Analytical and computational sliding wear prediction of ultrahigh molecular weight polyethylene UHMWPE in block-on-ring (BOR) tribometer

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ABSTRACT: In knee joint replacement, wear of Ultrahigh Molecular Weight Polyethylene (UHMWPE) can be a significant factor in shortening the implant life span. With advancements in computational technology, virtual testing has become more reliable at a lower cost compared to physical testing. This paper evaluates the wear coefficient, kD, from physical tests as a reliable predictor of wear volume in the computational method. The physical test run with a block-on-ring (BOR) configuration of UHMWPE against a steel counterface with 225N load for wear coefficient, kD acquisition. The computational methodology involved the use of an Abaqus solver incorporating the UMESHMOTION subroutine to implement Archard's law. The maximum FEA result error was 14% in the 225N load test. The results show that the wear coefficient,kD produced by coupling UMESHMOTION in computational method, is reliable for predicting wear volume in BOR physical test.

Keywords: *Umeshmotion; Knee joint replacement, Ultrahigh Molecular Weight Polyethylene*

1. INTRODUCTION

Most of these joint replacements are necessitated by the damaging effects of osteoarthritis (OA). Nowadays, many knee replacement designs can be offered to the patient. In most of these designs, the articulating joint surfaces consist of a prosthetic material such as ultra-high molecular weight polyethylene (UHMWPE), titanium alloy, or cobalt chromium. However, wear of UHMWPE remains a significant factor in limiting prosthetic life [1].

Physical wear testing for joint replacements is time-consuming and very costly. This is because, to mimic low-frequency walking gait cycles, many months of data must be collected. For this reason, prosthetic bearing material evaluation has been developed comprehensively in conjunction with computer simulations incorporating physical and numerical models of wear.

The purpose of the current study is to validate a wear-testing Finite Element simulation model developed using the Abaqus software, using experimental wear testing. The simulation and testing configurations represent a simplified approximation of the articulating surfaces and geometry seen in a novel knee prosthesis assemblage.

2. METHODOLOGY

2.1 Experimental procedure

Experiments were conducted using a BOR tribometer. A normal load was applied perpendicular to the test UHMWPE block, which has dimensions 12mm (width) x 12mm (height) x 18mm (length), as per the Ducom BOR machine test sample, model number TR-352. It is assumed that the force is evenly distributed over the block. The steel test ring has a diameter of 35mm and 10mm width. As the ring rotates, a tangential friction force is transmitted across the surfaces. The ring rotated at 1000rpm and was run for 50,000 cycles per measurement interval with a soybean as the lubricant.

2.2 Numerical modelling

The geometrical configuration in the experimental test was constructed to match exactly the experimental BOR set-up. Material properties for the individual components, presented in Table 1. Both components were assigned linear elastic material properties. An ALE adaptive meshing technique was adopted for the computational. The simulation was run for 20 cycles. Each cycle was divided into 100 increments and wear computational accumulated in every increment throughout the cycle, as Netter et al. (2015) [2]. This means 20 cycles in this simulation equivalent to 200 thousands cycles in the experiment. The geometry changes and updates based on the contact pressure at any particular node. All this was done by UMESHMOTION Fortran subroutines.

Table 1 Material properties

Material	Density [g/cm3]	Young Modulus [MPa]	Poisson Ratio	COF
UHMWPE	0.945	690	0.317	0.19
Steel	7.7	$2X10^5$	0.3	0.19

In the current study, Archard's wear law was implemented with the assumption that wear rate is a linear function of the contact pressure and sliding distance for the UHMWPE block in the steady-state region as acquired from the experiment:

$$q = kd.F.s \quad (1)$$

where q is the wear volume of material loss from the softer material [mm3], H is the material hardness of the softer material [N/mm2], F is the axial load applied [N], s is the sliding distance and kd is the dimensionless coefficient of wear.

The entire UHMWPE block was discretized using 720 three-dimensional C3D8R 8- node linear brick elements (1629 nodes). The solution was enhanced by applying reduced integration in elements to achieve faster computation. In the UHMWPE block, enhanced hourglass control is deployed to provide course mesh accuracy improvement. For sensitivity studies of wear convergence, mesh sizes are varied to acquire a consistent wear and contact pressure so that dependence of mesh element size on the wear result is avoided. For the boundary condition. An axial load was applied to the center of the ring, and the UHMWPE block was fixed at the bottom surface using encastre boundary conditions

The analytical estimation was done as the work from Zhao et. al (2008)[3].

3. RESULT AND DISCUSSION

The results at the first 50,000 cycles., wear rate is higher at the beginning of the sliding process due to the removal of surface impurities. As the wear increases consistently at an approximately constant wear rate, the wear rate is lower than in the initial running-in stage. The UHMWPE asperities soften, and the wear rate becomes steadier due to the lower surface roughness of the counter face [4]. The wear volume obtained from the experiment Finite Element Analysis (FEA) and analytical estimation is plotted in Figure 1. The maximum FEA prediction error is 14 %, occurring at the 200,000 cycles within the bounds obtained by previous researchers [5-6]. The illustration of the wear dept is in Figure 2.

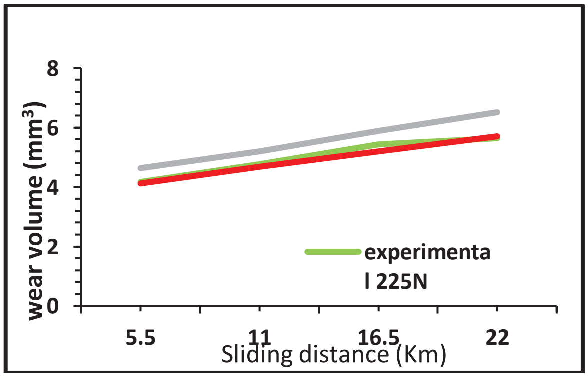

Figure 1 Wear volume obtained from the experiment Finite Element Analysis (FEA) and analytical estimation

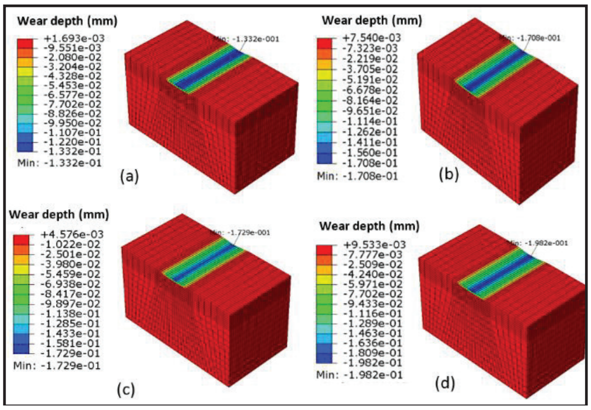

Figure 2 Wear depth visualization acquired from FEA

4. CONCLUSION

In this paper, sliding wear of a UHMWPE block was modelled successfully by developing a FORTRAN subroutine linked with ABAQUS. Material removal from the surface of the UHMWPE block in contact with steel counter face was defined by UMESHMOTION and Archard's wear law. ALE adaptive meshing method was implemented for geometry update due to surface ablation and despite some restrictions on material model selection, it was able to maintain mesh stability and distortion control. Results were in good agreement with experimental data obtained from the BOR wear tests. FE simulations tend to predict slightly higher wear rates as the BOR tests were conducted with lubrication, while the lubrication was solely depended on the average coefficient of friction (COF) in the FEM model.

5. REFERENCES

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