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TRIBOLOGICAL BEHAVIOUR OF A TOTAL HIP PROSTHESIS DURING NORMAL WALKING ACTIVE CYCLE

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Abstract

Total Hip Arthroplasty represents a modern surgical technique that allow for replacement of the natural hip joint by an artificial one. The lifetime of a hip prosthesis is highly connected with the contact mechanism and with friction and wearing processes that occur at the interface between the femoral head of prosthesis and the acetabular cup, considering the loading cycle induced in the joint by normal walking. The present work expose some results of an experimental research concerning the values of friction coefficients and wear rates of the acetabular cup of a total hip prosthesis (considering a couple Stellite 21/UHMWPE) obtained using a biaxial simulator. The study covers also the lubricated (physiological serum) and dry joints. A Finite Element Analysis adds to experimental results some data concerning the stresses, displacements and strains in the artificial hip joint during the normal walking.

Keywords: friction, wear, hip prosthesis, Finite Element Method, wear rate

1. INTRODUCTION

The active walking cycle of humans induces high mechanical loading in the hip joint. It is well known that the resultant force that occurs in the hip joint approximately equals 3.5...4 times the body weight, being accordingly to some authors even bigger than that [4]. For the patients with implanted total hip prostheses, the cyclic loads could conduct to the prosthesis damage. Using some prostheses replaced by revisions*) (being used between 12 and 15 years) we performed a quantitative and qualitative tribological analysis. We have noticed non-uniform tarnishing and some scratches having different dimensions and randomly located on the femoral heads of the prostheses. Also, the acetabular UHMWPE cups show damages of the internal surface (the material was pulled-out) or possible fretting traces. Nor photos neither-rsurface profiles showing the damages were possible technically speaking.

Based on the qualitative observations the authors tried a quantitative evaluation. In order to do that a femoral head meridian was divided in four equal parts and the profilograms of the equatorial plane and of the planes that limit the meridian divisions next to the equatorial line were registered. These plots are available in Figure 1.

In this figure we could noticed some areas where the surface is settled notifying the local superficial hardening. We performed hardness measurements on 12 meridians (equally distributed at 30 degrees one from another) the results showing significant differences of hardness in compressed areas, consolidating the hardening assumption. This fact confirms the effect of very high loads. Another effect is the local increase of the temperature at the contact interface, the melting of the UHMWPE surface and the fretting wear trend.

2. THE EXPERIMENTAL STUDY

For experimental study of the frictional and wearing processes of the total hip prostheses, a simulator of 2D movement was made using an electrical engine of 5.5 kW having variable speed between 0 and 3000 r.p.m. The frictional couple is made from a femoral head of a modulated Johnson & Johnson prosthesis (Stellite 21), who rotates under load, in the cavity of UHMWPE acetabular cup. The femoral head has a diameter of 28 mm and executes an oscillation of ±30°, corresponding to a stroke of 22 mm driving rod. The frictional couple functions in a small basin with physiological serum used as lubricant. This couple is doubled by a witness identical couple (Stellite 21/UHMWPE) under same loads but without movement. The both couples are mounted on a tensometric device, on which the variable, non-continuous working loads are applied. The witness couple is needed in order to determinate the lubricant absorption by the acetabular cups, knowing that the UHMWPE has hygroscopic behaviour. The loads are applied by means of a treated spring.

A partial view of the experimental setup could be visualised in Figure 2.

The experimental setup contains a strain gauge bridge with two measurement channels, one for normal force F_N and the other one for friction Ff, and a miniature thermocouple for measuring the temperature close to the contact surface.

The normal force and the friction are registered by a plotter.For tests only the 60 and 120 rpm frequencies are used (corresponding to a normal respectively accelerated walk). These correspond to some relative speeds of 527 and 1055 cm/min.

The duration of tests was $3 \cdot 10^6$ cycles, it means 834 hours (approximately 35 days). So, the total travel length was $44 \cdot 10^6$ respectively $88 \cdot 10^6$ mm (depends of the two relative speeds).

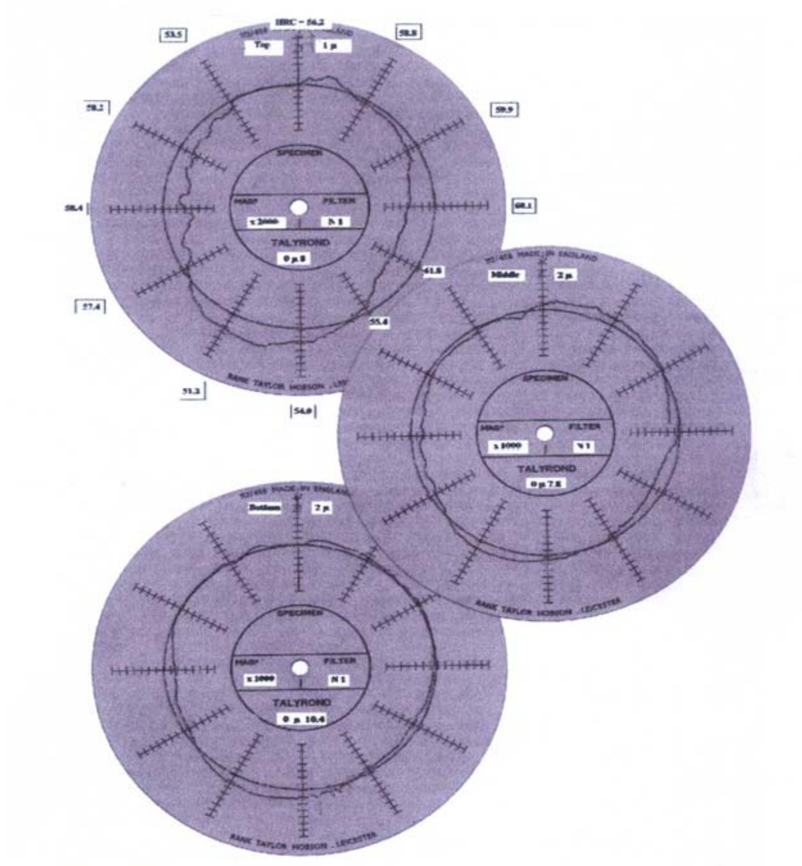

Fig.1: *Femoral head profiles for J&J prosthesis (made from Stellite 21) replaced after 12 years [3]*

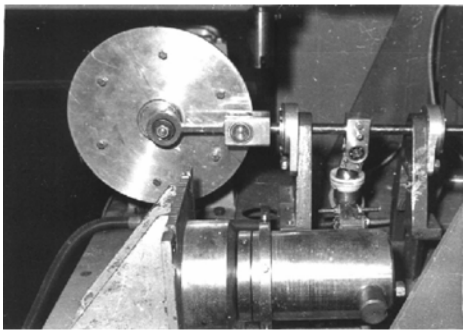

Fig.2: *Partial view of the experimental setup*

3. EXPERIMENTAL RESULTS

The measurement of the normal force and friction yields to the evaluation of the frictional coefficient, based on Coulomb Law.

Tabel 1. Frictional forces and frictional coefficients on a rotational couple Stellite 21/ UHMWPE (dry friction)

p MPa	v cm/min	FN N	Ff N	μ
0.7	527	500	14.25	0.285
1.4	527	1000	32.00	0.320
2.1	527	1500	51.3	0.342
0.7	1055	500	14.00	0.280
1.4	1055	1000	29.50	0.295
2.1	1055	1500	45.00	0.300

Tabel 2. Frictional forces and frictional coefficients on a rotational couple Stellite 21/ UHMWPE (in physiological serum

p MPa	v cm/min	FN N	Ff N	μ
0.7	527	500	1.75	0.035
1.4	527	1000	4.90	0.073
2.1	527	1500	9.75	0.090
0.7	1055	500	1.60	0.085
1.4	1055	1000	4.10	0.125
2.1	1055	1500	6.75	0.141

One could notice that for the contact pressure used in experiments the frictional coefficients is almost linear, the diagrams containing also the regression expressions.

The frictional coefficient decreases when the relative speed increases and linearly increases with the load.

The results of the experimental tests of wear of the acetabular cups, in the same loading conditions, based on gravimetric measurements are listed in Table 3 and plotted in Figure 4. The diagrams in Figure 4 show that the dependence between the wear rate and the contact pressure is

The wear of the UHMWPE acetabular cups was established by gravimetric measurements as being the difference in weight before and after the $3{\cdot}10^6$ cycles of loading, considering also the hygroscopic effect (measured as the difference on the witness specimen due to the lubricant absorption by the polyethylene).

The experimental conditions as well as the values of friction force and frictional coefficients at the interface between the femoral head (Stellite 21) and the acetabular cup (UHMWPE) are listed in Tables 1 and 2 for dry friction as for physiological serum lubrication. The dependence of the frictional coefficients by the contact pressure is plotted in Figure 3

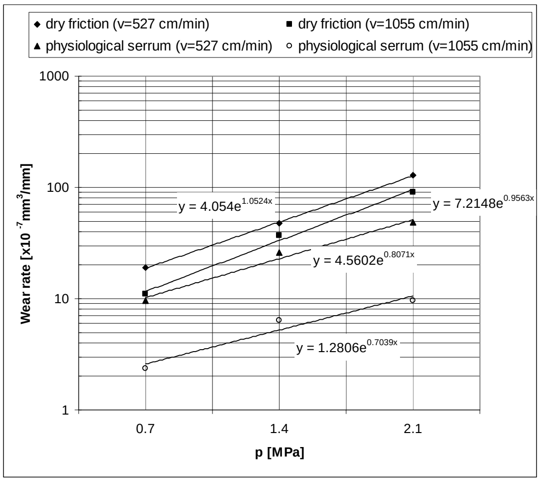

Fig.3: *Wear rate vs. contact pressure in dry friction and physiological serum lubrication*

exponential, this rate being doubled by the absence of lubrication.

Tabel 3 lists the values of wear rate resulted from experiments as gravimetric wear rate (10^{-11} g/mm of the length of entire travel) and volumetric wear rate also (10^{-7} mm^3/mm of the length of entire travel).

One could notices that in the dry friction case the wear rate is significantly increased as for lubricated friction (with physiological serum).

4. THE FINITE ELEMENT ANALYSIS

As previously stated some sort of dependency of wear rate by contact pressure was reported.

Because the measurement of the stress state in the vicinity of the contact area was impossible during the wear tests performed we take a closer look to stress values by intermediate of some Finite Element analyses.

The analyses cover all three load cases corresponding to normal walk (v=527 cm/min) for which we have determined the wear rate and the frictional coefficient: F = 500 N, F = 1000 N, and F = 1500 N. The speed being held constant we assumed that we have no inertial effects.

The model used for all analyses is presented in figure 5. We assumed a plane stress state. The model comprises a large part of UHMWPE (having circular form) in contact with the head of a femoral prosthesis made from Stellite21. The UHMWPE part is considered restrained on its exterior circumference located far enough in order to not interfere with the stresses at the contact interface. The loads are applied in the centre of femoral head, the direction of these loads varying by an angle of 30° against the vertical axis.

The elastic properties of the two components (the polyethylene part and the femoral head) are those described below:

Tabel 3. Wear rate for a rotational couple Stellite 21/UHMWPE

p *MPa*	v *cm/min*	L_f 10^6 *mm*	Dry friction			In physiological serum		
			Wear 10^{-5} g	Wear rate		Wear 10^{-5} g	Wear rate	
				10^{-11} *g/mm*	10^{-7} *mm³/mm*		10^{-11} *g/mm*	10^{-7} *mm³/mm*
0.7	527	22.02	27.90	176.277	18.955	14.10	89.086	9.579
1.4	527	22.02	79.10	445.602	47.914	38.40	242.618	26.088
2.1	527	22.02	188.90	1193.505	128.334	80.20	447.572	48.126
0.7	1055	44.04	32.30	102.038	10.972	6.90	21.798	2.344
1.4	1055	44.04	109.70	346.552	37.264	11.30	59.372	6.384
2.1	1055	44.04	348.30	837.279	90.030	14.10	89.086	9.579

- for UHMWPE part:

$$E = 890\, N/mm^2$$
$$\nu = 0.36$$

- for femoral head (Stellite21):

$$E = 2 \cdot 10^5\, N/mm^2$$
$$\nu = 0.28$$

The conditions at the contact interface (the frictional coefficient, the contact stiffness) are those measured in experiments. Only dry friction conditions are analysed.

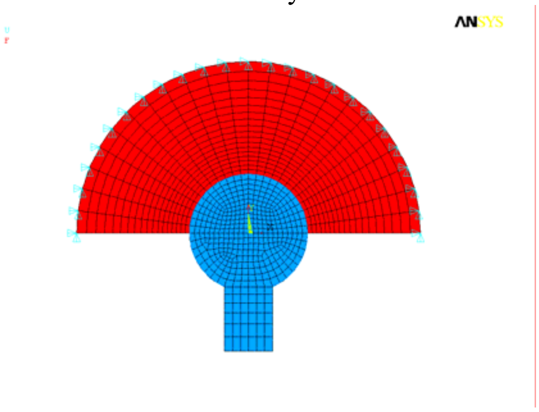

Fig.5: *FE Model for the Stellite21/UHMWPE couple*

To give an explicit description of the results, we choose three position of the femoral cup as being important (the femoral cup at 0° - corresponding to the start position, the femoral cup at 15° - corresponding to an intermediate position, and the femoral cup at 30° - corresponding to the large amplitude position). The angles are measured from vertical axis the positive direction being toward the X axis.

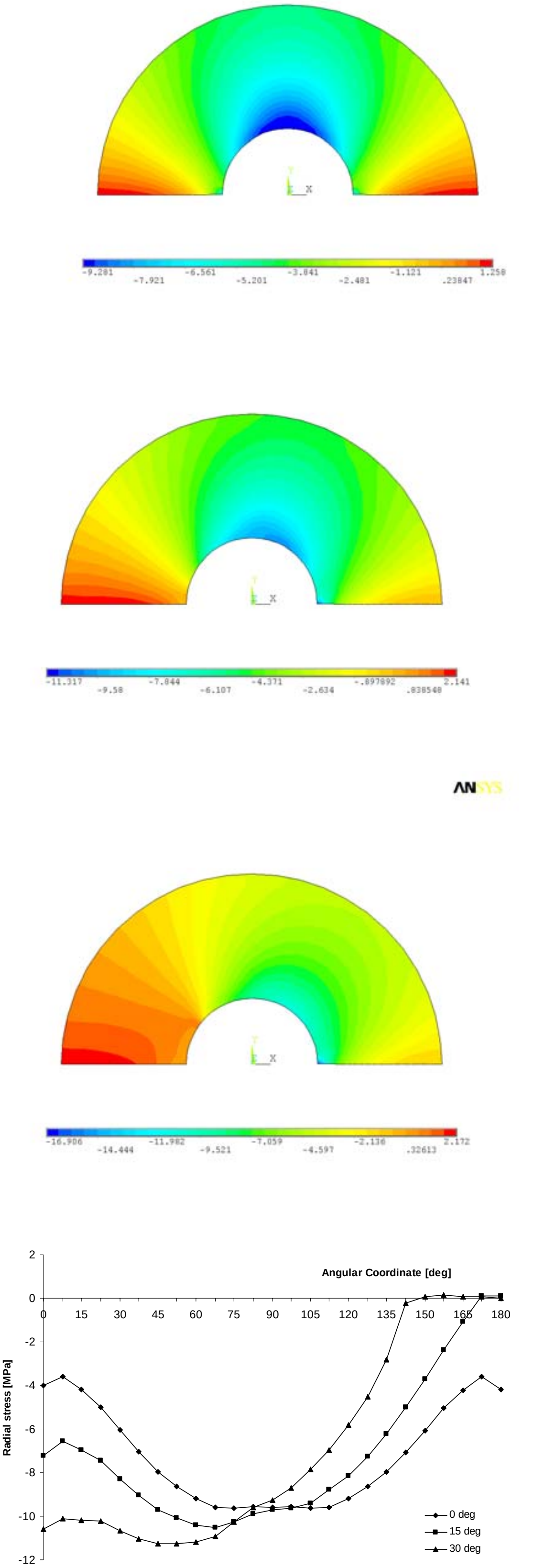

Fig.6: *Radial stress for three positions of the femoral head (0°, 15° and 30°)*

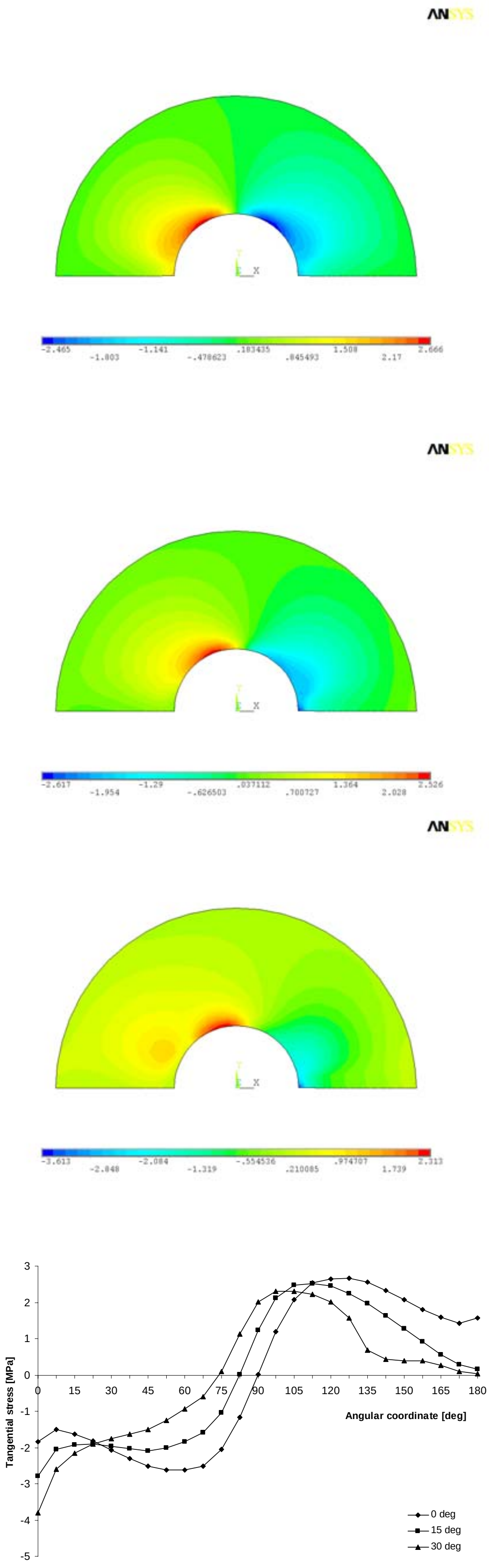

Fig.7: *Shear stress for three positions of the femoral head (0°, 15° and 30°)*

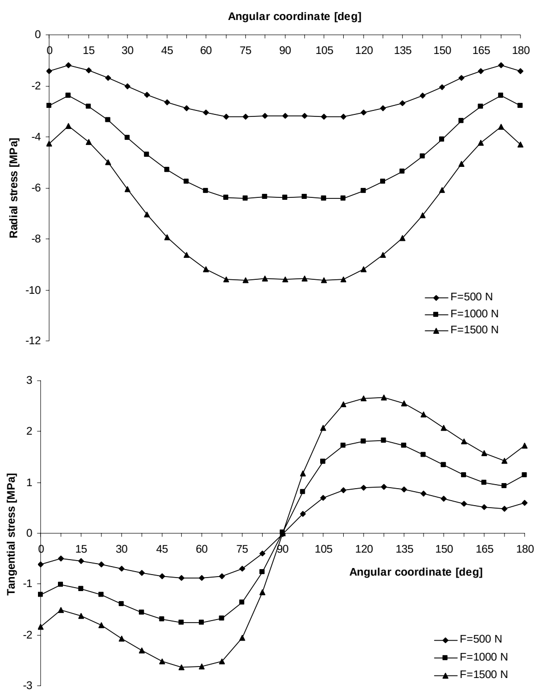

Fig.8: *Tangential stress for three positions of the femoral head (0°, 15° and 30°)*

The results for all these three positions are given in a polar coordinate system located on the centre of femoral head. The extreme values are listed in table 4.

The stress state in the polyethylene part was described here by the radial stress σ_{rr} interpreted as a measure of the kinematics of the contact surface and by the shear stress $\sigma_{r\theta}$ characterizing the frictional phenomena at the contact interface.

The plots presented in figure 6 shows the distribution of the radial stress for all the three positions of the femoral head considered (0°, 15° and 30°). The maximum stress is located around the point of intersection between the direction of load and the internal circumference of the polyethylene part.

The profiles of the radial stresses plotted versus the angular coordinate in the lower part of the figure 6 reveals the fact that closer to the maximum amplitude position the distribution of the radial stress have an unsymmetrical aspect. Also, we could notice that the stresses are increasing when the amplitude was increased and the contact gap is opening on that part far away from the centre of the maximum stress area (closer to the higher values of angular coordinates).

The distributions of the shear stress for all the three positions of the femoral head considered were plotted in figure 7. For this kind of stresses we have two maximum zones (corresponding of two different orientation of the friction) disposed anti-symmetric for initial position. This characteristic was removed as the femoral head approach to the maximum amplitude position. If for radial stresses we could notice an increase of a maximum value as the amplitude of femoral head was increased in the case of the shear stress we notice the opposite.

Tabel 4. Minimum/maximum stresses at the contact interface

Case no.	Force [N]	Radial stress [MPa]			Shear stress [MPa]		
		0°	15°	30°	0°	15°	30°
1	500	-3.203	-3.496	-3.767	-0.881	-0.702	-0.403
					0.912	0.837	0.777
2	1000	-6.403	-6.990	-7.535	-1.762	-1.406	-1.075
					1.823	1.686	1.560
3	1500	-9.621	-10.510	-10.918	-2.630	-2.088	-1.637
					2.650	2.526	2.313

The two local extreme values of the shear stress are decreasing (for large amplitude loosing even the character of local extreme).

In figure 8 the radial and shear stresses for initial position are plotted for all three cases considered (F = 500, 1000 and 1500 N). The symmetric and antisymmetric aspect of the two profiles for this particular position is revealed.

5. CONCLUSIONS

The evaluation of the wearing phenomena that occurs in a tribological couple often used in the hip replacement (Stellite21/UHMWPE) has a critical importance for the functionality of the prosthesis. The lifetime of a total hip prosthesis is highly connected to the contact mechanism that occurs in the frictional couple.

The hardness measurements and profilometric qualitative and quantitative evaluations of the elements of the couples presented in some replaced prostheses (after revision surgical procedure) shows non-uniform tarnishing of the femoral head, local surface hardening of it and local melting of the polyethylene cups due to the increased temperature that occurs due to higher loads.

Using an experimental setup special designed for this purpose we evaluated the behaviour of the frictional couple provided by a Johnson & Johnson total hip prosthesis during an oscillatory movement of the femoral head (± 30°) with two different frequencies (60 and 120 rpm) corresponding to the normal and accelerated walking.

The results show a linear dependence between the frictional coefficient and the contact pressure. Also this coefficient decrease when the speed is increasing.

The measurements of gravimetric and volumetric wear rate reveal an exponential variation of that measure with the variation of the contact pressure. Also, the absence of lubricant (physiological serum) doubles the wear rate.

Some Finite Element analyses were performed in order to determinate the real stress state at the contact surface. The results reveal the non-uniform distribution of stresses that could cause the non-uniform wear of the polyethylene cup.

Also, analyzing the values of stresses determined we could conclude that the tribological experiments described in the first part of this paper covers (by the three cases analysed) all the contact situations encountered during normal walking.

6. REFERENCES

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