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WEAR ANALYSIS OF A PLUNGER OF DIESEL INJECTION PUMP COMBINING EXPERIMENTAL TEST AND FINITE ELEMENT SIMULATION

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Abstract. *Performing experimental tests is the most common way to study wear of mechanical components and evaluate the parameters that affect it. In addition, studies using numerical simulations with the finite element method in combination with mathematical models for wear prediction have helped to understand some physical principles, as well to estimate the effects of this phenomenon. Within this context, this work aims to study the tribological behavior of the plunger-pump body of a diesel injection system through experimental tests and numerical simulations. A device is developed and built for carrying out experimental sliding tests on a tribometer. Dry tests are performed varying the normal force and the sliding distance. The experimental results are integrated in a numerical model through a subroutine that applies the measured wear along the simulation. The numerical finite element model is developed in order to represent the experimental tests and reproduce the wear in the plunger surface. The above mentioned subroutine applies the wear in a good agreement with experimental tests. With the results of the numerical model, it is possible to evaluate the components behavior, taking into account the wear evolution in the plunger, besides estimating the wear coefficient for the studied contact pair.*

Keywords: *wear, tribological experimental test, numerical simulation, finite element method, diesel injection pump*

1. INTRODUCTION

Most diesel injection components such as valves, plungers and washers are subjected to sliding motion and, although lubricated with diesel fuel, they may wear during operation (Barunovic, *et al.*, 2012). The goal of this work is to study the tribological behavior of the body-plunger system of a diesel injection pump through experimental tests combined with finite elements numerical simulations. The plungers, made of tool steel, with titanium nitride coating (TiN-layer), and the pump body, made of modified chrome molybdenum steel alloy, nitrated, are submitted to experimental tests in a tribometer, in order to evaluate the wear mechanisms and to measure the main wear factors. The obtained experimental data are coupled with finite element analyses to develop a numerical model able to generate the wear profile through an iterative method that simulates the material removal of the plunger surface, besides of calculating the wear coefficient.

2. METHODOLOGY

Initially, a simplified tridimensional numerical model by finite elements is created in the Abaqus code to evaluate the force levels, displacements and contact stresses acting in the plunger during the injection pump operation under a certain actual operating condition. This study provided information to design and built a device for the experimental tests of oscillatory sliding wear in a tribometer.

The experimental tests are performed in a CETR-UMT Bruker tribometer, with the parameters mentioned in Tab. 1, which were defined from some initial tests, in order to reduce vibration problems and to reproduce the wear in the plunger surface.

Table 1. Parameters of the experimental wear tests.

Parameter	Description / Value
Type of test	Oscillatory sliding
Stroke	5 mm
Frequency	5 Hz
Mean speed	50 mm/s
Test duration	Between 7 and 35 minutes
Number of cycles	Between 2100 and 10500 cycles
Total sliding distance	Between 21 and 105 m
Normal force	25, 30 and 35 N
Interface	Dry
Temperature	Lab temperature
Humidity	Lab humidity

Due to the wear characteristics on the plunger surface and the techniques used to measure it, a bi-dimensional finite element model of the longitudinal cross section of the plunger and pump body is created. With this model, it is possible to represent the worn profile where the maximal wear depth occurs. The corresponding finite element model, boundary conditions and loads are represented in Fig. 1.

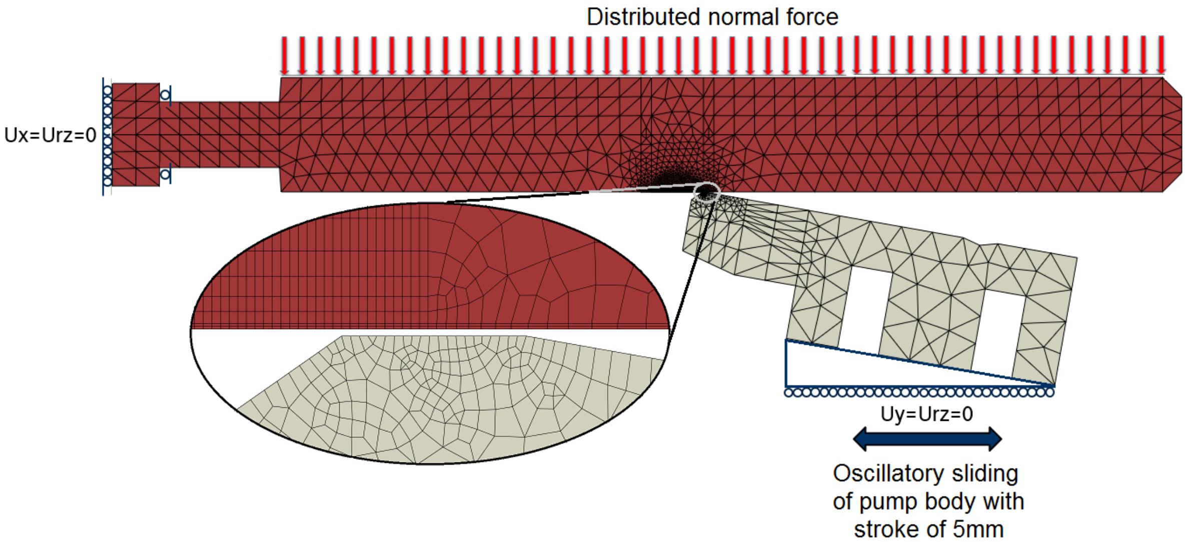

Figure 1. Bi-dimensional finite element model for wear simulation.

The experimental results of wear are integrated to the numerical model both as input parameters as for model validation. From the experimental tests, a general mean friction coefficient and the mean of maximal wear depth in the pump body is calculated, which are used as input parameters in the numerical model.

The maximal wear depths in the plunger surfaces are measured and correlated with the sliding distance, in order to obtain mathematical equations that define the wear evolution. These equations, together with the normal force value and the number of cycles to be evaluated, are inserted in the subroutine UMESHMOTION. This subroutine inserts a position variation in the nodes of contact surface, in the end of each numerical increment. This position variation corresponds to the wear depth, discretized to each node of the contact surface, depending on the sliding distance in the numerical model. This way, the wear depth can be calculated and implemented in the model for each increment, generating the wear profile in the plunger surface in contact with the pump body.

Besides the wear profile formation in the plunger surface, at the end of each wear cycle the subroutine calculates the wear coefficient from the modified Archard equation.

Figure 2 shows the flowchart of the numerical procedure to insert the wear depth in the numerical model.

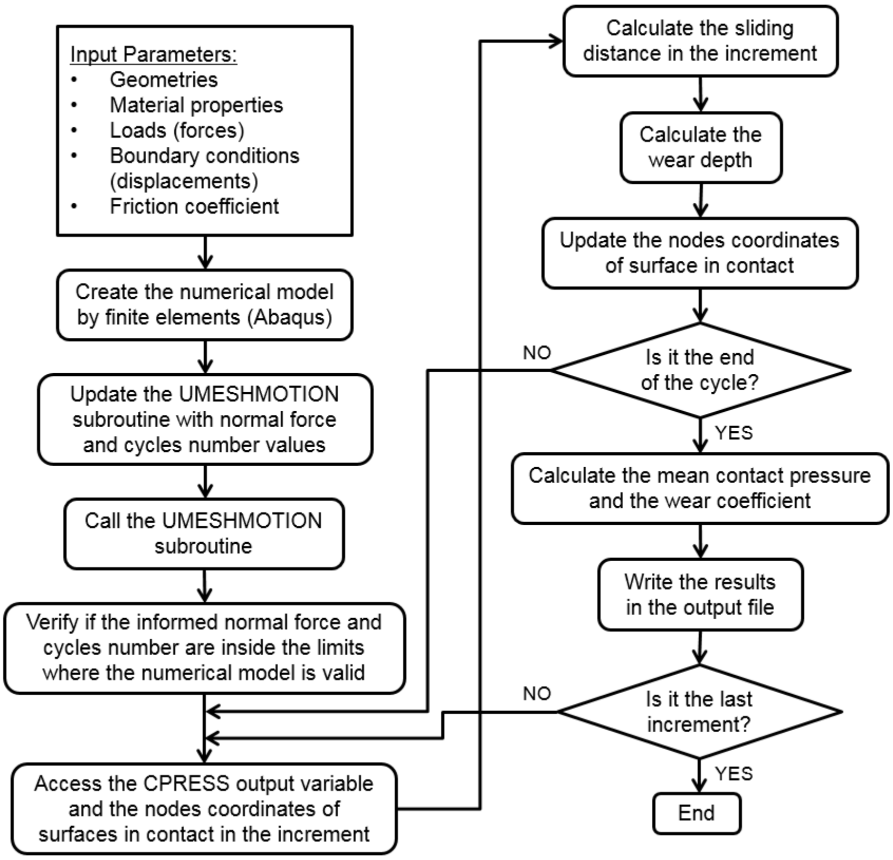

Figure 2. Flowchart of the numerical procedure to insert the wear.

3. RESULTS AND DISCUSSION

The evolution of the friction coefficient value in the experimental tests looks like the findings presented by Ma, *et al.* (2005), with three periods related to different wear behaviors, preceded of running-in. In the running-in occurs the softening of contact peaks and, after that, the stability of friction coefficient. In the stable period, the wear rate of the TiN layer is low until the amount and size of wear particles are able to generate grooves in the layer, increasing abruptly the friction coefficient and the wear rate, until the total rupture of the layer. For all cases, under the evaluated normal forces of 25, 30 and 35 N, it is observed the running-in until approximately 20 m and the stable periods until approximately 86, 54 and 40 m, respectively. These distances limit the region where the numerical model is valid, that is, in the region of stable behavior for normal forces between 25 and 35 N. From these friction coefficient curves, it is also calculated the general mean value of 0.48, used in the numerical model.

From the measurements of wear profile of the chamfer of plunger guide in the pump body are obtained the maximal wear depths depending on sliding distance in each test. For each applied normal force, linear correlations are obtained and they are used to calculate the wear depths at distance of 20 m and, from these values, to calculate the general mean value, equal to 19 µm. This value is applied in the initial numerical model, in order to represent the wear in the pump body, which is kept constant during the numerical analyses.

In the plungers, the maximal wear depth can only be measured in the more severe tests, after the stable region. Figure 3 shows the maximal wear depths measured in the plunger depending on accumulated dissipated energy. As proposed by several authors, as Huq and Celis (1997), Fouvry, *et al.* (2003), Jahangiri, *et al.* (2012), among others, there is a liner correlation between wear and accumulated dissipated energy. Figure 3 shows the liner equation, where it is possible to define the wear rate by energy of 8.2E-4 µm/J, which is used to estimate the maximal wear depth in the plunger of other less severe tests.

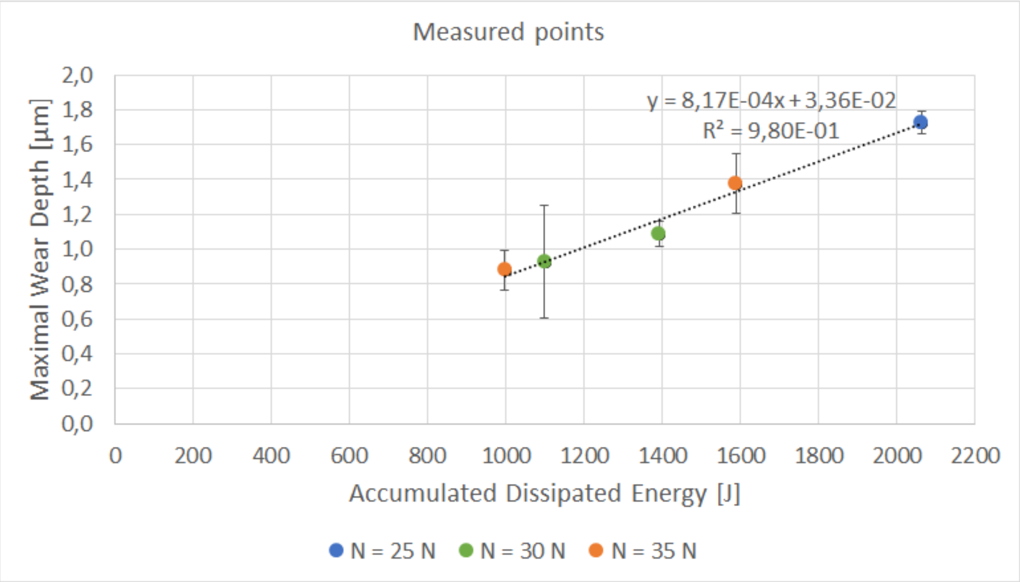

Figure 3. Maximal wear depths measured in the plunger surface function of the accumulated dissipated energy for different normal forces (c = 5 mm; f = 5 Hz).

From the correlation between the estimated maximal wear depths and the sliding distance in each test, it is observed the increase of wear increasing the sliding distance and/or the applied normal force, according to what was proposed by Archard (1953). Besides that, there are different wear rates in the stable region and after that, due to the changes in the wear mechanisms.

In the numerical model, for the wear application in the plunger surface, mathematical equations correlating the wear depth and the sliding distance are necessary. These equations are obtained from the measured data, shown in Fig. 4, considering only the results inside the stable region, where the numerical model is valid. The equations are inserted in the subroutine for the calculation of wear depth in each numerical increment. Thus, the wear depth is applied to each node of the plunger region in contact with the pump body, forming the wear profile in the plunger surface.

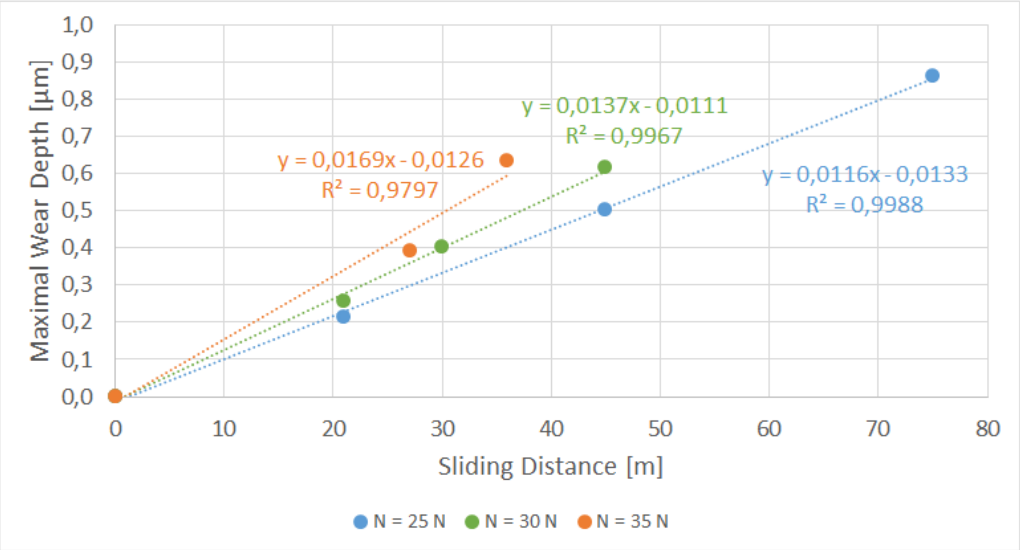

Figure 4. Equations of maximal wear depth in the plunger function of sliding distance for different normal forces, in the region where the numerical model is valid.

Table 2 shows the numerical and the experimental wear results, and the corresponding errors. The results show that the subroutine operates correctly, because the values of wear depths in the numerical models correspond to those calculated by the equations shown in Figure 4. The errors between the techniques are expected because the equations used by the numerical model are linear extrapolations from the mean values obtained experimentally.

Table 2. Numerical results of maximal wear depth in the plunger surface for the simulated cases.

Group	Force [N]	Number of cycles [-]	Maximal wear depth [μm]		Error [%]
			Numerical	Experimental	
1	25	2100	0.23	0.21	7.6
2		4500	0.51	0.50	1.3
3		7500	0.86	0.86	- 0.6
6	30	2100	0.28	0.26	8.1
7		3000	0.40	0.40	- 0.3
8		4500	0.61	0.62	- 1.7
11	35	2700	0.44	0.39	13
12		3600	0.60	0.63	- 5.9
-	27	7100	0.87	-	w/o ref.
-	33	4300	0.66	-	w/o ref.

Other result from the numerical model is the evolution of the wear coefficient as a function of the sliding distance. From the evolution of wear coefficient for the simulated conditions, the mean wear coefficient of (9.7 ± 0.7)E-8 $mm^2/N.m$ for the pump body-plunger system was obtained.

4. CONCLUSIONS

From the results of the experimental tests, it is observed different wear behaviors through the friction coefficient evolution. A first running-in period, with softening of contact peaks, followed by the stable period, where little wear of TiN layer occurs, and a third period characterized by the abrupt increase in the friction coefficient and in the wear of TiN layer. It is also observed the linear correlation between wear and accumulated dissipated energy, as proposed by others authors. Only due to this correlation that it was possible to measure the wear in less severe tests and obtain the equations of the wear depth as a function of sliding distance, which are necessary for the development of the numerical model. In the graphics of wear depth versus sliding distance, it is observed two wear rates: one when the system is inside the stable region, and another, higher, after this region. This difference is caused by the changes in the wear mechanisms.

The results from the numerical model show good correlation with the experimental results. The observed differences regarding the maximal wear depth values are related to the linear extrapolation of the experimental mean values. However, the model simulates the exact wear depth given by the equations obtained from the experiments, showing the accuracy of the developed subroutine.

It is possible to verify the viability of using a numerical procedure combined with finite elements to simulate wear, since experimental data are available to be implemented in a subroutine that applies the wear during the numerical calculation. The methodology applied in this work can be used for the development of new subroutines, applicable in more complex models, for example. With a numerical model like the one proposed here, it is possible to evaluate and compare, quickly and accurately, future project variations and operation conditions, reducing the requirement of experimental tests, samples and device costs, beyond the work time of specialized technicians.

5. REFERENCES

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6. RESPONSIBILITY NOTICE