Epoxy-UHMWPE Acetabular Cup Performance Based on Finite Element Study

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ABSTRACT

The articulate surface of the acetabular components are among the reasons of Total Hip Replacement (THR) failure. The types of the material used for the components are also equally important as the orientation of the acetabular component which must be complied to avoid failure. This study aims to find the mechanical properties of Epoxy-UHMWPE variants and compared with acetabular cup default material by using FEA. Two steps of methodology conducted; first by using hand technique layup for preparing Epoxy-UHMWPE samples and run compression testing, the second step is by re-run the data collected from the compression testing results into the FEA and compared with default material of acetabular cup. The results show that EpUHMWPE5 exhibits the highest Young's Modulus compared to other variants. The FEA run in ANSYS WORKBENCH V15 displayed that

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EpUHMWPE5 performs better compared to default material in term of Contact Pressure, Von-Mises stress and Total Deformation at 36mm femoral head with Maximum Safe Inclination Angle. The data of Contact Pressure, Von-Mises stress and Total Deformation for EpUHMWPE5 was at 5.0388MPa, 4.5042MPa and 0.01834mm compared to default material (UHMWPE) at 5.15MPa, 6.4211MPa and 0.02306mm, respectively. The results shows that EpUHMWPE5 could be a propose material to replace the UHMWPE material at the acetabular cup based on mechanical analysis aspect although further studies of the materials are compulsory.

Keywords: *finite element; acetabular cup orientation; contact pressure; total hip replacement; Epoxy-UHMWPE*

Introduction

Revisions of THR are caused by many factors. Among the top issues raised are aseptic loosening, dislocations, edge-loading and excessive contact pressure at the superior region of the acetabular cup[1–4]. These factors are interrelated among them as dislocation is induced by the edge-loading effect and excessive contact pressure inside the acetabular cup upon doing daily living activities (ADL). Edge-loading and excessive contact pressure is associated with improper orientation that will allow indentation deformation in the superior region of the acetabular cup and substantially increased equivalent plastic strain of the polyethylene liner[3]. It is believed that orientation of acetabular components is vital in THR application.

Besides, the issues exposed by the acetabular cup materials such as dislocation, fracture, indentation deformation, inflammation due to wear and micro-motion also consequences into revision of THR[5, 6]. The improvements and new fabrications were conducted to reinforce the material's mechanical properties such as performed by[7, 8] in their works. Most of the studies resulted in significance improvement of the cement and the acetabular cup properties in terms of mechanical wear, stiffness and toughness.

Ultra High Molecular Weight Polyethylene (UHMWPE) is regarded as the best solution for the polymer parts in THR due to its mechanical properties[9]. Since revolutionized by Sir John Charnley about more than half century ago, a system that commonly uses stainless steel femoral head and UHMWPE acetabular cup have become a standard use in THR[10]. The purpose of acetabular components made of polyethylene in hip prostheses mainly includes shock protection/ absorption, and displacement adjustments during gait motion, including mal-alignments and rotational strains[11].

The records show that there are many composite materials used in the joint replacement applications[12]. UHMWPE are regards as the best material selection for the studies of THR. Upon various materials incorporated into the UHMWPE, among the highlights for the usage of UHMWPE are the process of incorporating UHMWPE with natural coral (NC) which exhibits micro-hardness and scratch resistance that keep increasing with higher filler loading of NC particle[7]. Later in 2011, Chang et al.[13] investigated the effect of incorporating zinc oxide (ZnO) into the UHMWPE and the data shows that the performance in terms of tensile strength decreased with higher filler loading compared to pure UHMWPE. Two years later in 2013, again he proposed the Zeolite-reinforced UHMWPE for implant application which shows that the composites were fully covered, smooth and continuous compared to pure UHMWPE which will perform better at the articulate surfaces between femoral head and acetabular cup[8].

Although Epoxy has been studied for the joint replacement materials previously, the review conducted shows that Epoxy-UHMWPE composite combinations have never been tested for the THR application. However, there is a study that shows that the usage of Epoxy resin to the UHMWPE will serve as a physical cross-linking agent to limit the motion of PE molecules that consequently improve the mechanical properties[14]. The preparation of the samples was conducted using hand techniques layup with three stages of post-curing heating to improve homogeneity of UHMWPE powder. Another study of Epoxy-UHMWPE composite was also conducted with the results that show the usage of nano-epoxy instead of pure epoxy will improve the wettability of UHMWPE[15]. The samples were prepared by using digital sonifier of sonification method. In 2015, another study of Epoxy-UHMWPE composite was conducted which showed that the post-curing temperature gives effect to the composite stiffness and modulus[16]. The samples were prepared using vacuum-assisted resin transfer molding (VaRTM) method which was almost similar to hand techniques layup but with vacuum modification. The previous studies of Epoxy-UHMWPE exhibit that adding Epoxy to the UHMWPE filler/fiber will improve the mechanical properties of the composite.

It is believed that both criteria of acetabular orientation and material selection in THR are crucial to being studied; thus understanding both relationships is needed to be discussed in this project. The failure of the hip implant will be studied by taking the acetabulum part components as the objectives; thus aiming to develop the acetabular components orientation and acetabular cup materials to improve the implant life.

Materials and Methods

Two steps of methodology conducted in this study. The first method is by using the hand technique layup to find the Young’s Modulus of Epoxy-UHMWPE. The second method is by comparing the data of Epoxy-

UHMWPE composites with the default materials (UHMWPE) based from finite element study.

In this study, it is intended to incorporate the UHMWPE into the polymer matrix of Epoxy (Ep). Before heading to the sample preparation, the coding of the formulation will be tabulated for easiness on reading the composition value. The composite intended to be used as the substitute material is Epoxy-UHMWPE. The formulations of the polymer composite materials are shown in Table 1. Epoxy resins were obtained from the Faculty of Applied Science, UiTM with the coding of Morcote BJC-29 supplied by Vistec Technology Sdn Bhd. Meanwhile, UHMWPE graded GUR 4120 was supplied from Ticona Engineering Polymer, China in powdered form with molecular weight of $5x10^6 gmol^{-1}$.

Table 1: Sample formulation coding of the variation of filler loading in polymer epoxy matrix with UHMWPE

Coding	Matrix (wt %)	Fillers (wt %) UHMWPE
EpUHMWPE0	100	0
EpUHMWPE1	99	1
EpUHMWPE3	97	3
EpUHMWPE5	95	5
EpUHMWPE7	93	7
EpUHMWPE10	90	10

Density meter was used in the measurement of epoxy, ρ_s and the obtained value is $1.21 gcm^{-3}$. To calculate the respective amount of epoxy and UHMWPE, estimation method based on mould volume will be carried out. The mould volume, V_m was measured by the dimension of the cavity which are the value of length x width x height. For this experiment to be carried out, the mould volume of (80x10x10) mm is 80 cm^3. Mass will be determined from the density equation denoted as;

$$\rho = m/\upsilon \tag{1}$$

Here, the m is the mass in g and V is the volume in cm^3, thus the estimation mass of epoxy to be used in this experiment can be written as;

$$\rho_s = m_s/\upsilon_s \tag{2}$$

Figure 1 shows the step-by-step formulation on preparing the Epoxy-UHMWPE samples for the compression testing. The specimens had a parallel-piped form with a square section according to ASTM D695-96. The samples were loaded into a universal testing machine of Shimadzu brand which is possessed by Faculty of Applied Science, Universiti Teknologi MARA with the machine code of UiTM/PS01/A/090108/20080001118. The bottom plate was fixed and the top plate is mobile as in Plate 3.5. Test was conducted under ambient laboratory conditions, 23 ± 1°C. The load was applied at a constant displacement rate of 1.3mm/min with the stroke of 10% height of the sample. TrapeziumX is the built-in software that was included while running the testing machine. Due to material stiffness, it is sufficient to deduce the stroke of the top plate until 10% of the sample height. The compression test is compulsory to find the Young's Modulus of Epoxy-UHMWPE variant.

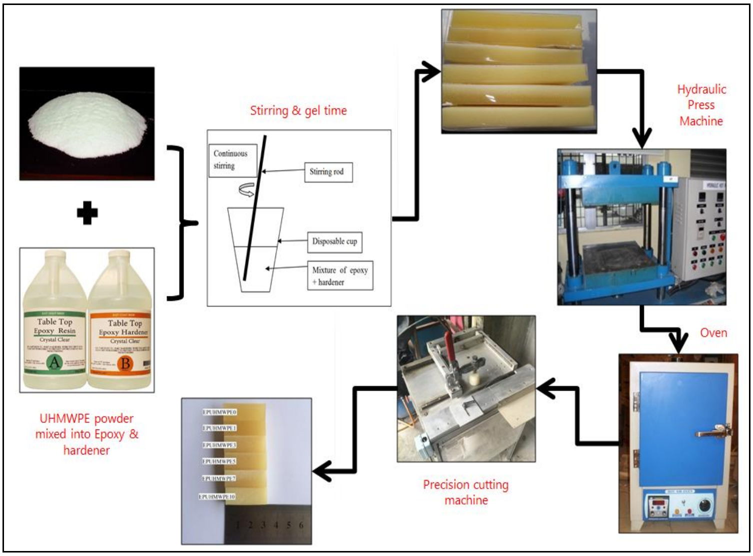

Figure 1: Step-by-step preparation of Epoxy-UHMWPE composites

The second method of this study which by comparing Epoxy-UHMWPE with default material in FEA was conducted based from previous studies data[17]. A brief explanation of the previous studies explained in this part. The focus will be on the hard on soft bearing combination with the femoral head and metal backing acetabular component assumed as rigid and represented by a sphere and cup respectively. The usage of metal backing cup procedure is meant that we intended on doing the simulation on the cementless acetabular component as the cementless acetabular component are have better bone ingrowth better on the younger patient[18]. The loading condition and constrained part of the model is illustrated as in Figure 2. There are 15 models of acetabular components analyze in ANSYS WORKBENCH V15 with different orientation angle and different femoral head sizes.

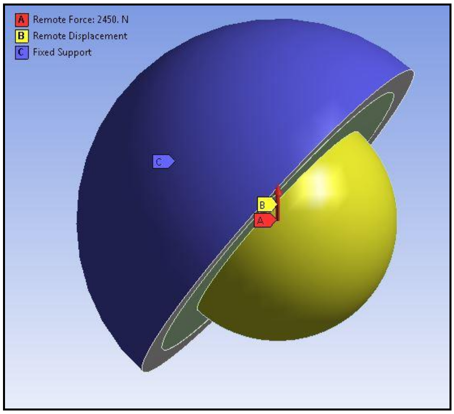

Figure 2: The loading condition and constrained part of the model

The mathematical modelling was conducted previously to find the optimum safe zone orientation angle based on the Equation (3) that sum up all the MATLAB commands[19].

$$\theta = A - 2\sin^{-1}\frac{n/2}{r} = A - 2\sin^{-1}\frac{1}{head/neck} \tag{3}$$

For the simulation in Finite Element Analysis (FEA), the contact analysis formulations was adopted where the bearing surface articulations between femoral head and cup are highly conforming and usually modelled as a ball-in-socket geometry (Equation 4-7) based on Hertzian Contact Theory[20]. Eliminating the surface roughness, the notations of R_1 and R_2 are characterized by the head and cup radii, respectively, giving a radial clearance $c = R_2 - R_1$ as shown in Fig. 1. Meanwhile, simpler configuration will yield the effective radius R' and elastic modulus E^* where E_1 , v_1 and E_2 , v_2 are the Young's Modulus and Poisson Ratio of the head and cup material, respectively

$$\frac{1}{R'} = \frac{1}{R_1} - \frac{1}{R_2} = \frac{c}{R_1(R_1 + c)} \tag{4}$$

$$\frac{1}{E^*} = \left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right) \tag{5}$$

From the theory, theoretical Total Elastic Displacement d can be calculated based on Equation (4) given the amount of force exerted, F on that configuration.

$$F = \frac{4}{3} E^* R'^{1/2} d^{3/2} \tag{6}$$

Applying the Hertzian Theory for a static dry contact will yield the radius of the contact area, a as shown in Equation 5.

$$a = \sqrt[3]{\frac{3FR'}{2E^*}} \tag{7}$$

Once the Young's Modulus of Epoxy-UHMWPE achieved from the compression testing, the data will be used to re-run in the FEA for comparison purposed in term of mechanical properties.

Results and Discussion

The results from every variant are tabulated in Table 2 with every variant showing a different value, and it is noticed that the EpUHMWPE5 gives the highest value of Young Modulus compared to other variants. As the variant percentages increased, the value of Young's Modulus also increased. However, it will increase only until 5% variants as the data showed that increasing the variant of more than 5% will reduce the Young's Modulus value. The assumption could be made that the variant of 5% is the maximum reinforcement material allowable to achieve the maximum Young's Modulus value.

Table 2: Young's Modulus and Compression Strength value of the variant proposed as a replacement of acetabular cup

Sample variant	Young's Modulus (MPa)	Compression Strength (MPa)
EpUHMWPE10	1031.49	34.8309
EpUHMWPE7	1188.43	40.0394
EpUHMWPE5	1338.29	44.6123
EpUHMWPE3	1155.38	38.5126
EpUHMWPE1	1049.52	34.9862
EpUHMWPE0	1099.76	36.6593

Based on FEA, three mechanical analysis were selected for the comparison studies. Here, only one orientation selected for this study which is the Maximum Safe Inclination Angle. Figure 3 exhibits the histogram of comparison material variations at the Maximum Safe Inclination Angle with three types of acetabular components. The 28mm femoral head case shows that the highest contact pressure recorded by UHMWPE and the lowest recorded by EpUHMWPE10 are 7.43MPa and 7.20MPa, respectively. At the meantime, the 32mm femoral head case shows that the highest contact pressure recorded by EpUHMWPE5 and the lowest recorded by EpUHMWPE10 at 6.67MPa and 6.59MPa, respectively. Final histogram comparison shows that the highest contact pressure for 36mm femoral head case is recorded by UHMWPE and the lowest is recorded by EpUHMWPE10. The values for the highest and lowest contact pressure are 5.15MPa and 4.98MPa, respectively.

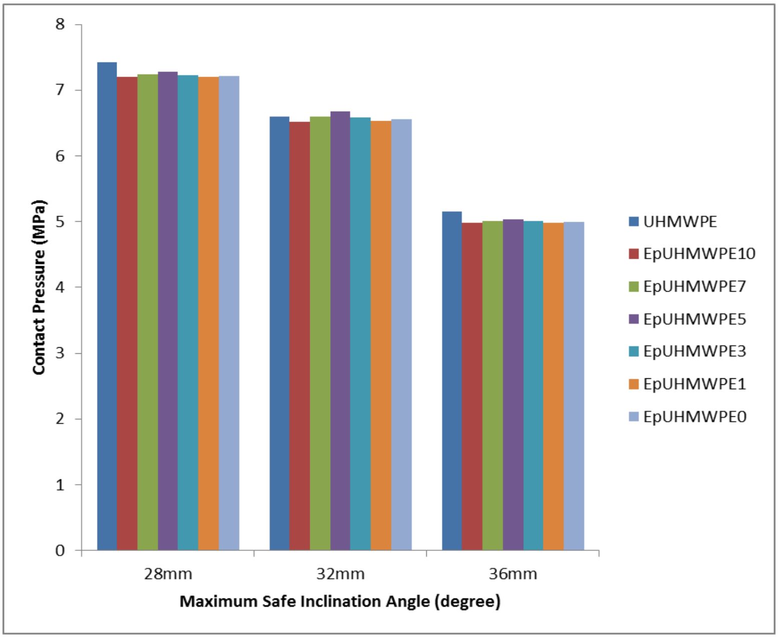

Figure 3: The Contact Pressure comparison of material variation in three types of acetabular components at the Maximum Safe Inclination Angle

On the other hand, Figure 4 shows the histogram comparison of Von-Mises stress with different material variations at Maximum Safe Inclination Angle orientation. The 28mm femoral head case shows that UHMWPE records the highest Von-Mises stress and the lowest is recorded by EpUHMWPE10 at the values of 7.05MPa and 6.65MPa, respectively. Meanwhile, 32mm femoral head also recorded the same variant of UHMWPE at the highest and EpUHMWPE10 at the lowest with the values of 7.46MPa and 5.85MPa, respectively. The final part which is 36mm femoral head has the highest Von-Mises stress recorded by UHMWPE and the lowest is recorded by EpUHMWPE5 with the values of 6.42MPa and 4.50MPa, respectively. On the other hand, the data recorded that transition from 28mm to 32mm femoral head at the Maximum Safe Inclination Angle using UHMWPE exhibits different pattern from our prediction. Increasing the femoral head from 28mm to 32mm will increase the Von-Mises stress at approximately 5.49%. Even though the author could not exactly explain the reason behind this fact, it is believed that orientation (Maximum Safe Inclination Angle) and UHMWPE properties played a vital role to this effect. The Poisson's ratio of UHMWPE close to 0.5 shows that throughout the compression of UHMWPE, it will easily undergo expansion; thus it might affect the Von-Mises stress value.

Meanwhile, other variants analyses show a reduction of Von-Mises stress with higher femoral head diameter size. Although the 32mm femoral head diameter case shows a higher value compared to 28mm femoral head diameter in the aspect from Maximum Safe Inclination Angle value, the value is still lower than UHMWPE Yield. The design is also safe when the analysis was conducted in Maximum Safe Inclination Angle orientation angle.

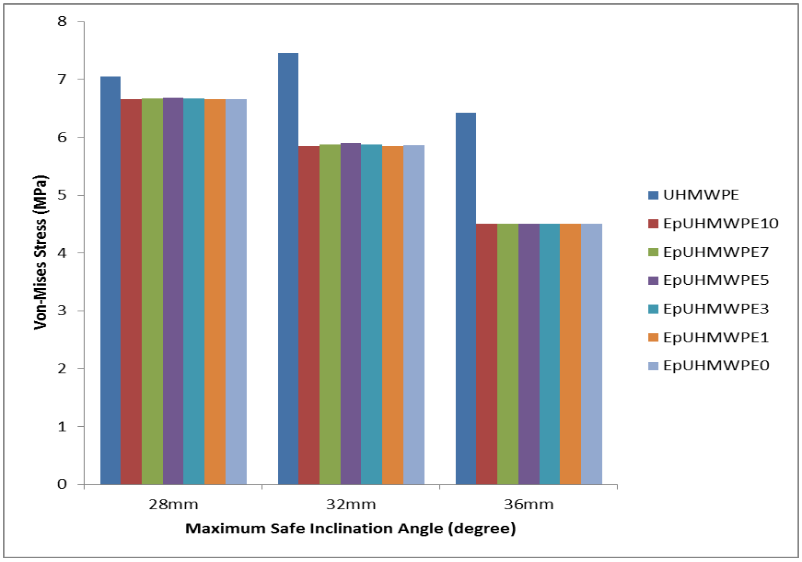

Figure 4: The Von-Mises Stress comparison of material variation in three types of acetabular components at the Maximum Safe Inclination Angle

The Maximum Safe Inclination Angle graph in Figure 5 shows that EpUHMWPE5 exhibits the lowest total deformation with the value of 0.02546mm, 0.02228mm and 0.01834mm in 28mm, 32mm and 36mm femoral head diameter, respectively. The bar graph also shows that existing material of UHMWPE recorded the second highest total deformation with the value of 0.02928mm, 0.02809mm and 0.02306mm for 28mm, 32mm and 36mm femoral head diameter, respectively. However, only 28mm femoral head diameter shows a reduction of 13.1% when replacing UHMWPE with EpUHMWPE5. On the other hand, the 32mm and 36mm femoral head diameter cases show a reduction of more than 20% in terms of total deformation.

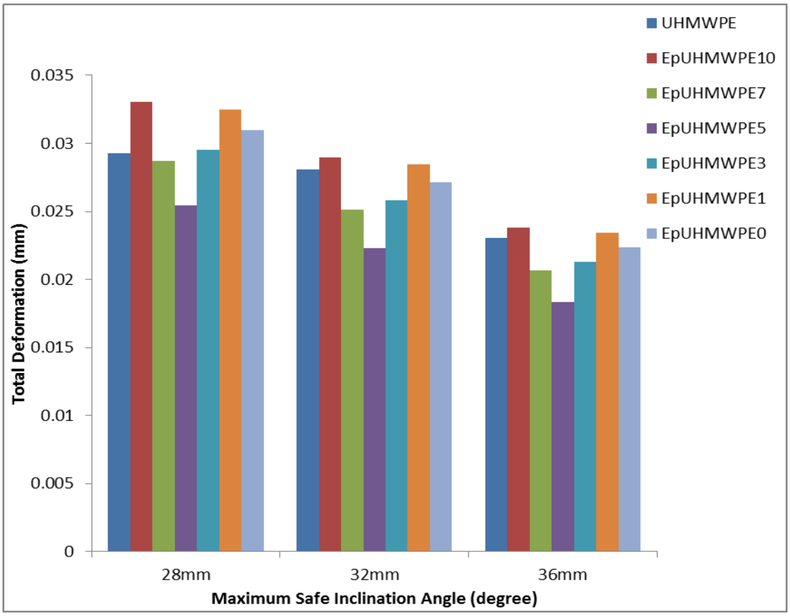

Figure 5: The Total Deformation comparison of material variation in three types of acetabular components at Maximum Safe Inclination Angle (degree)

The summarizations of Epoxy-UHMWPE composites based on FEA analysis at Maximum Safe Inclination angle are exhibit in Table 3. The results show that EpUHMWPE5 at 36mm femoral head diameter will improve the mechanical analysis; contact pressure, Von-Mises stress, total deformation at 2.16%, 29.85% and 20.45%, respectively when using EpUHMWPE5 instead of default material (UHMWPE).

Table 3: The summarization of FEA analysis comparison of EpUHMWPE5 with UHMWPE at Maximum Safe Inclination Angle

Orientation (degree)	Head size (mm)	FEA analysis	Default material (UHMWPE)	EpUHMWPE5	Reduction percentage (%)
Maximum Safe Inclination Angle	28mm	Contact Pressure (MPa)	7.4271	7.2830	1.94
	32mm		6.5940	6.6746	-1.22
	36mm		5.1500	5.0388	2.16
	28mm	Von-Mises stress (MPa)	7.0471	6.6781	5.24
	32mm		7.4565	5.9039	20.82
	36mm		6.4211	4.5042	29.85
	28mm	Total Deformation (mm)	0.029282	0.025458	13.06
	32mm		0.028091	0.022284	20.67
	36mm		0.023059	0.018344	20.45

There are two reasons the results in this part was importantly discussed, which the first results shows that EpUHMWPE variants will shows different Young's Modulus value even with a slight weightage different which is critical mechanical properties required as dealing with implant. The second reason exhibits that FEA is a simplified method tools of studying new materials composition studies based on mechanical analysis aspect. The results in FEA will be used as preliminary results on discovering better materials for hip implant.

The analysis conducted in this part shows that correct position of acetabular components and using bigger femoral head diameter will increase the performance of acetabular components. The reduction percentages show that EpUHMWPE5 may perform better compared to default material at 36mm femoral head diameter.

Conclusion

The EpUHMWPE composite could be a proposed material to replace the UHMWPE material of the acetabular cup. The range of the variants Young's modulus show almost identical values as compared to UHMWPE alone. Although further study needs to be made especially in vitro study and other mechanical aspect parameters, the results were promising especially for the EpUHMWPE5 variation. New finding discovered which the fact that Young's modulus keeps increasing with added filler of UHMWPE until 5%. The value of the Young's modulus dropped when the filler added is more than 7%. This matter could be caused by too much particulate of UHMWPE powder that may loosen the bonding of the new composite. However, the FEA indicated that EpUHMWPE5 could perform better than UHMWPE in terms of contact pressure,Von-Mises stress, and total deformation at 36mm femoral head diameter and at Maximum Safe Inclination Angle.

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