contact conditions to be performed. Under the wet contact condition, the container will be filled with water and the sample will be immersed in the water during the operating. The load cell can be operated under the wet contact conditions. The applied load can be increased up to 100 N and the sliding velocity can reach up to 7 m/s.

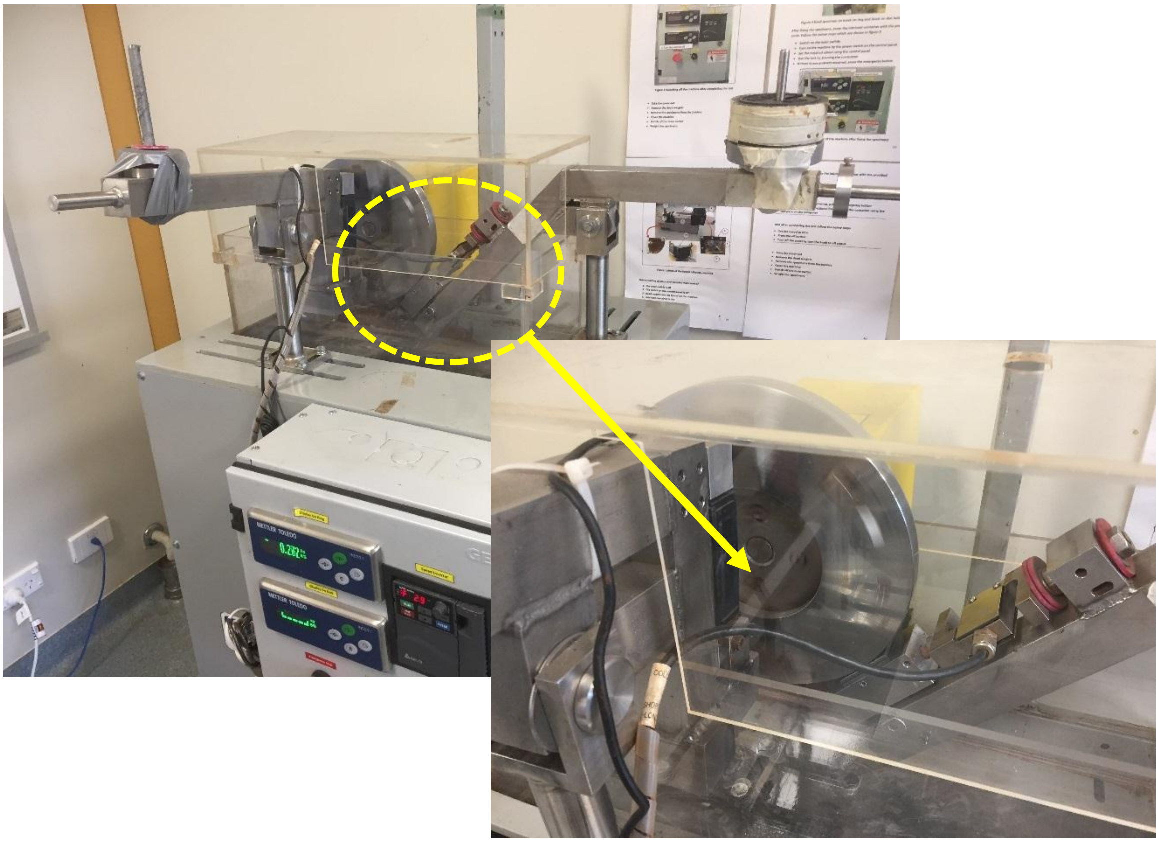


Fig 1. Tribology machine and zoom area of the interface of block on ring configuration

Experimental procedure

Firstly, the prepared samples were polished using polish machine using a SiC paper of 2000 G to ensure the adhesive wear will be presence during the sliding. The sample then weighted using a weight scale with very high precision scale of 0.01 µg, Figure 3.2. some safety equipment should be used before operating the tribology machine. The sample should be marked. Once the sample fixed in the holder of the block on ring machine, the sliding speed set and the applied load placed on the arm. A stop watch is used to count the duration and then to determine the sliding distance.

Then the machine is covered with and starts with a click on the run button on the control panel. The frictional force can be recorded or captured via the connected computer. After the duration is finished the machine is stopped and then the safety switch should be operated to remove the sample from the holder. The sample then weighed again to determine the weight loss.

After each test the samples were cleaned and dried to conduct the scanning electron microscopy (SEM) . Before conducting the SEM, the samples were coated with a thin layer of gold using smart coater given in Figure 3.4. The samples then placed in the SEM machine and the micrographs were captured using a software in a computer connected to the JOIL SEM machine.

RESULTS AND DISCUSSION

TRIBOLOGICAL RESULTS UNDER DRY CONTACT CONDITIONS

Wear Results

Ultra-high molecular weight polyethene (UHMWPE) has been tested tribologically using block on ring machine under dry and wet contact conditions. The wear results of the experiments under the dry contact condition is presented in Fig. 2 in weight loss and specific wear rate against sliding duration and sliding distances, respectively. In Fig. 4.1 a) the weight loss increases with the increase of the sliding time. The relation seems to be almost linear. But, there is two regions of weight loss before and after the 40 min of sliding time. Between the initial sliding time and the final stage, there is a transition time (between the 40 min to 60 min). this can be the separation between the running in time and the steady state time. Under the initial stage of the sliding time, the UHMWPE start adapting to the stainless-steel surface and there may be some materials transferred from the soft part to the hard part. When the materials are in adoption period, the weight loss reached a steady value. This can be seen in the second figure (Fig. 2b). In Fig. 2 b, the specific wear rate vs. sliding distance is presented. The figure displays that there is high specific wear rate before the 5 km sliding time and then start getting almost steady. Up to 5 km sliding distance, the specific wear rate was high. This is the natural behaviour of most of the materials. however, it should take longer sliding distance as can reach up to 10 km as reported by De Bona, Laino [7]. The specific wear rate is in the same range given by [8].

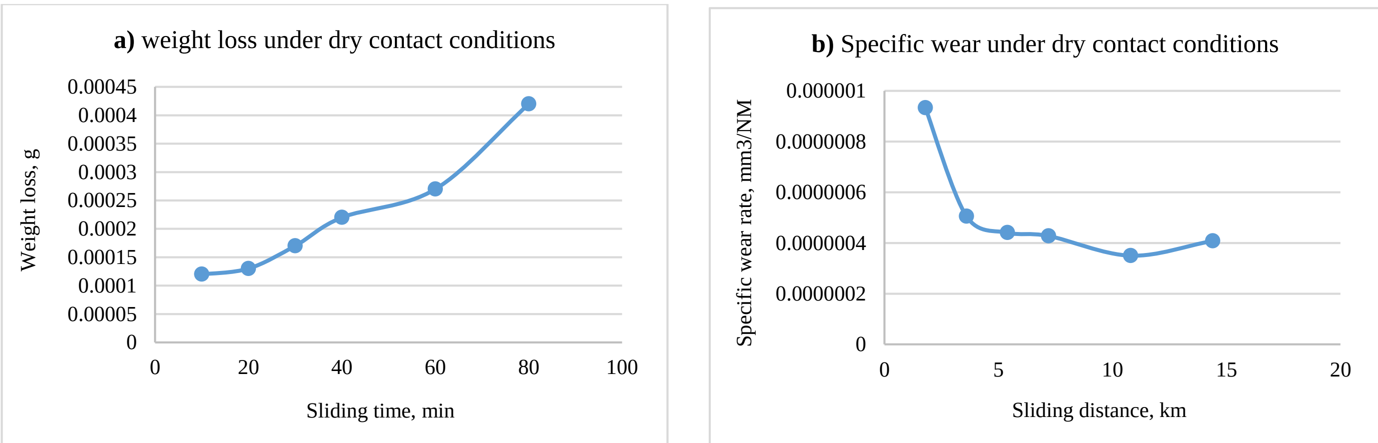


Fig. 2. Weight loss and specific wear rate of UHMWPE under dry contact conditions

Frictional Results

The frictional property of UHMWPE is presented in Fig. 3 The friction coefficient vs. sliding distance is displayed in the figure for the dry contact condition. The figure shows that there is a bit high friction coefficient before the 4-6 km and then dropped. This is kinetic friction and at the initial stage the friction can be considered as static which is much higher than the kinetic friction. After 6 km sliding distance, the friction reached the steady state. De Bona, Laino [7] reported that the friction coefficient is 0.12 when the UHMWPE slide against the stainless steel at 20 N applied load and 0.3 m/s sliding velocity. At the current condition, the applied load was 3 N and the sliding velocity is 3 m/s. the variation in the value of the friction coefficient between the current data and the published can be due to the change in the parameters since the friction is a response to the interaction between the two surfaces.

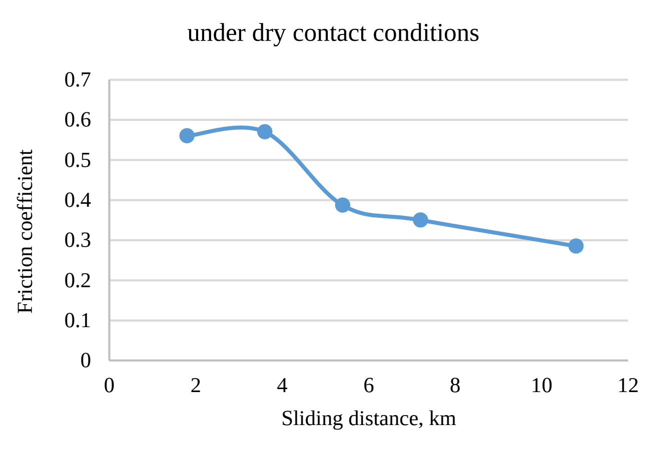


Fig. 3. Friction coefficient of UHMWPE under dry contact conditions

Under the severe condition (current), the pressure x velocity is much higher than the one reported by De Bona, Laino [7]. At high-pressure x velocity condition, there is burning noticed on the surface of the UHMWPE which can the reason in which sticking process took place during the sliding. Wang, Yin [4] reported that the friction coefficient of the UHMWPE is about 0.25 which is similar to the current results. However, Nečas, Sawae [9] reported higher friction than the one reported here which was about 0.35. since the friction is very important in the knee application, I would recommend further investigation about this point to confirm the friction coefficient value.

TRIBOLOGICAL RESULTS UNDER WET CONTACT CONDITIONS

Wear Results under wet contact condition

Under the wet contact condition, the value of the weight loss was very low when the applied load of 30 N used. Therefore, the applied load was increased to 70 N to gain some weight loss. The weight loss of the wear experiments under the wet contact condition is given in Fig. 4 a. the weight loss increases with the time but not proportional linear relation. This can be due to the presence of the water in the interface which reduce the interface temperature and resulting in low materials removed from the UHMWPE surface. Wang, Yin [4] reported similar behaviour when they tested the UHMWPE reinforced with glass fibres and tested under dry and wet contact conditions. The specific wear rate given in Fig. 4b shows steady state after 5 km sliding distance. The value of the specific wear rate is very low which is in similar range to the one reported by [4]. The current value is very competitive to other UHMWPE composites such as the carbon/UHMWPE which should about 12 E-7 mm3/N.m specific wear rate as reported by [4]. Nano diamond reinforced UHMWPE has been tested by Golchin, Villain [8] under dry contact condition and the specific wear rate was to power -6. It seems the wear under the wet contact conditions is much lesser than the dry contact condition which can represent the real application of the UHMWPE in the knee implementations.

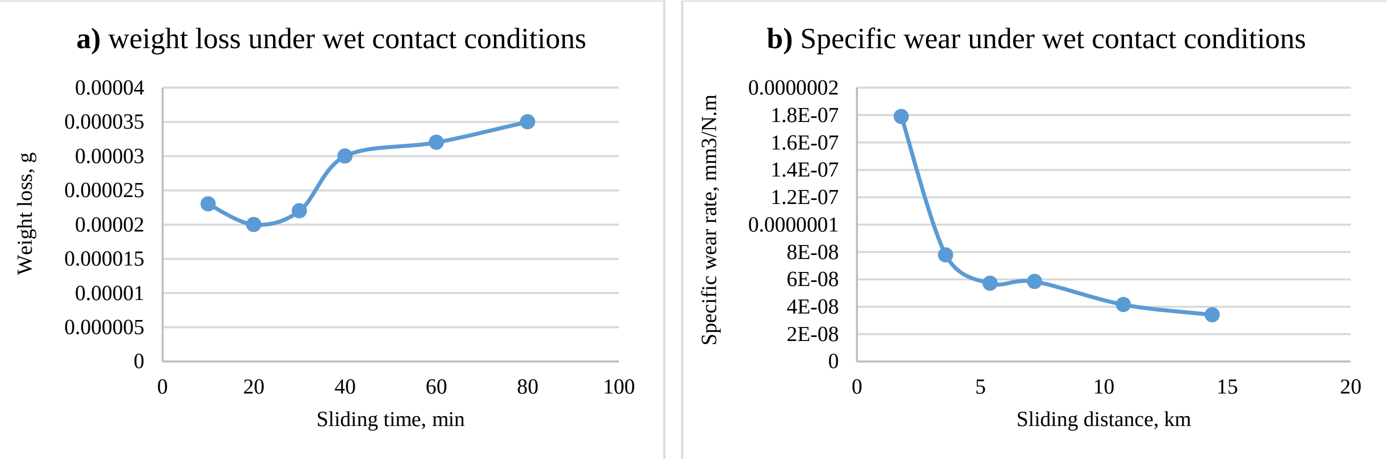


Fig. 4. Weight loss and specific wear rate of UHMWPE under wet contact conditions

Frictional Results under wet contact condition

The frictional results of the UHMWPE sliding against stainless steel under wet contact conditions is given in Fig. 5. The friction value is always below 0.012 which gives a promising result of using such material in knee implementation. The trend of the friction is almost steady at the ranged sliding distance. The presence of the water in the interface acting to clean the debris and also to cool down the surfaces. In addition, water can be used as lubricant at the same time. These are the main reasons of the low friction coefficient. Wang, Yin [4] reported similar values of this friction. However, the value has been measured when the roughness of the surfaces was less than 1 µm. at higher roughness value of 0.3 µm, the friction coefficient increased to 0.12 despite the presence of water. In the current study, the roughness of the counterface was in the same range of the reported work (0.12 µm). Xiong, Yang [10] found similar friction coefficient range when UHMWPE tested against Titanium counterface with the presence of distilled water.

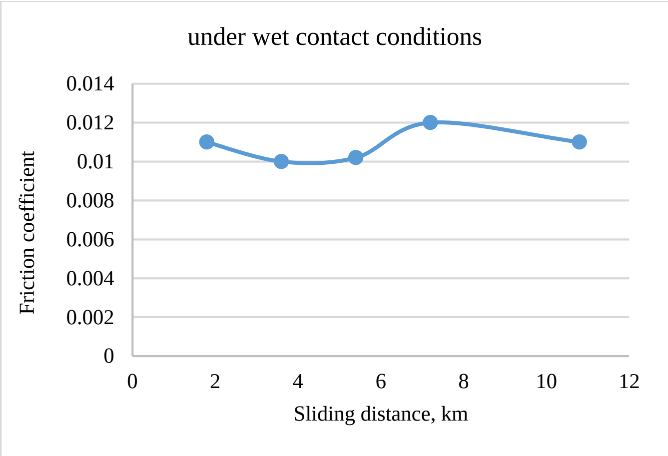


Fig. 5 Friction coefficient of UHMWPE under wet contact conditions

SEM EXAMINATION

In this section, specific wear rate and friction coefficient results of UHMWPE sliding against stainless steel are presented under dry and wet contact conditions with the worn surface micrographs. Fig. 6 shows the specific wear rate against sliding distance under wet and dry contact conditions. It is clear that the wet condition reduces the specific wear rate by about 80%. The presence of the water helps to reduce the material removal from the surfaces. This has been explained previously. It should be mentioned here that the applied load under the wet condition was 70 N while 30 N under the dry contact condition.

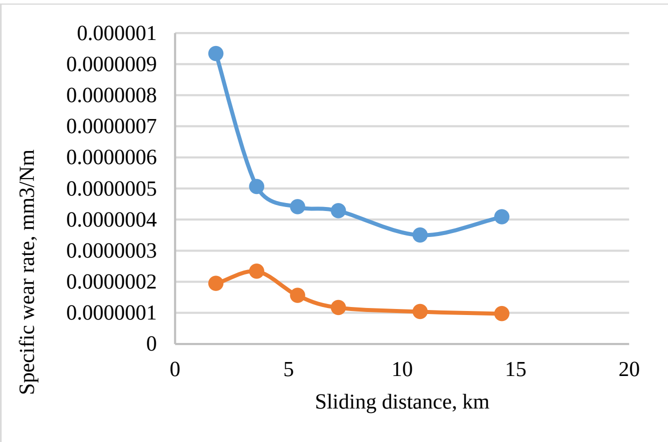


Fig. 6. Wear results of UHMWPE under dry and wet conditions

With regards to the frictional behaviour, Figure 7 displays the friction coefficient of the UHMWPE under wet and dry conditions. It is obvious that the wet condition produces much less friction coefficient compared to the dry contact condition. Under the dry condition, the surface of the UHMWPE is in direct contact with the stainless steel counterface surface which can generate some stick behaviour and prevents the movement. This can result in high resistance to the shear force which produces high frictional force. With the presence of the water, there are different thoughts such as the washing of the debris to prevent any stick behaviour and also it helps to polish the surfaces which can results in very low roughness. This is pure adhesive wear mechanism. The next paragraphs may help to understand this point with the aid of the worn surface micrographs.

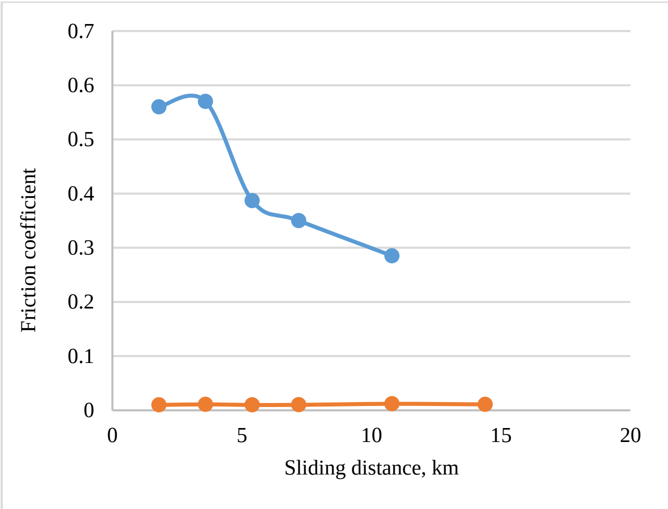


Fig. 7 Frictional results of UHMWPE under dry and wet conditions

The micrographs of the worn surface of UHMWPE under dry contact condition are presented in Fig. 8. All the graphs show abrasive nature on the surface of the UHMWPE which can indicate high material removal as explained previously under the dry condition. In addition, there is large debris can be seen in the surface which were exposed to plastic deformation since they are loose and about to be removed from the surfaces. Meanwhile, Fig. 9 shows relatively smooth surface compared to the one shown in Fig. 8. In addition, there is no presence of debris on the surface or plastic deformation. The wear under wet condition is pure adhesive wear. This helps to further understand the high wear rate in the dry condition (abrasive wear) compared to the wet condition (adhesive wear).

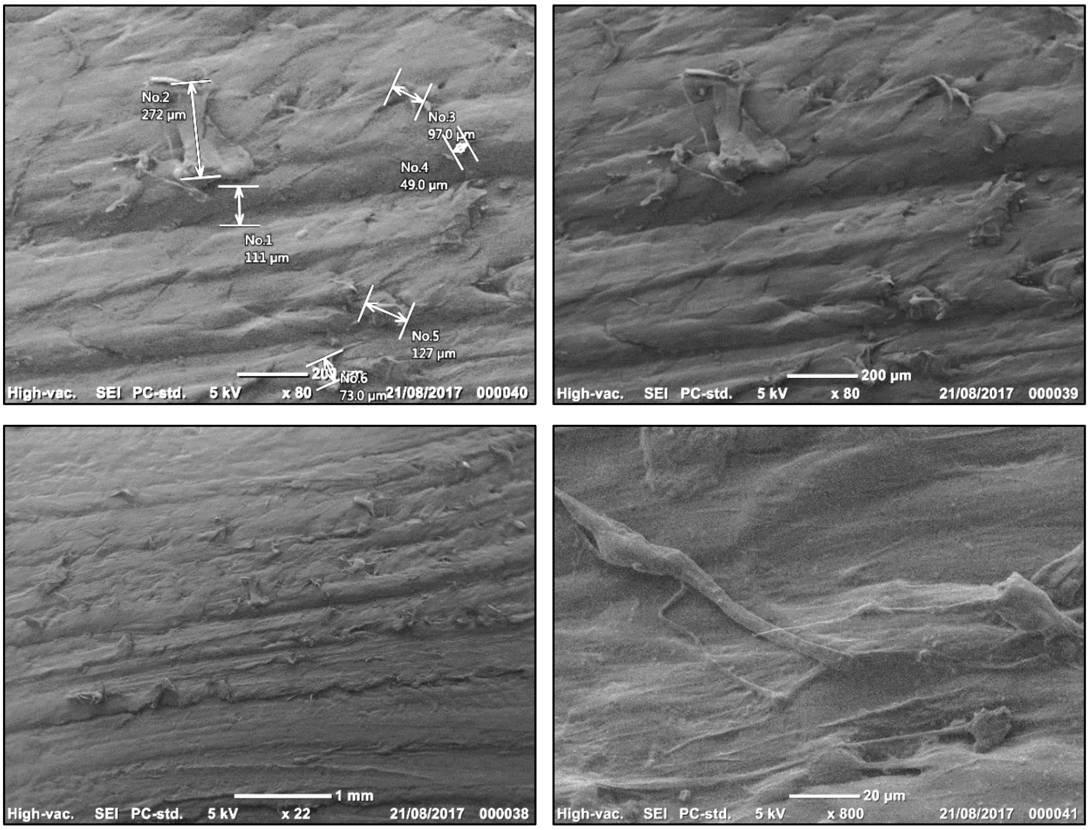


Fig. 8 SEM observation on UHMWPE under dry conditions

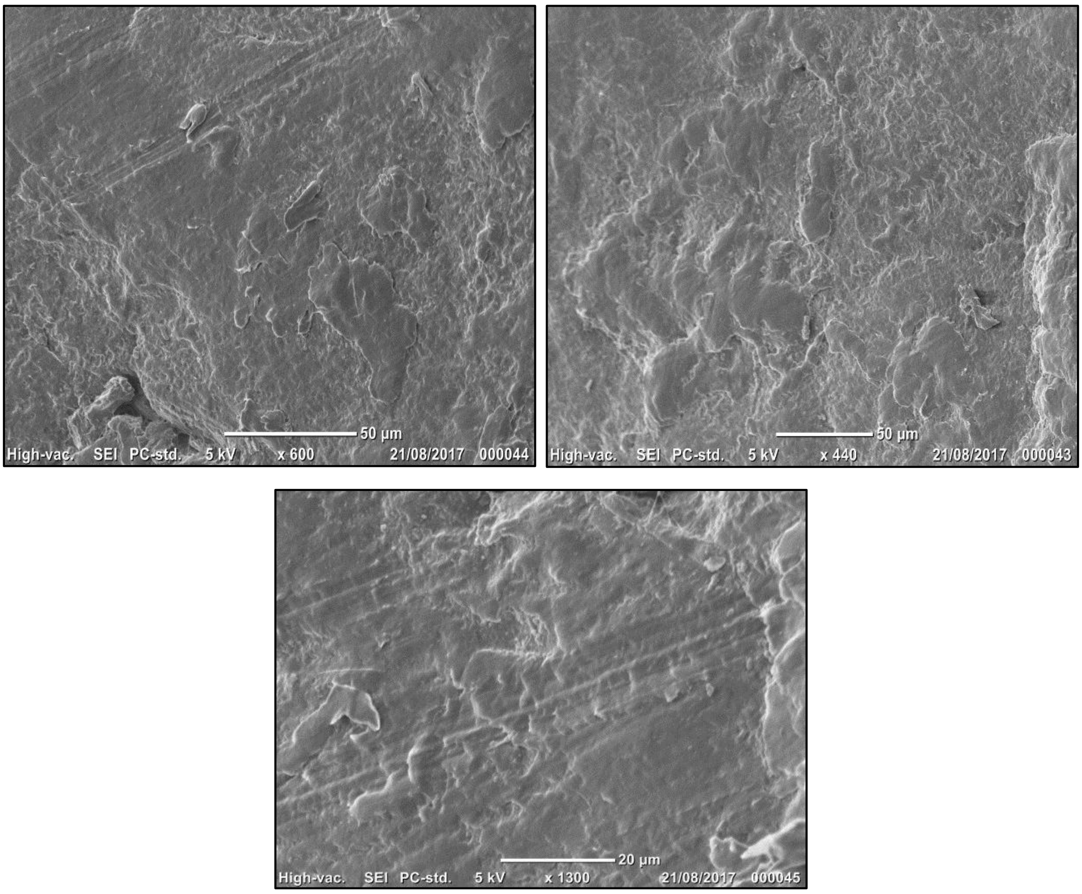


Fig. 9 SEM observation on UHMWPE under wet conditions

CONCLUSIONS

The current study investigates the wear and friction characteristics of UHMWPE under dry and wet conditions. The main findings of the work are

1. The contact condition extremely controls the wear and friction characteristic of the UHMWPE
2. Under dry contact condition, the specific wear rate was much higher than the ones conducted under the wet contact conditions.
3. The friction coefficient under the wet condition was about 0.012 Meanwhile under the dry condition was about 0.3 at the steady state conditions.
4. The presence of the water helped to reduce the heat in the interface and polish the surfaces which was the key of the better wear and frictional performance of the UHMWPE under wet condition compared to the dry condition
5. SEM observations showed abrasive wear nature on the worn surface of the UHMWPE under dry contact conditions. Meanwhile, under the wet condition, pure adhesive wear took place which explained the better tribological result of the material under the wet contact conditions

In the article, there is an argument on the frictional performance of the UHMWPE and there is some confusion about the values of the friction. It is recommended to further study the frictional behaviour of the material under different operating parameters to confirm the friction coefficient value which will significantly determine the usage of such material in knee replacement. In addition and due to the limited time of this project, the debris generated from the wear need attention since it is important to study the size and the shape of the debris which can play important element in the implementation of the UHMWPE in the knee.

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