Enhancing wear rate of high-density polyethylene (HDPE) by adding ceramic particles to propose an option for artificial hip joint liner

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Abstract. Wear of total hip prosthesis is a significant clinical problem that nowadays involves a growing number of patients. To acquire further knowledge on the tribological phenomena that involve hip prosthesis, wear tests must be done on new biomaterials to increase life of orthopaedic implants, the average serviceability of an artificial hip joint is around 15 years, this average looks fine for a patient over 60 years old while number of young patients is increasing due to life style or accidents which raise a caution for researchers to propose new materials or design in order to extend the average over 15 years. In this work an experimental work that concerned with improving HDPE for acetabular liner part, which is improved by adding ceramic (Alumina and Zirconia) to form hyper-composite material, a three percentages of ceramic (3%, 6% and 9%) will be added to remaining percentage of polyethylene which is tested with Pin on Disc wear test machine and the results obtained for specific wear constant \((k)\) are \((2.08, 1.28, 0.77 \text{ and } 1.40) \times 10^{-4} \text{ mm}^3.\text{N}^{-1}.\text{m}^{-1}\). The results shows that the composite with (94% HDPE, 4.8% Alumina and 1.2% Zirconia) has least wear rate among other composites, percentage of alumina to zirconia is kept at 80:20 as studies have shown that at this percentage best properties are gained as the density is at highest level. Microhardness is also tested for all specimens and showed a mild increment in hardness as ceramic content increase, although hardness increased but this does not necessarily impose lower wear rate as the equation of specific wear rate is derived from Archard equation which is based on theoretic model of hemispherical asperities with a constant \((K)\) that compensate for asperities shape and other factors.

Keywords: Polyethylene, Total Hip Arthroplasty, Wear, Tribology, HDPE, UHMWPE, Hip Joint, Hyper composite, Alumina, Zirconia.

1. Introduction

Wear of Artificial Hip Joint prosthesis is a major issue nowadays, especially that the patients are now from various age range which requires the prosthesis to have low wear rate in order to stay serviceable for a long time, generally 15 years of serviceability is considered average. Artificial Hip Joints consist of four parts (Stem, Femoral Head, Acetabular Liner and Acetabular Cup).

The first trial of using polyethylene is back to 1962, as Sir John Charnley used polyethylene as liner against stainless steel femoral head, at that time it was known as low torque arthroplasty. Later, this material was developed into Ultra-High Molecular Weight Polyethylene (UHMWPE) but still it had problems of wear, loosening and fluid absorption, [1].
Many studies on hip joint were presented in many aspects like material selection, hip joint design, material improvement, etc. At (2005) Henry RihardPasaribu, [2], Proposed a trial to improve alumina and zirconia composite by doping it with copper oxide to reduce friction and wear. Addition of CuO (0%, 0.5% and 1%) to alumina showed coefficient of friction of (0.45, 0.40 and 0.47) for 0.1 m/s sliding velocity, the results was still valid to be best at 0.5% CuO at 0.2 m/s, but at 0.4 m/s the friction coefficient was almost constant, all these tests applied with normal load of 5 N. Zirconia doped with CuO results were not so clear but it is obvious that CuO has adverse results as friction coefficient increased. At (2014) Steven M. Kurtz, SeviKocagöz, Christina Arnhold, Roland Huet, Masaru Ueno, and William L. Walter, [3], explored the addition of zirconia into alumina which was deeply studied and explained the advantage of adding zirconia, a composite of mainly alumina (70-95)% and zirconia (5-30)% is known as zirconia toughened alumina (ZTA), the addition of zirconia improve strength and fracture toughness with slight reduction in hardness and modulus of elasticity as compared to pure alumina, phase transformation of zirconia from tetragonal to monoclinic phase at ambient temperature results in volume expansion (3-5)% and about 7% shear strain, this expansion oppose crack propagation thus fracture toughness is improved. Then at (2015) Kenneth R. St. John[4], evaluated the wear rate of UHMWPE against CoCr alloy and Zirconia femoral heads, 32mm and 26 mm cups were examined for 10 million cycles with periods of stoppage for cleaning and taking measurements, the wear with ceramic head showed early wear than metallic, then both reached steady wear rate, final conclusion was that both heads are acceptable options.

This work proposes a new material for Acetabular Liner as it can be made of (Metal, Plastic or Ceramic) while Femoral Head can be made of (Metal or Ceramic) only, the idea of this study was derived from previous works by mixing Alumina and Zirconia with HDPE in order to improve the material as it has lower cost and then proposing it as an option for Metal on Plastic (MoP) or Ceramic on Plastic (CoP).

2. Theoretical Equations
The theoretical technique is solution using to given exact results for engineering problem, [5-11], by solvation of the generated equation for system, [12-21], accordant on the load types applied and system behavior, [22-32]. Then, its calculated results must be comparison with other results which calculating by other experimental or numerical techniques to give the agreement for its results, [33-43].

Pin on Disc wear test machine (Aluminum disc) is going to be used to compare the results of proposed composites against pure HDPE. The governing equation is known as Archard equation [2],

$$K = \frac{Q}{WL} = \frac{m_{belt} - m_{sleeve}}{\rho \frac{WL}{WL}} \ldots \ldots \ldots (1)$$
weight before test, \( m_{\text{aft}} \): weight after test; \( \rho \): density; \( W \): load; \( L \): sliding distance. The term \( (k) \) is called specific wear rate constant that has the unit of \((\text{mm}^3\cdot\text{N}^{-1}\cdot\text{m}^{-1})\) is used to compensate the terms from original equation that contains wear constant \( (K) \) / Hardness \( (H) \). Simplifying the big term and compensating it by one factor \( (k) \) makes it more easily to be applied, it can only be measured experimentally. Density is measure by utilizing the following equation by setting HDPE \( (x) \), Alumina \( (y) \) and Zirconia \( (z) \).

\[
\rho = 0.95x + 3.95y + 5.68z
\]  
\[\text{........(2)}\]

The sliding distance \( (L) \) is calculated simply by multiplying the disc circumference by number of revolutions \( (N) \)

\[
L = \pi \cdot D \cdot N
\]  
\[\text{........(3)}\]

Load \( (W) \) is simply calculated by setting the applied pressure from wear test machine and then multiplying it by specimen’s diameter

\[
W = P \cdot A
\]  
\[\text{........(4)}\]

3. Experimental Work

The experimental techniques are important work given approximant results for system with various applied load and different parameters effect, [44-56], where, by its techniques can be adding various parameters did not added at theoretical work. Then, the experimental results calculating comparison with other results evaluated by other techniques to give the agreement for the results evaluated, [57-66]. Therefore, the experimental work for the presenting work included different steppes as, manufacturing for samples, manufacturing of the same required machine, and testing its samples.

Specimens Manufacturing

Three materials are used in order to have hyper-composite material composed of High-Density of Polyethylene (HDPE), Alumina \( (\text{Al}_2\text{O}_3) \) and Zirconia \( (\text{ZrO}_2) \). First, pure HDPE will be tested (Specimen A) and then compared to the composite specimens \( (B, C \text{ and } D) \) which contains \((97%, 96\% \text{ and } 91\%)\) of HDPE, the ration between alumina and zirconia is kept at \(80:20\). Powders weights are first measured by sensitive scale \((0-500g)\) (Figure 2 a, b and c) and then mixed for 6 hours (Figure 3), each bottle contains a total of 10g which is enough to produce at least two pins of 8 mm diameter and 30 mm length.

![Image a. HDPE Weight](image)
![Image b. Alumina Weight](image)
![Image c. Zirconia Weight](image)

Figure 2. Weight for Sample B
After 6 hours, the powder is ready to be used, first the mold (Figure 4) must be heated up to 150°C for pure polyethylene, and then powder is poured until mold’s hole is filled (8mm diameter, 70mm height) and then when the powder melts it is compensated by more powder until the hole is filled, the previous procedure is for pure HDPE only, composite needs higher temperature (190°C - 240°C), as ceramic content increases the required temperature increase. For pure polyethylene the powder can fill the hole and then as it melts you can compensate with more powder, while the composite behaves differently as it becomes viscous and easily cooled which is then stick to the surface of the mold, for this reason the composite powder should be poured slowly with continuous monitoring of temperature using infrared thermometer as the composite tend to burn at high temperature while pure polyethylene melts.

The mold is then left to cool slowly to room temperature, when the temperature of mold outside surface is 70°C cooling by water is possible. Extruding is done by screw pin pushed slowly to extrude the specimen, extrusion with hot mold cause deformation to specimen.

Although the surface finish is expected to be good, but it is still possible to sand the face of the pin as it is the important part which is going to be in contact with the disc.

The percentage between Alumina and Zirconia is kept at 80:20 as this percentage generate the highest density and best properties, [67], the percentage of HDPE mixed with (3%, 6% and 9%) ceramic content and then tested in Pin on Disc wear test machine, Polyethylene is much easier to be manufactured than pure ceramics as it is going to be explained, plus low cost and has good reputation as MoP is the most used coupling.
Pin on Disc Wear Test
This test is intended to measure and compare the wear performance of a material against a standard aluminum disc, it is summarized in the following procedure:
1. Prepare the specimen by sanding the face and measuring the weight \((m_{\text{bef}})\) then making sure the aluminum disc is cleaned before each test.
2. Set the applied pressure on pin at 0.66 bar, and measure the diameter of the pin in order to calculate the load \((W)\) on the disc
3. Start the motor to rotate the aluminum disc against the polyethylene composite specimen and set a number of revolutions, in this test it was set to 700 revolutions.
4. Measure the weight of the pin after the test is finished \((m_{\text{aft}})\)
5. Apply Archard equation to measure the specific wear rate constant \((k)\) which will be the comparison factor between specimens.

The specimen is turned for about 700 revolutions, having more or less revolutions will not affect the procedure as it would change the value of \((m_{\text{aft}}\) and \(L)\). The process is shown in Figure 7, as it is clear how the face of the specimen would wear after around 700 revolutions at 0.66 bar.

Microhardness Test
This test is performed in order to show the increment of hardness as the ceramic content increase, a load of 500 grams was required to have a trace and all specimens were tested, with the indication light of the machine it was useful to make sure that the jaw has touched the specimen and it was left for 30 seconds, then check with the microscope of the same machine to get the trace then check the number of lines forming the triangle and estimate the point that is out of the line and then get the reading from the manual, refer to Figure 10, 11 and 12

4. Results and Discussions
The equation of Archard is applied by measuring the weight before and after the test (Table 1), density equation is applied by taking the standard density of HDPE, Alumina and Zirconia as shown in (Table 2) then multiplied by percentage (Table 3).

| Specimen | \(m_{\text{bef}}\) (g) | \(m_{\text{aft}}\) (g) |
|----------|-----------------|-----------------|
| A        | 0.88            | 0.73            |
| B        | 0.59            | 0.49            |
| C        | 0.77            | 0.71            |
| D        | 0.74            | 0.62            |
Pressure is applied at 0.066 N/mm² and since the specimens’ diameter is not exact, it had to be measured for each piece for Specimen A, B, C and D (Table 4). Then the load W is calculated by multiplying pressure by area, the disc had 100 mm diameter and each specimen had revolutions (N) and then multiplied by the sliding distance as shown in Table 5. The complete calculation is mentioned in Table 6, then the results are graphed as shown in Figure 8 to illustrate k value against %HDPE while Figure 7 shows Pin condition when tested.

Temperature of aluminum disc in contact with pins is almost constant at 31.5°C (Figure 9) while disc temperature before test was 24°C. Microhardness test with 500g load (Figure 10) then using instrument table (Figure 11) showed mild increment as ceramic content increase from 990 to 1030 HV. (Table 7, Figure 12).
Table 7. Microhardness results

| Specimen | Load (g) | HV  |
|----------|----------|-----|
| A        | 500      | 990 |
| B        | 500      | 1003|
| C        | 500      | 1017|
| D        | 500      | 1030|

Manufacturing of specimens shows direct difference when ceramic content increases as it become more viscous, more temperature monitoring is required, it becomes more difficult to melt with tendency to burn at high temperature and as ceramic contents increase the cooling rate increase while lead to creating cavities in case of poor mold temperature monitoring leading to failure of specimen. The wear test of HDPE composites specimen was performed on Pin on Disc Wear Test Machine, all calculations were performed to apply Archard Equations and then specific wear rate was calculated. The specific wear rate of specimen © composed of 94% HDPE and 6% ceramics (80% (Al2O3), 20% (ZrO2)) showed the best result with specific wear rate of $0.77 \times 10^{-4} \text{ mm}^3\cdot\text{N}^{-1}\cdot\text{m}^{-1}$. The specific wear constant (k) is used to compensate theoretical assumption of hemispherical asperities and to correct for any factor affecting the wear in Archard equation, results shows the specific wear rate of (Specimen C) decrease by 62.8% from pure polyethylene.

Although Microhardness results were slightly increasing but Specimen C had lower wear rate than D as higher hardness is not a direct indication of lower rate, the result of Microhardness increased from A to D at rate of around 1.3% only.
Temperature of aluminum disc in contact with these specimens is around 31.5 °C, which gives an indication that coefficient of friction being almost constant.

The results obtained from wear test are for polyethylene which is the suggested as a material for acetabular liner, while femoral head can be Metal or ceramic which forms the coupling of Metal on Plastic (MoP) or Ceramic on Plastic (CoP).

5. Conclusions
The experimental work and results lead to the following conclusions and remarks:
1. Wear test showed specimen (C) that contains (94% HDPE, 4.8% Alumina and 1.2% Zirconia) has the best result with specific wear rate of 0.77*10^{-4} \text{mm}^3\cdot\text{N}\cdot\text{m}^{-1}.
2. The specific wear rate of Specimen (C) decrease by 62.8% in comparison with pure HDPE.
3. Microhardness test showed mild increment as ceramic content increased, still Specimen (C) at 1017 HV had better results than Specimen (D) with 1030 HV
4. Temperature of aluminum disc during wear test was around 31.5°C which indicate the coefficient of friction was not affected.

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