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Wear characteristics of UHMW polyethylene by twist method

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Wear characteristics of UHMW polyethylene by twist method

***Chişiu G.*[1], *Popescu A. M.*[1], *Tudor A.*[1], *Petrescu A. M.*[1], *Stoica G.F.*[1], *Subhi K.A.*[1, 2]**
[1] *University "Politehnica" of Bucharest, Department of Machine Elements and Tribology, Spl. Independentei 313, Bucharest 060042, Romania*
[2] *AL-FURAT AL-AWSAT Technical University, Iraq*
georgiana.chisiu@upb.ro[1], andreitudor17@gmail.com[1]

Abstract: A wear test of the twist movement was performed as a new method to estimate the in vivo wear behavior of an acetabular cup material for total knee replacements. A series of UHMWPE samples was used to evaluate the dynamic coefficient of friction in twist movement in contact with steel. The experimental data were conducted to validate the related theoretical model developed in the present study.

Keywords: UHMWPE, friction, wear, twist, rolling joint

1. Introduction

It is well known that polyethylene ultra high molecular is the choice for hip and knee replacement arthroplasty. It is also used in industry. But, for medical using the failure of the artificial components usually is due to wear of acetabular component made of ultra high molecular weight polyethylene (UHMWPE) from total hip joint replacements and the wear of femoral component from total knee replacements. This material, in combination with metallic or ceramic biomaterials, provides low friction joint and generally excellent results for the short and medium term [1]. The motions occurring in an artificial joint, but also like in natural, are complex. The kinematic conditions in can include sliding, rolling and pivoting. In this work we focused on the twist movement.
The aim of this study was to evaluate the dynamic coefficient of friction in twist movement of UHMWPE in contact with steel.

2. Theoretical aspects

The contact we supposed to be studied in this paper is sphere on flat plane in pivoting motion. Such a sphere is shown in cross-section in figure 1. Pivoting occurs when a fixed point of the metallic component is rotating around a still axis. For simplify theoretical aspects we consider the hertzian contact between the bearing ball, which is elastic, and the flat surface as a rigid plan of UHMWPE.

The axi-symmetrical pressure distributions are given by [2]:

$$p_n = p_0\left(1 - \frac{r^2}{a_H^2}\right)^{\frac{1}{2}} \qquad (1)$$

We assume that pressure is exerted on a circle-shaped area with the radius a_H .

The resulting total force is:

$$F_n = \int_0^{a_H} p_n \cdot 2\pi r dr = \frac{2}{3} p_0 \cdot \pi a_H^2 \tag{2}$$

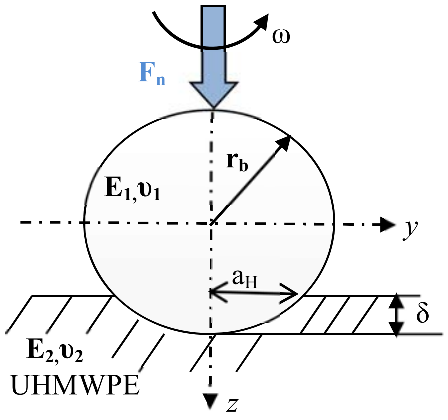


Figure 1. Hertzian contact sphere on flat plane, when is considered the bearing ball is the elastic sphere and the flat surface is a rigid plan of UHMWPE.

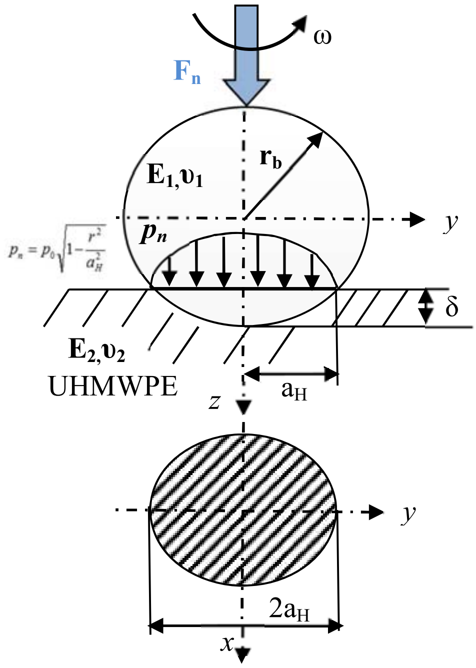


Figure 2. Contact stress has an elliptical distribution across contact over zone of diameter $2a_H$.

The displacement of the points on the surface in the contact area between an originally even surface and a sphere of radius r_b is equal to:

$$u_z = \delta - \frac{r^2}{2r_b} \tag{3}$$

We will try to find the parameters a_H and p_0 that cause exactly the displacement in Equation 3.

$$\frac{1}{E^*} \frac{\pi p_0}{4a_H}\left(2a_H^2 - r^2\right) = \delta - \frac{r^2}{2r_b} \tag{4}$$

The following expression for E* is:

$$\frac{2}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{5}$$

Here, E_1 and E_2 are the moduli of elasticity and ν_1 and ν_2 the Poisson's ratios of bearing ball and polyethylene samples.

The pressure in the center of the contact area can be calculated as the contact radius as a function of the normal force:

$$p_0 = \left(\frac{6F_n E^{*2}}{\pi^3 \cdot r_b^2} \right)^{\frac{1}{3}} \tag{6}$$

And the contact radius:

$$a_H = \left(\frac{3F_n r_b}{4 \cdot E^*} \right)^{\frac{1}{3}} \tag{7}$$

The tangential tractions which act in a circumferential direction induce a state of torsion in the half-space. Johnson [2] consider the traction:

$$q_r = q_0 r_{red} \left(a_H{}^2 - r_{red}{}^2 \right)^{-1/2}, r_{red} \le a_H \tag{8}$$

Where r_{red} is radius reduced of contact area.
Thus the traction produced a rigid rotation of the loaded circle. The traction gives rise to a resultant twisting moment:

$$M_z = \int_0^{a_H} q(r)\, 2\pi r\, dr = \frac{4}{3} \pi a_H^4 \cdot q_0 \tag{9}$$

The twist moment could be written also:

$$M_z = \frac{3\pi}{16} \cdot \mu_{pivoting} \cdot F_n \cdot a_H \tag{10}$$

The coefficient of friction in pivoting movement is resulting from equation 10:

$$\mu_{pivoting} = \frac{16 \cdot M_z}{3 \cdot \pi \cdot F_n \cdot a_H} \tag{11}$$

The penetration depth is:

$$\delta = r_b - \sqrt{r_b^2 - a_H^2} \tag{12}$$

Table 1. Values for calculating Hertzian contact stress for a sphere on flat [3].

Item	Symbol	Value
Load	F_n	200, 300, 400, 600 *N*
Radius of rotating ball	r_b	6.375 *mm*
Poisson's ratio of steel ball	υ_1	0.3
Poisson's ratio of UHMWPE samples	υ_2	0.4
Young's modulus of steel ball	E_1	200 *GPa*
Young's modulus of UHMWPE samples	E_2	500 *MPa*

3. Experimental details

A four-ball apparatus specially adapted to pivoting movement, connected to a computer, was used to evaluate the twist moment of the UHMWPE against steel under dry and egg albumen lubricated conditions.

3.1. Test method

During the experiments, the polyethylene specimens were pressed against the metallic ball, at the constant load, as shown in figure 3. The ball rotates uniformly around its vertical axis, occurring the pivoting movement. For the experimental tests the load was obtained with this formula:

$$F_n = m_g \cdot g \cdot k \tag{13}$$

Where is m_g - weight; $g = 9.81\, m/s^2$ gravitational acceleration; $k = 10$ constant of balance.

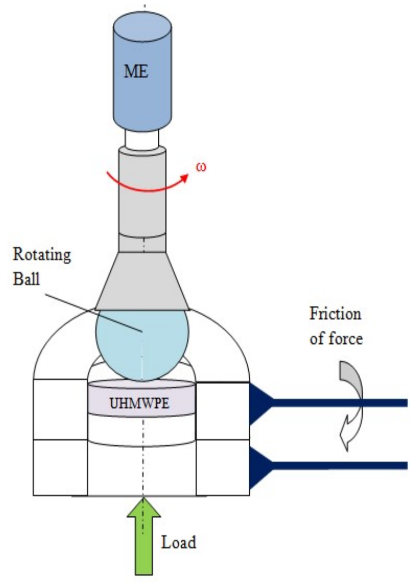


Figure 3. Illustration of the ball-on-flat assembly.

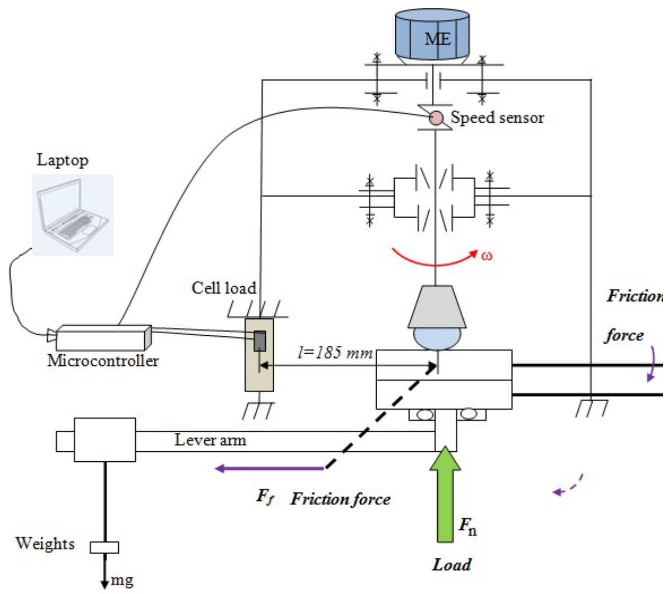


Figure 4. Schematic illustration of the four-ball tester specially adapted to pivoting movement.

3.2. Test equipment

The realization of the test method is possible using the modified four-ball tester, under dry conditions and at the controlled temperature of 23 ± 1^{0}C. The employed four-ball tester was controlled via special microprocessor-aided controller (ARDUINO), motor speed controller (tipul de ME) and PC with a special program installed. The motor speed controller has the role to changing the frequency of electric current that is enable to set the rotational speed within a wide range. A schematic representation of the arrangement used for testing the materials is shown in figure 4. A stationary polyethylene specimen was placed in twist contact with the surface of a steel ball of 12.27 diameter and 4 mm thick. The polyethylene specimens were cut from extruded sheets of UHMWPE GUR 1050. A series of pivoting tests were carried out on UHMWPE and the mechanical properties of the material were presented in previous works [4,5]. The mean roughness of the samples was 0.4± 0.6 μm. The wear tests were performed using a velocity of the rotation of the ball of 144 rpm, 173 rpm and 323 rpm. The applied load values were 200 N, 300N, 400 N and 600 N. For each load, the test was repeated three times. The polyethylene specimens were changed after each test. The steel ball and the polyethylene samples were cleaned thoroughly with propanol and then allowed to dry at open air, before each run.

The tests were carried out under dry pivoting and egg albumen lubricated conditions. The lubricant was distributed over the entire surface of the sample in an amount sufficient to ensure the presence of this during the test period. During the test, the force of friction was measured by a transducer mounted to the arm and recorded with a data acquisition system. The worn surface of tested samples were observed by optical microscopy using optical microscope Olympus back sight Gx51 by the magnification in the range 50× to 1000×.

4. Experimental results

4.1 Surface analyses

The optical microscopy examination of worn surfaces of UHMWPE samples against bearing ball at 200 N to 600 N applied load and at rotating speeds test for dry and lubricated conditions can be seen in table 2 and table 3.

Table 2. The optical microscopy examination of worn surfaces of UHMWPE samples in dry conditions.

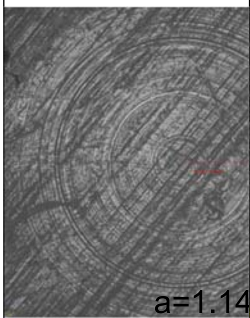
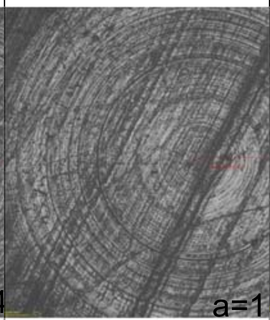
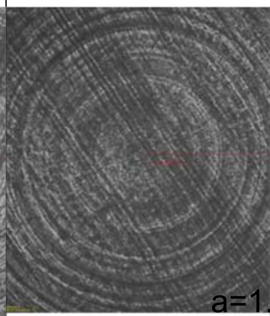
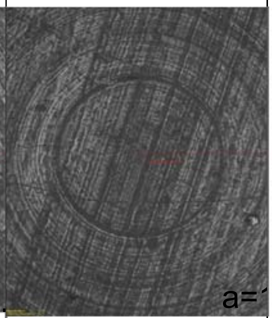
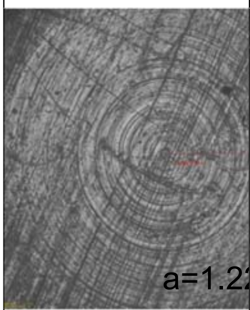
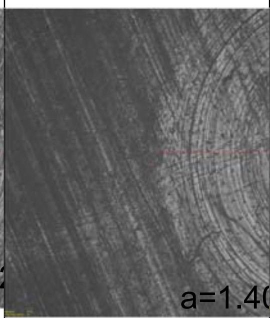
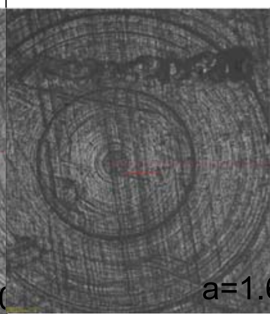
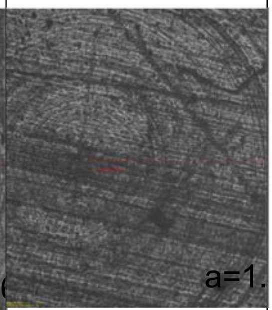
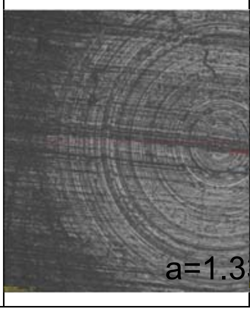
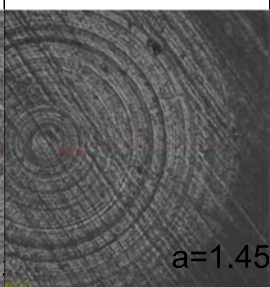
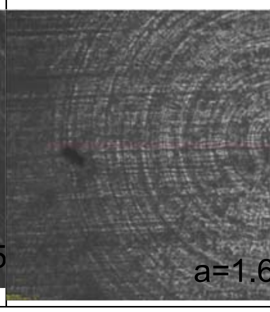
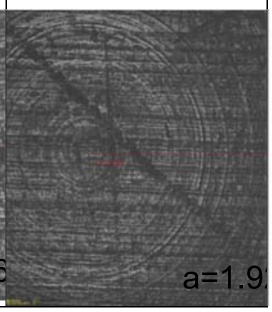
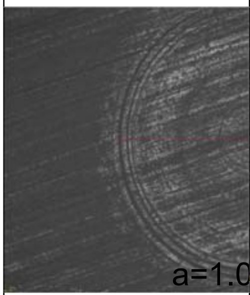
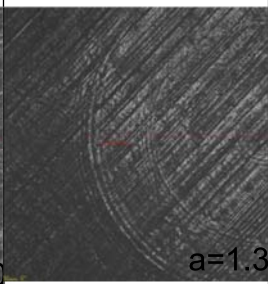
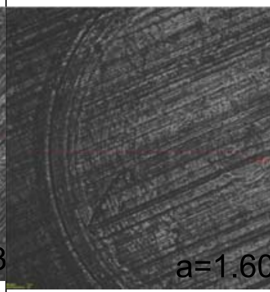
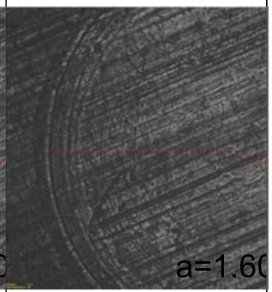
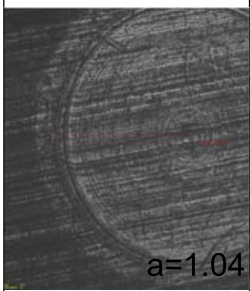
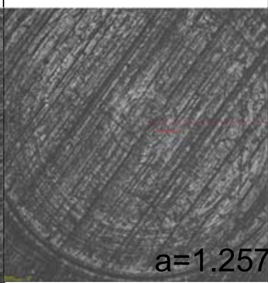
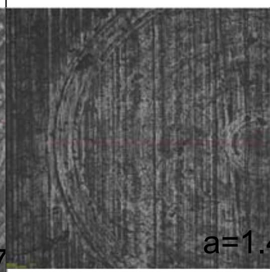
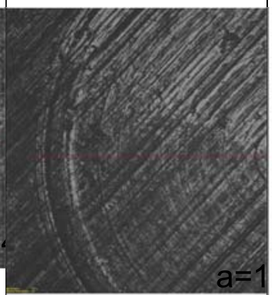
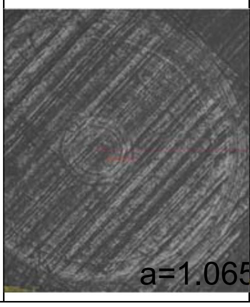
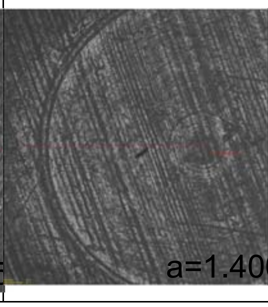
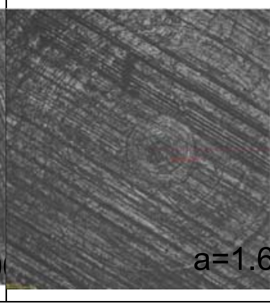
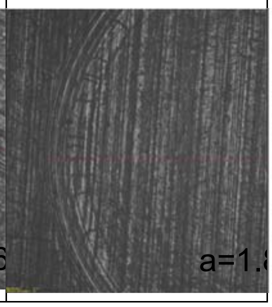
	Load			
Rotational speed	**200 N**	**300 N**	**400 N**	**600 N**
144 rpm				
173 rpm				
323 rpm				

Table 3. The optical microscopy examination of worn surfaces of UHMWPE samples in lubricated conditions.

	Load			
Rotational speed	**200 N**	**300 N**	**400 N**	**600 N**
144 rpm				
173 rpm				
323 rpm				

4.2 Tribological experiments

The results of tribological investigations are presented in figures 5-12. Figures 5 and 6 illustrate the comparison between theoretical and experimental results of contact radius of UHMWPE in contact with a steel ball under dry and lubricated conditions. The following notes used in this figures concerns: the experimental 1at the rotating speed 144 rpm, the experimental 2 at the rotating speed 173 rpm, the experimental 3 at the rotating speed 323 rpm. For each tested sample of UHMWPE the contact pressure was calculated with formula: $p_{Stribeck} = \frac{F_n}{\pi r_b^2}$

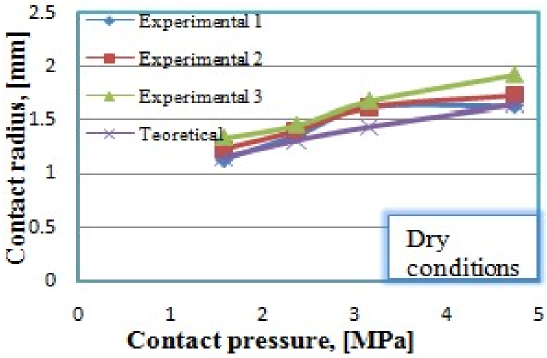


Figure 5. Experimental contact radius – contact pressure curves for UHMWPE under dry conditions.

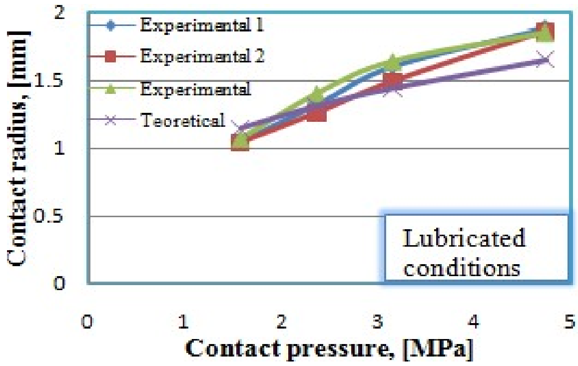


Figure 6. Experimental contact radius –contact pressure curves for UHMWPE under lubricated conditions.

Figures 7 and 8 illustrate the experimental results of penetration depth of UHMWPE in contact with a steel ball under dry and lubricated conditions.

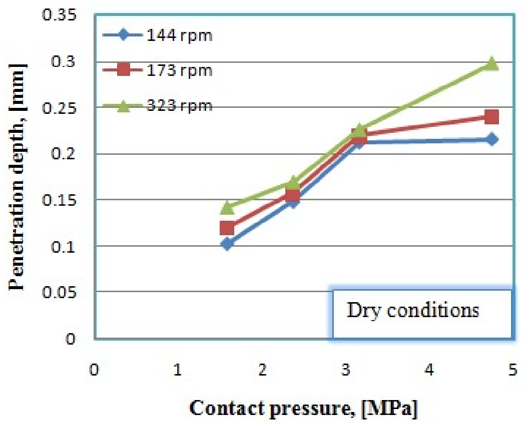


Figure 7. Experimental penetration depth–contact pressure curves for UHMWPE under dry conditions.

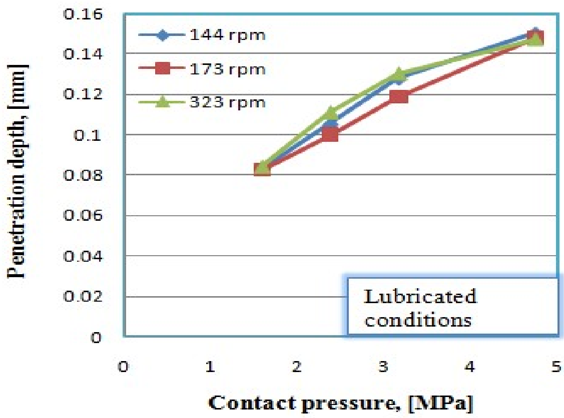


Figure 8. Experimental penetration depth – contact pressure curves for UHMWPE under lubricated conditions.

Figures 9 and 10 illustrate the experimental results of twist moment of UHMWPE in contact with a steel ball under dry and lubricated conditions.

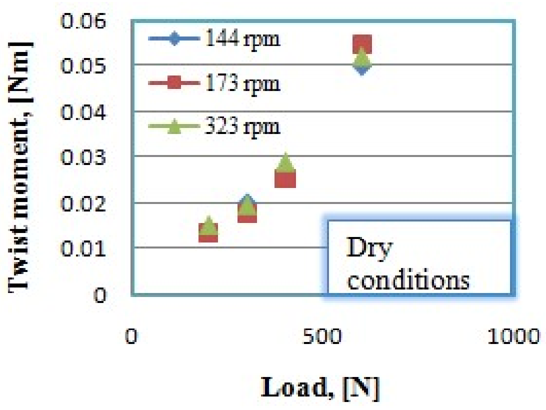


Figure 9. Experimental contact radius – contact pressure curves for UHMWPE under dry conditions.

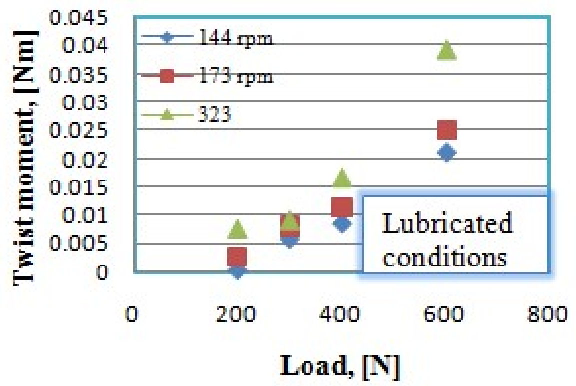


Figure 10. Experimental contact radius –contact pressure curves for UHMWPE under lubricated conditions.

Figure 11 shows the variation of the dynamic coefficient of friction of UHMWPE in contact with a steel ball and rotational speed. Figure 12 shows the variation of the dynamic coefficient of friction of UHMWPE in contact with a steel ball and load.

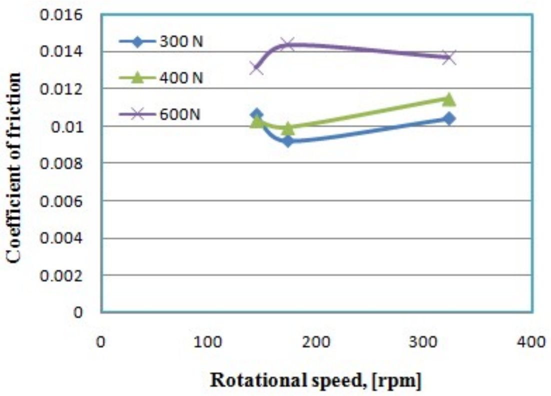


Figure 11. Experimental coefficient of friction-rotational speed curves under dry conditions.

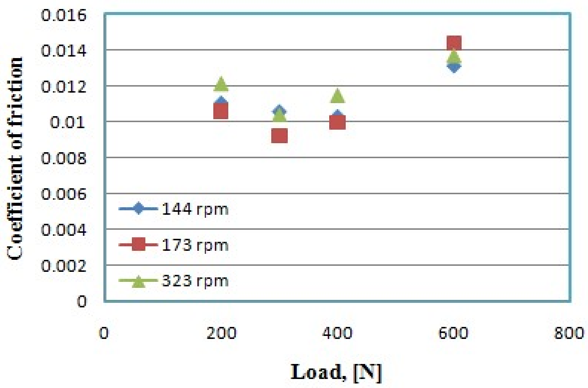


Figure 12. Experimental coefficient of friction-load curves under dry conditions.

Conclusions

A model for the contact between a ball bearing and an UHMWPE plane surface has been developed using the twist method**.** Also, an experimental study has been elaborated for the analysed problem.

Contact radius calculated has the appropriate values like at the contact radius measured from optical investigations. Penetration depths increase with the contact pressure. Twist moment calculated increases with the load. The coefficient of friction obtained is very small and increases with the rotational speed. Subha K.A. et al. [6] in their research also found that the coefficient of friction of the cow skin in contact with the steel increases with the rotational speed.

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