ISSN 2580-0817

Wear Property of Machined Ultra High Molecular Weight Polyethylene (UHMWPE) Acetabular Liner Product with CNC Milling

W D Lestari[1*], A T Danaryanto[2], A Nugroho[3], R Ismail[2], J Jamari[2], A P Bayuseno[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Pembangunan Nasional "Veteran" Jawa Timur,
Jl. Raya Rungkut Madya, Gunung Anyar, Surabaya, 60294, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Diponegoro University,
Jl. Prof. Soedarto, Tembalang, Semarang, 50275, Indonesia
[3]PUTP (Pusat Unggulan Teknologi Plastik) Politeknik ATMI,
Jl. Mojo No.1, Karangasem, Laweyan, Surakarta, 57102, Indonesia
**Corresponding author:wahyu.dwi.tm@upnjatim.ac.id*

ABSTRACT

UHMWPE has been used as a cushion in artificial hip joint for the last decades. The reliability of the components of a hip joint implant can be achieved by understanding their wear behavior. This study observed the tribological performance of the UHMWPE acetabular liner manufactured with a CNC milling machine on the femoral head made of SS 316L. Materials commonly used for tribo pairs in hip joint replacement. The wear tests were performed on a hip joint simulator in dry condition. The wear test is carried out by applying a constant load of 800N. Before and after the wear test, measurements of surface roughness and dimensional accuracy were carried out on the UHMWPE acetabular liner specimen. The correlation between the surface roughness of the machining process and the wear rate is seen from the value of the wear depth and the wear coefficient obtained. The results showed that the machining process affects the surface roughness of the acetabular liner, where the roughness also affects the wear rate of acetabular liner product.

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Keywords: *Acetabular liner, milling, surface roughness, UHMWPE, wear*

I. Introduction

One of the vital parts of the human body is the hips [1]. The hip joint has an important role in the human body such as performing daily activities (walking, going downstairs, running, exercising, salat for muslim, etc.) because of its ability to transmit static and dynamic loads. Some of the problems that are often experienced by the hip joint include osteoarthritis, joint fractures, damage to the components of the femoral head and acetabular cup, and reduced synovial fluid in the joints. This makes the delivery painful, and an artificial hip implant is needed. The process of removing the diseased hip joint with an artificial hip joint that is similar in shape and function to the natural hip joint which is made of biocompatible materials, is known as Total Hip Replacement (THR). Many pairs of materials have been used for artificial hip joints. One of the most successful and widely used material pairs is UHMWPE against metal [2]. UHMWPE is the superior material used for today's artificial hip joint components [3]. As for metal components commonly used for biomedical applications is stainless steel 316 L due to its strength, thermal stability, high specific moduli and most importantly good wear resistance [4].

DOI: 10.17977/um016v5i22021p110

Despite its excellent properties, UHMWPE as a cushioning material in artificial joints has significant tribological problems. These problems include the appearance of wear debris of small size, which causes an adverse reaction in the surrounding tissue, resulting in aseptic loosening of the prosthesis components [5]. Because of this, UHMWPE materials have a limited lifespan of 15-20 years [6]. The wear behavior of hip implant materials depends on the condition of the surface, which can be obtained through the manufacturing process. Several scientific papers report on the effect of the manufacturing process on the characteristics of the resulting surface, which will certainly have an impact on the performance of the implant.

The application of multiple passes and cryogenic cooling to achieve high surface quality can improve wear performance [7], and also, there are correlation between surface integrity, surface topography, and material response [8]. Furthermore, the effect of surface roughness on the wear rate was also studied on the CoCrMo femoral head [9], MoM pairs material [10], and due to manufacturing process [11]. The wear of implant products is appreciated by the fact that the appearance of a large amount of wear has an adverse effect that can impact the life of the implant [12]. This wear rate can be reduced, and its life can be significantly extended by improving the quality of the bearing material [13-14]. Based on these reasons, research analysis and testing is an important part in the design and development of the hip joint to improve function and quality before the implantation process. Wear tests on hip prosthetics are usually performed on a steady motion walking cycle obtained from the biomechanical literature [15-16]. The hip simulator is an experimentally proven tool for basic investigations and preclinical testing to minimize patient harm when receiving a new type of implant.

Hip joint simulator conducted to observe the changes in surface topography at the research stage of ball and socket friction pair [17], the wear performance of a non-cross linked UHMWPE pair versus two metal counterfaces, namely stainless steel (SS) and cobalt-chromium (CoCr) alloys, ceramic on ceramic [18], and cross linked ultra-high molecular weight polyethylene liners [19] on a variety of daily activities [16]. However, from some of the available literature, no one has paid attention to the influence of the UHMWPE acetabular liner machining process using a milling machine on the wear rate. Therefore, the purpose of this study was to observe the effect of the acetabular liner machining process for UHMWPE hip joints on wear behavior. The machining process is carried out using a CNC milling machine in dry conditions. A hip joint simulator was used to evaluate the wear rate of the UHMWPE acetabular liner from the machining process. Wear resistance tested for 30.000 cycles under walking cycle conditions. Wear quantity is calculated based on weight loss.

II. Material and Methods

A. Specimens Preparation

The hip joint was consists of a ball and socket located between the acetabulum and the femur in the pelvis [20]. In this study, the acetabular liner component is derived from UHMWPE rod-shaped material which is manufactured using a CNC milling machine in dry conditions (Figure 1). The CNC milling machine used is YCM 1020 EV 20 with 3 axes. In this research, 9 samples of acetabular liner were produced with CNC milling machine cutting parameters such as feed rate, toolpath strategy, step over, and spindle speed [21]. The size of the UHMWPE acetabular liner formed is with an inner diameter of 28.2 mm. The result of this acetabular liner milling process must have a surface roughness below 2 μm and dimensional tolerance in the range of +0.3 and -0.0 according to ASTM F2033-12. Furthermore, optimization was carried out on 9 samples of acetabular liner from the results of the manufacturing process to get 3 samples with the best roughness value. The 3 samples (Figure 2) of the acetabular liner from the optimization results were then tested for wear. Based on the measurement results, the size range of the acetabular liner specimen is obtained, namely the outer radius of 18.5 mm and the inner radius of 14.1 mm, where the three samples are still within the dimensional tolerance. The femoral head component is made of SS 316 L material with a diameter of 28 mm.

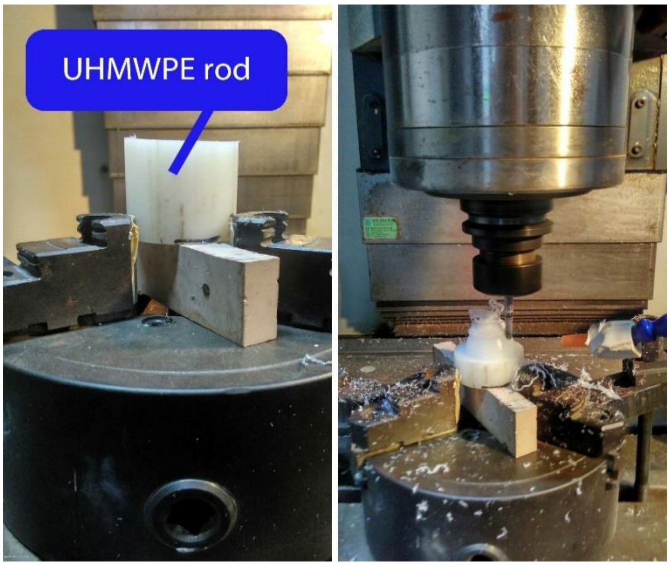

Fig. 1. Experimental set up for the milling of UHMWPE acetabular liner

Fig. 2. Acetabular liner

UHMWPE acetabular liner products resulting from the machining process are measured for surface roughness before wear testing is carried out. The process of measuring surface roughness was carried out using the Mark Surf PS1 surface roughness tester. The surface roughness measurement is carried out again after going through the wear test process, where the results can be seen in Table 1.

Table 1. The value of roughness of the inner acetabular liner before and after the test

Acetabular liner	Surface roughness	
	Before	After
Specimen 1	0.926	0.7756
Specimen 2	1.161	0.7182
Specimen 3	0.848	0.6786

The surface roughness values obtained from this study are in accordance with previous studies [22], which stated that the initial surface roughness of the polymer ranged from 0.4 µm - 2.2 µm, but generally has a surface roughness level of about 1 µm - 2 µm. In another study showed that the maximum initial surface roughness level of UHMWPE was 2µm before the wear test was carried out [23-24].

B. Wear Test using Hip Joint Simulator

The prototype joint generated from the manufacturing process is then carried out preclinical testing using a simulator that is able to imitate motion behavior, biomechanics, and environmental conditions in the human body [24]. Tribological measurements in this study were carried out using a specially modified tribometer in the chamber to test the wear of the acetabular liner. The working principle of this tribometer machine is similar to the human hip joint, where there is a femoral head which is a parable of a human femur and a cup as a human pelvis. The maximum load that this testing machine can accept is 3000N. According to Hua et al. [25], the resultant force of the hip joint is 2500N, which is equivalent to 3-4 times the human body weight of 70 kg. The test design applied in this study is to provide as much insight as possible about the physical loading and motion that occurs between the femoral head and the acetabular liner upon contact.

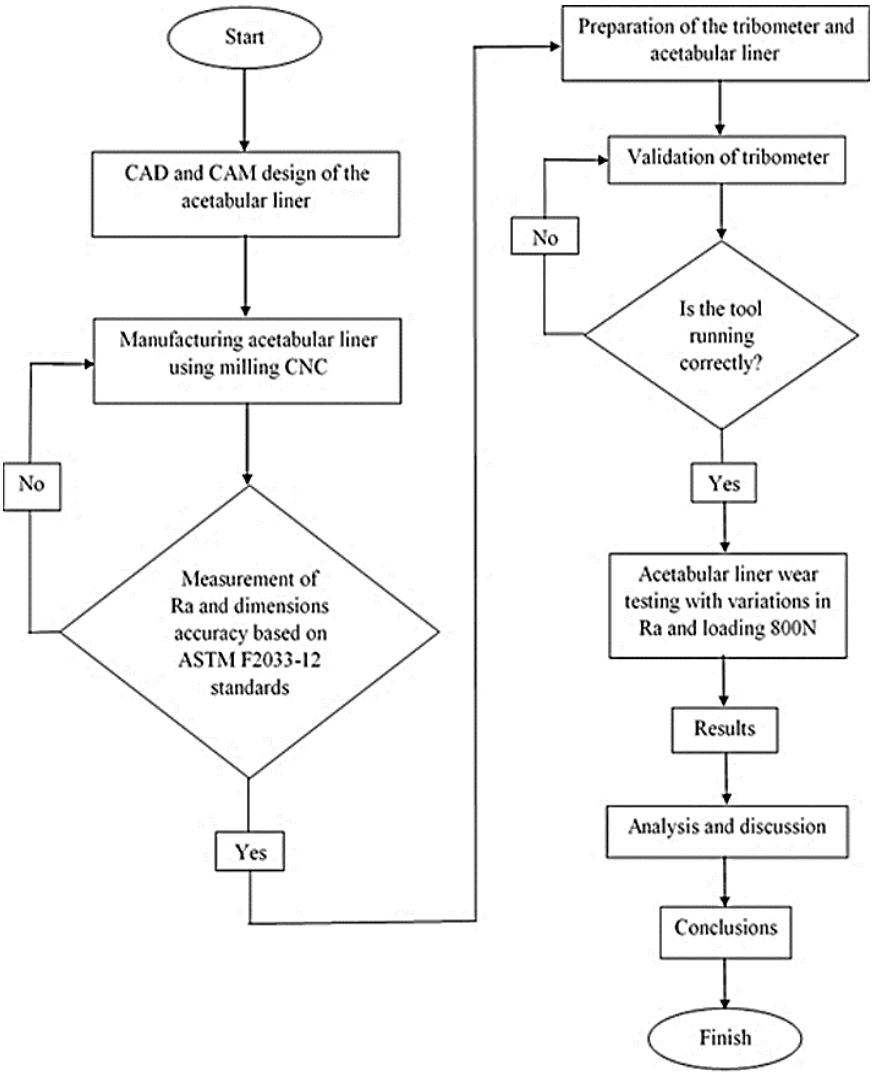

Fig. 3. Flowchart of the testing procedure of the UHMWPE acetabular liner using a tribometer

The testing parameters in this study are based on the ISO 14242 standard and previous research [26]. This study focuses on the effect of the UHMWPE acetabular liner machining process with CNC milling machine on the wear rate. The amount of force on the acetabular liner is determined by the weight of the human body. In this study, the amount of force applied is 800N which is based on the assumption of the patient's average weight [26]. The number of cycles applied in this test is 30000 cycles. The UHMWPE acetabular liner is attached to the SS 316L femoral head and encapsulated in the specimen chambers. The pair of specimens were sterilized first using 70% alcohol before being installed on the test machine. The wear testing process is carried out in dry conditions and at a temperature of 20^0C. Gravimetric wear was obtained from the test results based on mass transformation. The entire experimental process in this study is shown in the flow chart in Figure 3.

C. Dimensional Accuracy Measurement

In addition to surface roughness, this study also measures the dimensional accuracy of the acetabular liner product. This measurement is carried out to ensure whether the resulting product conforms to the specified dimensional tolerance or not. Dimensional accuracy measurement using a coordinate measuring machine (CMM). Measurements are also carried out before and after the wear test process.

III. Results and Discussion

The results of this study will be used as a reference to improve the hip implant prototype. The resulting data in the form of the number of cycles and the depth of wear will be made into a graph of the relationship between the cycles and the depth of wear of the three test specimens. Changes in the volume of the acetabular liner were obtained by weighing. Changes in the initial and final weight data of the acetabular liner are shown in Table 2. Changes in the weight of the three samples prove that there is wear caused by the testing process in the walking cycle. Based on the weight change data contained in Table 2, it can be seen that test sample 2 has the largest weight change among the three samples. Furthermore, the data changes in the three samples are compared into a single graph to determine the difference in the depth level of each specimen (Figure 4). The wear rate is determined by linear regression of the wear (mm) with the number of cycles. The wear depth (mm) of the UHMWPE acetabular liner is recorded as a function of the cycle length with a force of 800N.

Table 2. The initial and final weight of the acetabular liner

Specimens	Initial weight (g)	Final weight (g)	Weight change (g)
Specimen 1	6.8274	6.8260	0.0014
Specimen 2	6.3646	6.3350	0.0296
Specimen 3	6.1734	6.1720	0.0014

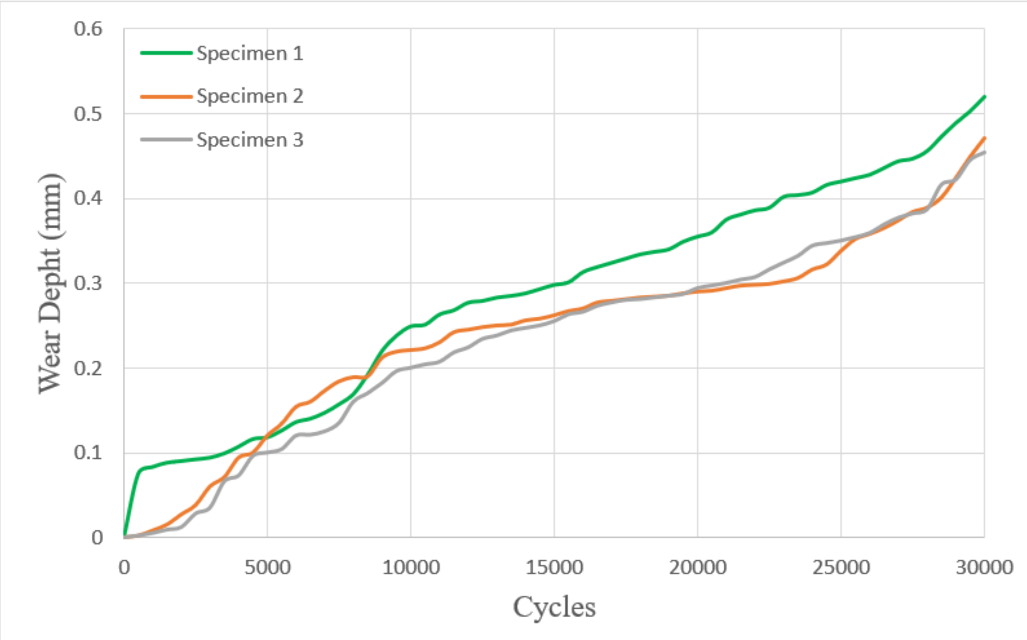

Fig. 4. Comparison of test results of 1,2,3 specimen with 800 N force

Based on Figure 5, it can be seen that the test results of the three specimens showed almost the same trend. The lowest wear depth is owned by specimen 3, where the largest wear depth is owned by specimen 1. There is a difference in the wear depth on the test results of specimen 1 from cycle 0 to cycle 3000 compared to specimen 2 and specimen 3. Furthermore, the trend of the three objects shows the same trend after cycle 3000 to cycle 30000. The test results in this study indicate that there are different wear values of each acetabular liner specimen, where this is influenced by the presence of different roughness as well. Based on the graph, the value of the depth of wear for each specimen is obtained through 30000 cycles of wear testing. Each specimen has a wear depth of 0.52 mm, 0.471 mm, and 0.454 mm from specimen 1, specimen 2, and specimen 3, respectively.

An understanding of wear behavior is an urgent part of obtaining preclinical data on the prosthesis prior to implantation. In this regard, in this study, we conducted a wear test on a laboratory scale to determine the wear behavior of the acetabular liner from the machining process as a bearing on an artificial hip joint. Wear measurement is especially needed to measure new designs and materials because of the continuous need to manufacture new joints. One solution to get the right component prosthesis design is to take geometry measurements before, during, and after wear testing. For this purpose, this study uses a coordinate measuring machine (CMM) to measure the dimensional accuracy of the acetabular liner specimen before and after the wear test. The results of dimensional accuracy measurements on the three acetabular liner specimens are presented in Table 3.

Table 3. The value of dimension accuracy of the inner acetabular liner before and after testing

Acetabular liner	Accuracy Dimensions	
	Before	After
Specimen 1	14.439 mm	14.331 mm
Specimen 2	14.470 mm	14.134 mm
Specimen 3	14.354 mm	14.228 mm

Uddin et al.[27], in their research, measured the wear of polyethylene acetabular liner with CMM where the average linear and volumetric wear rates were 0.12 mm/year and 37.18 mm^3/year, respectively. Previous studies [28] also reported acetabular linear and volumetric wear rates with XLPE materials of 0.024 mm/year and 4.5 mm^3/year, respectively. In this study, specimen 2 had the biggest difference between before and after the test, which was 0.336 mm during the testing of 30000 cycles. Furthermore, specimens 1 and specimens 3 had differences in accuracy dimensions of 0.108 mm and 0.126 mm, respectively. This result is bigger when compared to previous studies.

Validation is needed before carrying out the wear testing process using a tribometer machine to find out whether the tool used is valid enough to take data. The validation method is to calculate the wear coefficient value generated from the test using the Archad equation with the femoral head radius of 14 mm and the acetabular liner radius of 14.1 mm. The load used is equal to 800 N with 30000 cycles. The value of the wear coefficient produced in this test is equal to 1.945 x 10^{-4} mm^3 N^{-1} m^{-1}. This value is then compared with the results of research conducted by Dowson [29] by entering the research parameters in the formula. Dowson et al. [29] conducted a wear test and obtained two wear coefficient values, namely 1.35x10-7 mm^3 / Nm and 4.49x10-7 mm^3 N^{-1} m^{-1}. The results of the validation can be seen in Figure 5 as for the wear depth formula [29], namely:

$$p = \frac{0.001186}{\pi}\left(\frac{kBN}{R_1}\right)\left[1+\sqrt{1+1686\pi\frac{R_1(R_2-R_1)}{kBN}}\right] \quad (1)$$

Where P is penetration or wear depth (mm), k is wear coefficient (mm^3 N^{-1} m^{-1}), B is Body weight (N), N is number of cycles (cycles), R_1 is femoral head radius (mm), and R_2 is acetabular liner radius (mm). The results show that there are differences in the test results where the wear value obtained is higher than that produced by Dowson when the cycle runs more than 4,500 cycles, but the trend is almost the same. Thus, it can be concluded that the tools used are valid enough to be used in conducting research.

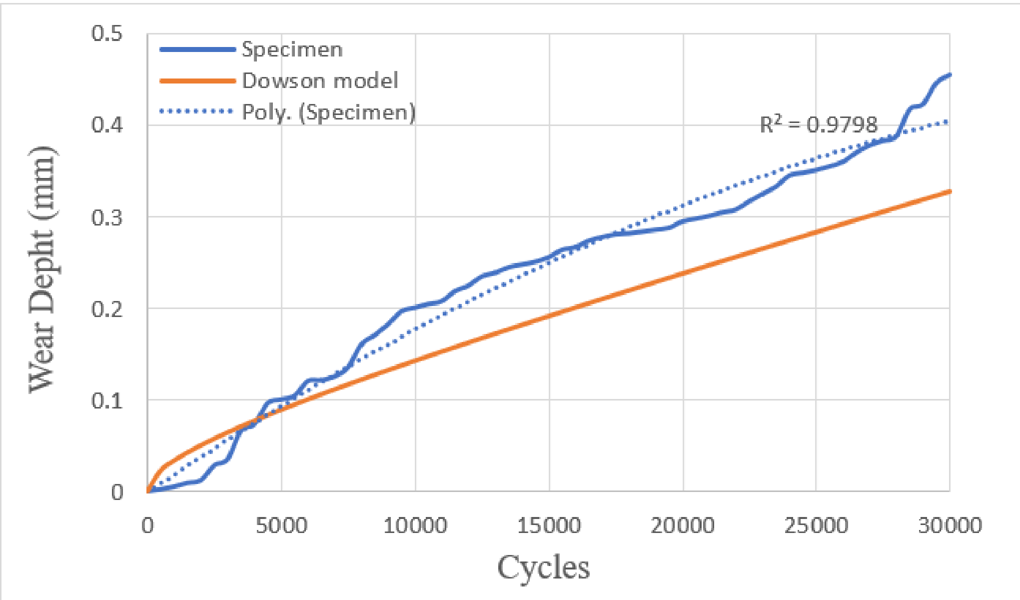

Fig. 5. Validation of test with Dowson model

The level of wear on biomedical components such as acetabular liners with variations in specifications and materials can be predicted through in vitro tests. The hip simulator test is the most commonly used tool by researchers to test the wear level of the acetabular liner with various parameter tests. In this study, the tribological behavior of the UHMWPE acetabular liner from the results of the CNC milling process with the femoral head pair was observed using a hip simulator based on the walking cycle. The difference in the wear rate of each specimen is caused by the difference in the surface roughness values obtained from the machining process [30]. This study took three samples of UHMWPE acetabular liner with the best roughness value based on the optimization results of nine samples made. The calculation results of the wear coefficient with the difference in the surface roughness values are shown in Figure 6, where the values of the wear volume and the level of penetration are presented in Table 4.

Table 4. Summary of UHMWPE wear behaviour in the simulator test condition.

Sample	Wear volume (mm^3)	Penetration rate (mm/year)	Wear coefficient ($mm^3N^{-1}m^{-1}$)
Specimen 1	102.98	0.33	2.78 x 10-4
Specimen 2	79.54	0.289	2.2 x 10^{-4}
Specimen 3	75.46	0.279	1.95 x 10^{-4}

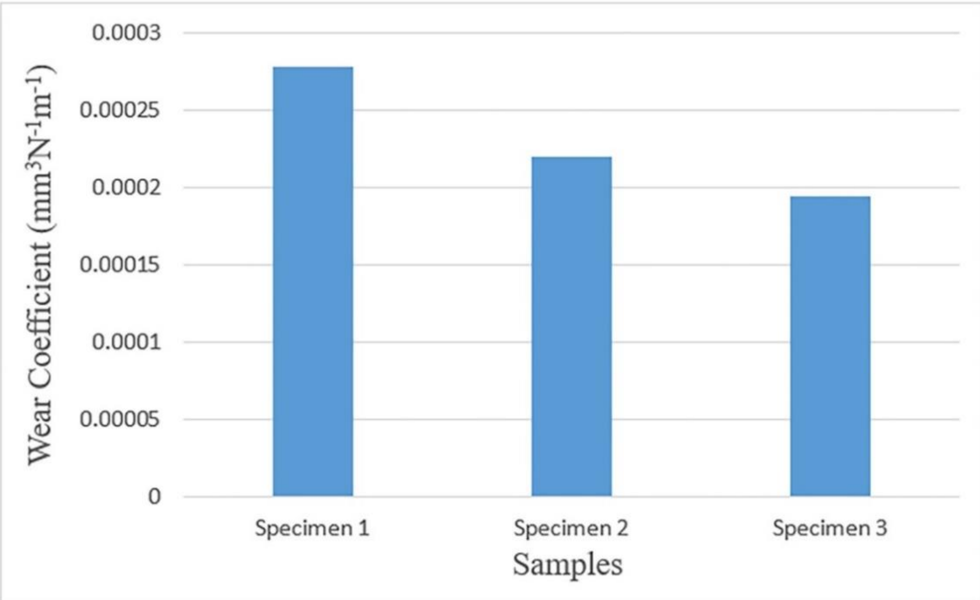

Fig. 6. Graph of wear coefficient calculations

Based on the graph in Figure 6, it can be seen that the highest wear coefficient value is found in specimen 1 of 2.78 x 10^{-4} mm^3 N^{-1} m^{-1}. They were then followed by specimens 2 and 3 with values of 2.2 x 10^{-4} mm^3 N^{-1} m^{-1} and 1.95 x 10^{-4} mm^3 N^{-1} m^{-1}, respectively. If observed, these results are related to the value of surface roughness. In accordance with previous studies [31], where the wear coefficient value produced is different in the contact test between UHMWPE which has an initial roughness value range of 1-2 µm with high-density alumina ceramic in dry conditions and lubricated with distilled water. After the wear test process, the surface roughness of the UHMWPE acetabular liner became smoother and the value decreased from the initial surface roughness value (Table 2). This is as a result of the contact surface. This is also supported by previous research where the surface roughness value of UHMWPE was reduced from the initial value after going through a wear test process with a hip joint simulator for 5 million cycles [23-24]. Furthermore, the average surface roughness of UHMWPE acetabular liner decreased, ranging from 0.053 µm and 0.25 µm from the initial average surface roughness of 0.95 µm [32-33]. The observations results on the surface of the acetabular liner sample after testing 30,000 cycles indicate the presence of wear areas such as polish due to continuous loading. The surface of the acetabular liner may be scratched due to the appearance of a third body particle trapped between the polymer and metal surfaces.The scratch occurs because the counterface metallic is forced to move against the surface of the acetabular liner polymer and also a third body abrasion characterized by random directional scratches on the acetabular liner [23-24].

In this study, the wear mechanism that occurs is the third body abrasion with the test results in the form of wear depth and wear coefficient. The amount of wear in vivo generally ranges from 50-100 mg per year [33]. In various simulators, it is found that the wear value of polyethylene is in the range of 20-35 mg per 1 million cycles [34]. The total wear of the UHMWPE acetabular liner was 6378 mg for the acetabular liner with gamma irradiation and 7672 mg for the acetabular liner with EtO sterilization after going through five million cycles of testing [35-36].With a linear wear rate of 0.16 mm/year, UHMWPE wear around 48 mg/106 cycles [23-24]. Furthermore, UHMWPE wear about 31.73 mg/million cycles and 15.20 mg/million cycles at 784 N and 392 N loadings, respectively [36]. An annual wear rate similar to the annual wear rate obtained from the observed popular MoP hip reconstruction, which was 25 mg per million cycles [37-38].

In this study, the lowest weight obtained after going through the wear testing process was 0.0014 g (1.4 mg/30000 cycles). The data obtained from this study cannot be compared directly with the results of wear experiments from the literature using a hip endoprosthesis simulator because the mechanism used is still simple on a laboratory scale [36]. The focus of this research is to examine the effect of the UHMWPE acetabular liner manufacturing process with CNC milling on surface roughness, where this roughness will affect the wear level of product for artificial hip joints. However, if plotted on a graph and calculated based on a linear equation of 1 million cycles, the wear rate of UHMWPE manufactured using a CNC milling machine is still in accordance with the in vivo wear rate provisions in the literature [38]. The wear tests performed in this study are in accordance with the literature, which describes the material wear of a commonly applied hip implant component under appropriate loading. Based on the test data and observations on the sample, it can be obtained that the surface roughness of the acetabular liner resulting from the milling process affects the depth and coefficient of wear.

IV. Conclusions

This study explores the influence of the UHMWPE acetabular liner manufacturing process with a CNC milling machine on the level of wear. Based on the results of the study, the conclusions obtained that the results of the wear coefficient calculation of the UHMWPE acetabular liner specimen indicate that the greater the surface roughness value of the acetabular liner, the greater the wear coefficient value, where the highest wear coefficient value is owned by specimen 1 of 2.57 x 10^{-4} mm^3/Nm. The rate of wear depth and the wear coefficient of the UHMWPE acetabular liner produced in this study is influenced by the surface roughness value of the machining process with CNC milling.

Acknowledgment

The authors would like to acknowledge the LPPM of the University of Pembangunan Nasional Veteran Jawa Timur, which has supported financially for this publication. We also thank to the tribology laboratory of Diponegoro University and the PUTP ATMI for holding this experiment.

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