Study of wear performance of crosslinking UHMWPE acetabular liner for artificial hip joint made from CNC milling

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Abstract. Crosslinked ultra-high molecular weight polyethylene (UHMWPE) is a preferred material used as a bearing material in the artificial hip joint. The purpose of this study was to analyze the effect of dose cross-linking acetabular liner manufactured by CNC milling on wear depth. The wear test is carried out with a tribometer machine by loading the acetabular liner in a certain cycle. The test results found that specimens given a crosslink dose of 50 kGy with a load of 800 N resulted in a greater wear depth compared to specimens given a crosslink dose of 100 kGy with a load of 800 N. Specimen with crosslink dose 50 kGy yield greater wear depth than specimens given a crosslink dose of 100 kGy. Based on these results it can be concluded that the greater the crosslink dose given to the specimen will increase the wear resistance of the specimen so that the test results in a smaller wear depth.

Keywords: Crosslinking; UHMWPE; Wear Depth; Artificial Hip Joint.

1. Introduction

The joint is the link between the bones so that the bones can be moved. The hip joint is a very important joint in the lower limbs, because it carries the greatest load compared to other joints in the human body. Some of the permanent damage that can occur in the hip joint is the result of calcification, aging and accidents that require replacement with an artificial hip joint. Artificial hip joint replacement is a surgical method to replace the damaged part with a metal, ceramic, or polymer model so that the hip can move normally [1]. A total of 427,181 joint replacement procedures were performed in the United States of Amerika between 2012 and 2015 [2]. The most commonly used artificial pelvic pairs are stainless steel and UHMWPE pairs. UHMWPE with a molecular mass between 3500 and 7500 kDa has properties such as, lubricity, chemical stability, abrasion and impact resistance which are widely used in orthopedic applications [3]. However, it is known that the wear particles of the UHMWPE polymer in the artificial hip joint have been a major factor causing osteolysis and joint loss, thus limiting the lifetime of the implant and ultimately requiring surgical revision. Based on this, the wear and tear of UHMWPE has been studied extensively in industry and academia [4], where most of the focus is on the negative effects of wear debris on the body [5], and techniques to reduce the total wear volume, by means of crosslinking [6]. Crosslinking is the process in which carbon atoms of same or different polyethylene chains are combined together to form a threedimensional network structure [7]. One way of the cross-linking process is by immersing UHMWPE specimens in 1,7-octadiene, methylacethylene and ethylene, and exposing the sample to an electron beam at doses of 25, 50 and 100 kGy [10]. Therefore, cross-linking assistances in reducing elongation at break and yield index while improving creep resistance, impact strength, and resistance to fatigue and environmental stress cracking resistance (ESCR) [11]. Crosslinked ultra-high molecular weight polyethylene (UHMWPE) is extensively operated as a bearing material in artificial hip joint components [12].

Several researchers conducted research on crosslinked UHMWPE. Saiko [13] investigation the effect of lubrication on wear factor of highly crosslinked UHMWPE and unirradiated UHMWPE using multidirectional pin on disk tests. The outcomes presented that the wear factor of high cross-linked UHMWPE was 5.7 times lower than that of unirradiated UHMWPE. Garcia et al [2] studied the effect of oxygen plasma on crystallinity, hardness, surface chemistry and structural composition of UHMWPE at different treatment times. The results show that the cross-linking of the polymer can increase micro-hardness. Vidya et al [11] perform cross linking to reduce the wear rate of UHMWPE and compare its properties with conventional UHMWPE and its biocompatibility. The results show that an increase in cross-linking efficiency is followed by an increase in the wear resistance and mechanical properties of UHMWPE. Sirimamilla and Rimnac [14] investigated the resistance of crosslinked UHMWPE to crack initiation for clinically relevant notches under static and cyclic loading conditions. The results show that cross-linked UHMWPE is more resilient to crack initiation from the notch under static loading conditions compared to fatigue loading. The objective of this study was to investigate the effects of radiation dose on UHMWPE acetabular liner wear rate under cyclic/static loading condition. This study tested the wear depth of acetabular liner as a result of the optimization of the crosslinked UHMWPE cutting parameters with a load variation of 400 N and 800 N using a tribometer testing machine in dry condition (without lubrication).

2. Materials and methods

2.1. Materials / Sample preparation

The specimen used in this study was the acetabular liner specimen and its partner, the femoral head. The acetabular liner specimen is made of UHMWPE polymer material, while the femoral head is made of SS 316L material. Both materials are approved by their nature to be used in hip joint replacement. The computer numerical control milling machine (YSM 1020 EV 20) with 3 axes used to process the acetabular liner under dry condition (without lubricant). The acetabular liner specimen produced had an outer radius of 18.5 mm and an inner radius of 14.1 mm which corresponded to dimensional tolerances. According to ASTM F2033-12 specifications for acetabular liners, the results of this milling process must have a dimension tolerance between +0.3 and -0.0 and a roughness value below 2 μm. The 4 acetabular liner sample (Figure 1), was then given a crosslink treatment with a dose of 50 KGy and 100 KGy. Before testing, the specimens are cleaned using 70% alcohol to remain sterile.

Figure 1. Acetabular liner specimen with crosslink 50 kGy (1 and 3), 100 kGy (2 and 4).

2.2. Wear test using hip joint simulator

The joint prototype resulting from the fabrication process should be verified in a simulator that models biomechanical loads, motion, and environmental conditions in the body [15]. Acetabular liner wear testing results of the milling process in this study were carried out with tribometer test equipment that has been specially modified to carry out testing (Figure 2). The working principle of this machine is like a human hip joint where the femoral head is in contact with the human femur, and the cup is the human pelvis. This test machine has an acceptable maximum load of 3000 N. The resultant contact strength of the fixed hip joint is 2500 N, corresponding to about 70 kg for 3-4 times body weight [10]. The test design applied is illustrative and practical with respect to movement and physical loading between the femoral head and the acetabular liner.

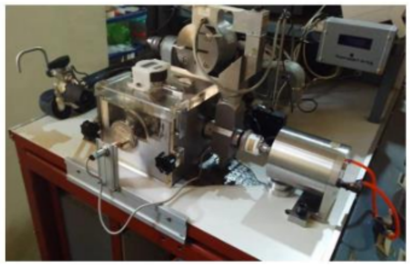

Figure 2. Tribometer machine.

The two parameters that underlie this test are the number of cycles and the force applied. As with previous studies conducted by [17], [18], these acetabular liner test parameters are in accordance with ISO 14242 standards. ISO 14242 standards state that wear testing up to 5 million cycles. Wang et al [19] tested specimens for intervals of a total of 2 million cycles by physiological loading under diluted alpha serum lubricating conditions. Saikko and Shen [20] tested the UHMWPE acetabular liner for up to 5 million cycles. The number of cycles in this study is dissimilar from earlier studies. The focus of this research is to observe the effect of the machining process of acetabular liner products which are then given crosslink treatment on their wear value. The amount of force applied to the wear test is in accordance with the load received by the pelvis on the human body, which is 800N [21]. The acetabular liner sample was attached to the femoral head and packed in the specimen chamber as shown in Figure 3. The specimens were then tested for 30000 cycles. The wear test was carried out at room temperature with a temperature of 20°C with conditions without lubrication. The process of testing the UHMWPE crosslink acetabular liner wear is shown in the flow diagram in Figure 4. Measurement of roughness, dimensional accuracy, and mass is also done to find out the comparison between before and after wear testing.

Figure 3. Setting acetabular liner on the tribometer machine chamber element.

2.3. Measurement of surface shape

The measurement of dimensional accuracy after all machining steps and wear tests had been finished by a coordinate measurement machine (CMM). Measurement after the machining process is carried out to determine the difference in dimensions between the design and the product machining results. The measurement of dimensional accuracy after wear testing is to observe the difference in dimensions that occur due to wear. The measurement procedure using CMM follows the standard found in the tool. In this study, the measurement of dimensional accuracy using a CMM machine was carried out by measuring the acetabular liner specimens in a space that had length, width and height which were then translated into X, Y and Z Cartesian coordinate systems and converted into diameters. The wear volume of implants (hip) both in vivo and ex vivo in some experiments was also measured using CMM, which illustrates its potential in calculating the exact wear volume with suitable [22].

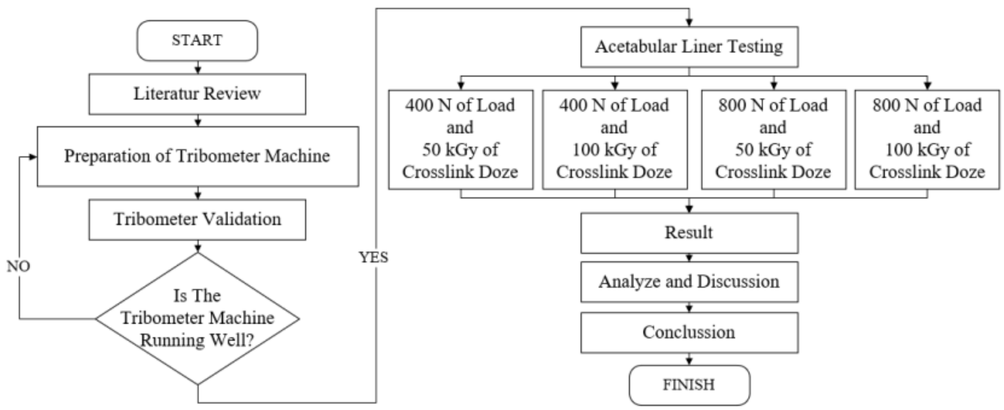

Figure 4. Flow chart of the UHMWPE acetabular liner testing procedure with a tribometer machine.

3. Experimental results

3.1. Measurement of wear mass

The specimen was weighed to determine the change in the volume of the acetabular liner after testing. Figure 5 shows the graph of the test results of acetabular liner specimens with crosslink doses of 50 KGy and 100 KGy and with loadings of 400 N and 800 N. Based on the graph, it can be seen that the value of the wear depth on specimen 1 reaches 0.417 mm for 30,000 test cycles. For specimen 2, it shows a wear depth value of 0.359 mm, specimen 3 reaches a wear depth value of 0.377 mm and specimen 4 reaches a wear depth value of 0.266 mm. The following table 1 shows the initial weight and final weight of the acetabular liner after testing.

After the initial and final weighing after testing, it was found that specimen 1 and 4 had a difference in initial and final weight of 0.0005 grams, specimen 2 had a weight difference of 0.0004 grams and specimen 3 had a weight difference of 0.0007 grams. From these data, it can be seen that specimen 3 has a greater difference in initial and final weight after testing than specimens 1, 2 and 4. The change in weight for these 4 specimens proved that the wear occurred during the test which was simulated for a 5 year gait cycle. Figure 6 is a graphical comparison of the wear mass for specimens 1, 2, 3 and 4.

Table 1. The initial and final weight of the acetabular liner after testing.

	Wear Mass		
Specimens	Before testing (gr)	After testing (gr)	Deviation (gr)
Specimen 1	6.7535	6.753	0.0005
Specimen 2	5.685	5.6846	0.0004
Specimen 3	6.4644	6.4637	0.0007
Specimen 4	6.5237	6.5232	0.0005

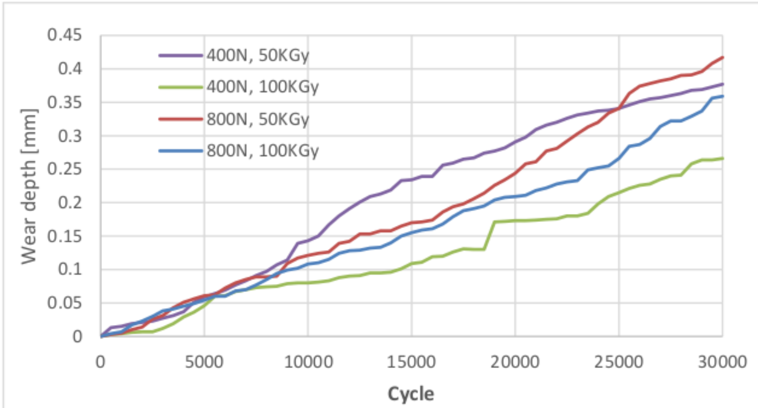

Figure 5. Comparison of the wear depth test results of acetabular liner specimens.

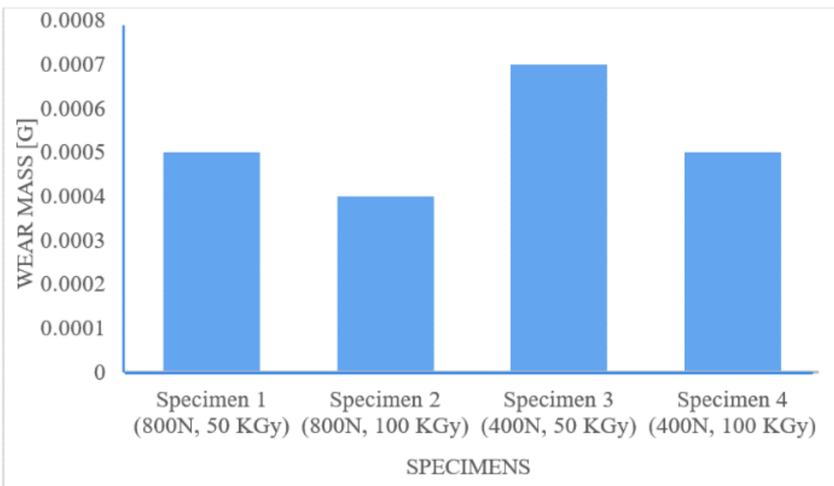

Figure 6. Comparison chart of wear mass specimens 1, 2, 3 and 4.

The mass measurement of the UHMWPE acetabular liner specimen was carried out to determine the difference in mass that occurred after wear testing. The results of mass measurement of acetabular liner specimens are shown in Table 4.8. Based on the table, it can be seen that the UHMWPE acetabular liner specimen with crosslink variation shows that specimen 3 has a greater difference between the beginning and the end after testing than specimens 1, 2, and 4. The weight change in all UHMWPE acetabular liner specimens proves that wear occurs during the test which is simulated for a 5 year gait cycle.

Based on Table 1, it can be seen that the mass difference proves the presence of particles and wear that occurred during the testing process. However, for the test of 30,000 cycles, the particles are still not clearly visible because the wear mass that occurs is still very small. Based on the table, it can also be seen that the crosslink treatment has an effect on the change in mass (wear mass), where the results show that if the greater the crosslink dose is given, the wear resistance is greater and the mass change is smaller.

3.2. Dimensional accuracy measurement of acetabular liner

Understanding the level of laboratory wear is an important characteristic in preclinical authentication of prostheses. In this study, the wear test of the acetabular liner component made from UHMWPE on the hip joint simulator was carried out for 30,000 cycles to evaluate the wear behavior of the material. The elements are machined and finished following an organized standard implant specification. The measurement of joint wear and its evaluation is very important for the design and use of new materials. This is because it is imperative for researchers to continually create new joints and evaluate new materials to continuously improve implant design and performance [15]. To do this, a coordinate measurement machine (CMM) is needed to measure dimensional accuracy before and after wear testing.

The process of machining acetabular liner products made from UHMWPE in this study was carried out in a laboratory and obtained a quality product. Dimensions of UHMWPE acetabular liner products were measured using CMM and all data were recorded. Measurements were made of the outer and inner radii of the acetabular liner. The target dimensions of outer and inner radii of acetabular liner based on CAD design are 18.50 mm and 14.10 mm, respectively. According to ASTM F2033-12 (mm), the product must be within dimensional tolerances in the range of +0.3 mm and -0.0 mm. The dimensional accuracy for the four components of the acetabular liner made from UHMWPE which is subjected to wear testing is given in Table 2.

Table 2. Inner acetabular liner dimensional accuracy value before and after wear testing.

Acetabular Liner	Dimensional Accuracy (mm)	
	Before	After
Speciment 1	14,384	14,304
Speciment 2	14,469	14,392
Speciment 3	14,234	14,154
Speciment 4	14,466	14,386

Uddin et al [23] reported that the average linear and volumetric wear rates of acetabular components made from polyethylene as measured by CMM were found to be 0.12 mm / year and 37.18 mm^3 / year, respectively. The linear and volumetric wear rates of acetabular liner with XLPE material were also reported by Uddin [24] to be 0.024 mm / year and 4.5 mm^3 / year. In this study, the four acetabular liner specimens with crosslink treatment had almost the same difference in dimensional accuracy, which was around 0.08 mm during the 30,000 cycle test, where this result was smaller than the research conducted by Uddin et al [23].

4. Discussion

4.1. Validation

Validation is needed to ensure whether the tool used is good enough before the actual test is carried out using a tribometer machine. The validation method used in this study is to calculate the value of the wear coefficient resulting from the test using the Archad equation with the radius of the femoral head 14 mm and the radius of the acetabular liner 14.1 mm. The load used for validation is the same as that used for testing, namely 800N with as many as 30000 cycles. The value of the coefficient of wear in this validation is 1.945 x 10^{-4} mm^3 / Nm. This value is then compared with research from Dowson and Jobbins [25] by including the parameters in the formula generated from the study. Dowson and Jobbins [25] conducted a test and obtained two values for the wear coefficient of the two tests, namely 1.35×10^{-7} mm^3 / Nm and 4.49×10^{-7} mm^3 / Nm. The validation results can be seen in Figure 7. The wear depth formula from Dowson and Jobbins, [25] is:

$$p = \frac{0{,}001186}{\pi}\left(\frac{kBN}{R_1}\right)\left[1 + \sqrt{1 + 1686\pi\frac{R_1(R_2 - R_1)}{kBN}}\right] \quad (1)$$

where P is penetration or wear depth (mm), k is the wear coefficient ($mm^3\ N^{-1}\ m^{-1}$), B is body weight (N), N is the number of cycles, R_1 is the radius of the femoral head (mm), and R_2 is the radius of the acetabular liner (mm).

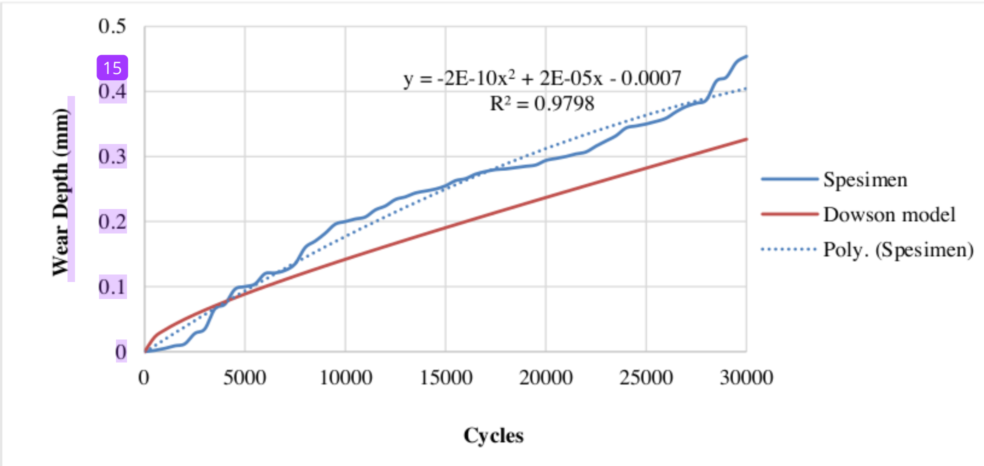

Figure 7. Testing validation with the Dowson model.

The calculation of the wear coefficient for the validation sample of this tribometer using a UHMWPE acetabular liner specimen with a crosslink variation of 50 kGy and a load of 400 N yields a value of 4.09 x 10^{-4} mm^3/ Nm. This value is then entered into the Dowson equation formula and input into the calculation. The calculation results obtained are then plotted on a graph comparing the test results with Dowson's [26] model, the results of which can be seen in Figure 7. The validation results show that the two graphs have almost the same trend. However, in the test results the wear value obtained in this study is greater than the results from the Dowson equation. Thus it can be concluded that the tools used to carry out the test are good enough so that they can produce the same wear trend as the research.

4.2. Wear behaviour

The wear rate of a bearing material can be estimated through testing for various specifications and different activities with orientation to the actual body conditions. In this study, the wear test of the acetabular liner made from UHMWPE was carried out using a tribometer machine on the current cycle. The wear test of the acetabular liner specimens with UHMWPE was carried out by varying the load and dose crosslink for 30,000 cycles. There were 4 acetabular liner samples that were subjected to wear testing with these variations as shown in Table 3.

The data generated from the wear test of UHMWPE acetabular liner specimens are the number of cycles and the depth of wear. Then the data is processed and a graph of the relationship between the number of cycles and the depth of wear is made as shown in Figure 5. Based on the graph, it can be seen that the value of the wear depth on the crosslink specimen shows the value of the wear depth on specimen 1 which reaches 0.417 mm, specimen 2 reaches 0.359 mm, specimen 3 reaches 0.377 mm and specimen 4 reaches a wear depth value of 0.266 mm.

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Table 3. Acetabular liner specimen variation.

Specimens of Acetabular Liner	Load	Crosslink Dose
Specimen 1	800 N	50 kGy
Specimen 2	800 N	100 kGy
Specimen 3	400 N	50 kGy
Specimen 4	400 N	100 kGy

The acetabular liner wear test with crosslink and load variations showed almost the same trend. Based on the graph in Figure 5, it can be seen that each variation of the crosslink dose and load given shows different results. Specimens given a crosslink dose of 50 kGy with a load of 800 N resulted in greater wear depth compared to specimens given a crosslink dose of 100 kGy with a load of 800 N. Based on these results it can be concluded that the greater the crosslink dose given to the specimen will increase the wear resistance of the specimen so that the test results in a smaller wear depth. Based on the crosslink condition, the lowest wear coefficient value is owned by the specimen with the crosslink dose of 100 kGy with a load of 400 N, and the highest value is the specimen with the crosslink dose 50 kGy with a load of 400 N. The results of the calculation of the wear coefficient for the loading parameter of 800 N specimens with a crosslink dose of 50 kGy have a value of 1.46×10^{-4} mm^3 / Nm and a specimen with a crosslink dose of 100 kGy has a value of 9.32×10^{-5} mm^3 / Nm while for the loading parameter of 400 N the specimen with a crosslink dose of 50 kGy has a value of 4.09×10^{-4} mm^3 / Nm and a specimen with a crosslink dose of 100 kGy has a value of 4.55×10^{-5} mm^3 / Nm. The greater the crosslink specimen dose, the smaller the wear coefficient value.

The amount of polyethylene wear in the body generally ranges from 50-100 mg per year [27]. The value of polyethylene wear found in the simulator experiment is in the range of 20-35 mg per 1 million cycles [27][28][28]. In addition, the total wear of UHMWPE acetabular liner after testing for five million cycles was 7672 mg (EtO sterilized acetabular liner) and 6378 mg (gamma irradiated acetabular liner) [18]. Trommer and Maru [29] obtained a UHMWPE wear rate corresponding to a linear wear rate of 0.16 mm / year about 48 mg / 106 cycles. Shibo et al [29] resulting in a wear value of 31.73 mg / 1 million cycles and 15.20 mg / 1 million cycles with each loading 784 N and 392 N in distilled water lubrication. Bragdon et al [28] in his study resulted in mean annual wear from simulator tests similar to that obtained from metal on polymer (MoP) total pelvic reconstruction of 25 mg / 1 million cycles. The lowest weight loss of acetabular liner component made from UHMWPE after wear testing in this study was shown by a specimen with a crosslink dose of 100 kGy and a load of 800 N of 0.0004 g (0.4 mg / 30,000 cycles). The results of this experiment cannot be compared directly with previous studies that have used a total pelvic endoprosthesis simulator, because it uses a simplified wear mechanism.[17][18]. However, the wear rate of UHMWPE acetabular liner from manufacturing using a CNC milling machine is in accordance with the in vivo wear rate requirements in the literature when plotted into a graph and calculated based on the one million cycle linear line equation [27]. Based on the results of the experiments conducted, it can be concluded that the variations in the load and the crosslink dose have an effect on the level of wear depth and the wear coefficient of the acetabular liner specimen.

5. Conclusion

Based on the experimental results obtained in this study, it is concluded that the trend of the acetabular liner test results obtained shows the same results, namely that the depth of wear continues to increase with the increasing number of cycles. Then for the results obtained from the two loading parameters and the dose cross-link given showed different results. This shows that the cross-linking treatment of the UHMWPE acetabular liner milling product has the effect of increasing resistance to wear depth in the normal gait cycle.

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