Performances of automotive lubricants – tests on four ball machine

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Abstract. In this paper an automotive full synthetically lubricant is tested on a four ball machine. A new data acquisition system is developed, based on tensometric strain gauges principle. In order to interpret the data statistically (signal to noise ratio, skewness and kurtosis etc.) and to directly display the values of the instantaneous friction coefficient, a LabVIEW interface is created. The effect of the sustaining rolling bearing on the mean friction torque and instantaneous friction coefficient between the rotating upper ball and the three stationary balls of the four ball machine’s testing device is also evaluated. For the synthetically motor oil the last non-seizure load (LNSL), initial seizure load (ISL), and the weld points (WP) were established. The new data acquisition system and interface allow the exact prediction of lubricant film seizure. The experimental values of the friction coefficient correspond as order of magnitude with those from literature.

1. Introduction

Lubrication plays an essential role in wear reduction of various mechanisms, eliminating surface to surface contact of components. In automotive field the lubricants, in form of oils or greases, are presented in motors, gearboxes, distributors, differentials, pumps, bearings etc. The quality and the condition of lubricants influence the performance of afore mentioned machine parts through their properties, as: high pressure resistance, viscosity and viscosity index, anti-wear and anti-corrosion resistance etc. A proper lubrication augments the efficiency and the reliability of engines and protects against corrosion and wear. Oppositely, wear affects the life of engines - in direct relationship with motor oil quality and condition.

The main function of lubricant is to reduce friction, temperature, wear, corrosion, and shocks. Motor oils are complex mixtures, containing primarily two elements: the base (stock) oil and the additives. Anti-wear additives eliminate metal to metal contact by forming a thin lubricant film between the contact surfaces, protecting the tribocontact against abrasive, adhesive and corrosive wear phenomena.

The four ball tribometer is the most used to investigate the anti-wear and extreme pressure properties of lubricants at various loads and constant rotating speed of the upper ball, according to internationally adopted and recognised standards. Conforming to the recommendations of ASTM D2783-3, various lubricants performances can be determined on a four ball machine: compensation line, last non-seizure load (LNSL), initial seizure load (ISL), load - wear index (LWI), the weld point, etc.
The previous published studies in the field focused on hydraulic oil performances [1, 2], and kerosene and cutting fluid wear resistance [3, 4]. The new trends to cope with the environmental requirements are oriented on biodegradable lubricants [5-8].

Nevertheless, when choosing the best oil for a combustion engine, we usually take into consideration the recommendation of cars’ producers, but sometimes the intense use of the car in harsh regimes (severe temperatures, long ways of many thousands of kilometres in a short while), requests the employment of better lubricants which resist in a good state for a longer running, permitting extended service periods. In this situation bio-degradable oils, mineral oils, and semi-synthetically oils usually fail, and the use of additived full-synthetically oils is requested.

In spite of this the drivers are still reticent to put into the motor different oils than recommended by car manufacturers. In this case, to establish the performances of such oils, tests on tribometer are imposed.

The aim of the present paper is to determine the tribological performances of a full synthetically oil designated for a running up to 50,000 kilometres with no oil and filters change services.

Furthermore an improved data acquisition system is presented, taking into account the influence of the supporting nonrotating axial ball bearing on the overall friction coefficient measured in four ball tester.

The designed LabVIEW virtual instrument directly displays the values of the mean friction torque, sustaining rolling bearing torque and mean friction coefficient, besides the evolution of the instantaneous friction coefficient during tests, allowing the exact prediction of the time of scuffing initiation.

2. Materials and testing machine

2.1. Materials

| Table 1. Properties of the tested balls (AISI 52100 bearing steel). |
|---|---|
| Units | Value |
| Diameter mm | 12.7 |
| Hardness HRC | 62 – 65 |
| Roughness (Ra) μm | 0.018 – 0.035 |
| Ball grade | 3 |
| Composition [wt. %] | C: 0.95-1.1 ; Si: 0.17-0.37; Mn: 0.25-0.45; Cr: 1.30-1.65 |

| Table 2. Properties of the full synthetically oil. |
|---|---|
| Units | Value |
| Viscosity | |
| - CCS @ -25 °C (cold crank viscosity) mPa·s | 4819 |
| - CST (@ 100 °C) | 14.45 |
| Density @ 20 °C, ρ Kg/m³ | 855.5 |
| Ash wt. % | 0.62 |
| TBN mg KOH/g | 6.5 |
2.2. Testing machine and running conditions
A view of the standard testing machine equipped with the data acquisition system is presented in figure 1. The electrical motor and the belt transmission (1) rotate the shaft (2). At the end of the shaft there is a tapered chuck with the clamped upper rotating ball. The testing device (3) contains the three stationary lower balls placed in a pot and completely covered by lubricant, in order to assure a lubrication film between the upper ball and the lower ones.
All the tests were carried out at constant speed of 1500 rpm, established by a frequency variator (6), and increasing axial load. The ball samples in the device’s pot were completely submerged in about 30 ml of lubricant. The running time of each test is 60 seconds.

![Figure 1. General view of the four ball machine and data acquisition system [4]](image)

2.3. Data acquisition
The data acquisition system allows the measurement of the friction torque between the upper ball and the three lower balls. A metallic leaf (5) with two strain gauges brazed on it composes a half Wheatstone bridge for bending measurements. The metallic leaf joints the testing device, being
blocked from movement by a pin screwed to the base of the machine, so the friction forces between the tested balls create a torque which produces the bending of the tensometric leaf.

Accordingly, the strain gauges modify their length directly proportional with the bending moment of the leaf, bending generated by the friction forces between tested balls. The entire data acquisition system is calibrated by dead weight method, the variation being linear. The calibration coefficient relating the friction torque, \( M_f \), produced in the center of the device and the strain gauges elongation \( \varepsilon \) is given by equation (1).

\[
M_f = 3.66 \cdot \varepsilon
\]  

The strain bridge Vishay P3 (7) collects the data and is connected to the laptop (8) with the bridge dedicated software and LabVIEW program. The interface created in LabVIEW program allows the computation of the mean friction torque and friction coefficient.

The contribution of the non-rotating axial ball thrust bearing from 51111 series that sustains the testing device on the base is appreciated for different axial loads [9], being estimated by the so called starting moment, \( M_{f\text{ start}} \) (figure 3). This friction moment is subtracted from the overall measured friction torque. The starting friction torque of the axial ball bearing is computed as [9]:

\[
M_{f\text{ start}} = M_{SL} + M_{rr} + M_{seal} + M_{drag}
\]  

where:
\( M_{f\text{ start}} \) - is the starting friction moment of bearing, N x mm;
\( M_{SL} \) = sliding frictional moment;
\( M_{rr} \) = rolling frictional moment;
\( M_{seal} \) = frictional moment in seals;
\( M_{drag} \) = drag frictional moment;

The last three terms are nil in our case, as the rolling bearing has no seal and is none rotating. Equation (2) becomes:

\[
M_{f\text{ start}} = M_{SL}
\]  

where \( G_{SL} \) is a variable that depends on the rolling bearing type.

\[
G_{SL} = S_1 \cdot d_m^{0.05} \cdot F_a^{4/3}
\]  

\( S_1 \) = geometric constants for sliding frictional moment; \( d_m \) - mean diameter of bearing; \( F_a \) - axial load.

\[
S_1 = 1.6 \cdot 10^{-2}
\]  

\( \mu_{SL} = \mu_{BL} = 0.15 \)

\( \mu_{BL} \) = constant friction coefficient for starting torque calculation.

The obtained values for the starting friction torque versus axial load were interpolated, the graphical representation and the curve fitting equation being presented in figure 3.
3. Results and discussions
The main results obtained from tests on four ball machine for the full synthetically motor oil are:
- last non-seizure load (LNSL);
- initial seizure load (ISL);
- the weld point (WP);
- mean friction torque and friction coefficient;
- wear scar diameter;
- statistical parameters regarding data acquisition quality: signal to noise ratio – SNR, kurtosis, skewness, maxim value of the friction torque and the time of occurrence etc.

3.1. Tribological parameters
The LNSL was found as 1900 N (figure 4a), and the wear scar diameter is around 0.8 mm. A microscopic image of the wear scar with 180x magnification is presented in figure 5a. The corresponding mean friction coefficient is $\mu = 0.06$.

The ISL was detected during the end of the test at 2000 N (figure 4b), the wear scar diameter being about… mm. It can be observed that at the end of the test the seizure initiation conducted to some deeper grooves in the center of the wear scar, the friction coefficient increasing instantly from 0.075 to 0.12 in just one second (figure 5b). To respect the established standard procedure, the test was stopped at exactly 1 minute of running.

The WP occurred for the immediately above ISL point, corresponding to an axial load of 2100 N (figure 4c). The time to welding was just 7 seconds, when the friction coefficient got values corresponding to a dry regime ($\mu = 0.28$). The wear scar is higher in diameter (above 2 mm), traces of scuffing being evident (figure 5c). The test was stopped in second 7 because of strong vibrations.

3.2. Statistical parameters
During the tests the values of the SNR were very high, being around 10 for LNSL and ISL tests and 1.4 for the WP test (due to the small number of points, just 7). Anyway, a SNR above 1 indicate reliable data acquisition sequence.

The low skewness and kurtosis values in the LNSL test ($s=0.41, k=1.8$) prove a stable running with uniform distribution of data. For the ISL test a positive skewness, $s=3$, and a high kurtosis of $k=22$ indicate a sudden data arithmetic mean moving to high values, corresponding to seizure initiation in contacts at the end of the test.
Figure (a) shows the statistical parameters of the signal for the first set of input data. The mean friction torque is 513.166 N*mm, and the mean friction coefficient is 0.06039. The rolling bearing torque is 68.909 N*mm.

Figure (b) shows the statistical parameters of the signal for the second set of input data. The mean friction torque is 655.893 N*mm, and the mean friction coefficient is 0.07204. The rolling bearing torque is 73.788 N*mm.
Figure 4. Test results for LNSL (a), ISL (b), WP (c) of full synthetically motor oil.

Figure 5. Microscopic wear scar view (180x) for LNSL, ISL, WP tests
a) LNSL test, d= 723 μm
b) ISL test, d= 876 μm
c) WP test, d= 1788 μm

For the WP test the low values of the s and k parameters (s= 0.66 and k=1.48) are due to the small number of data acquisition points, as the scuffing instantly started after just 3 seconds and the welding occurred suddenly, in the next 3 seconds.

The weld point corresponded to a mean pressure on the wear spot, expressed as contact load divided by the theoretical Hertz spot area, of about 4GPa. For the LSNL the Hertz pressure is 3.86 GPa, and for the ISL the value is 3.93 GPa.

The oil film strength parameter (OFS), introduced by Paleu et al. [1] as the normal contact load divided by the mean experimental measured wear spot for each test, is 0.3 GPa for the WP, 1.4 GPa for the ISL and 1.9 GPa for the LNSL point. This proves once again the technical meaning of the OFS factor, which allows a clear differentiation of the specific tribological parameters of lubricants.
The computed minimum lubricant film thickness using combined Roelands-Barus equations [10] is around 58 nm for all the tests, with a very slow decrease, proving that at very high Hertz pressure the role of the additive is crucial.

As our data acquisition system and the LabVIEW interface allows the detection of the scuffing initiation with a precision of one second (the maximum sampling frequency imposed by the Vishay P3 bridge), it can be concluded that our four ball machine equipped with data acquisition system is an efficient and reliable equipment for seizure detection in four ball machine tests.

The results regarding the values of the mean friction coefficient during test are the same order of magnitude with those related in other prestigious scientific researches [11], obtained in a modern ready-to-start machine manufactured by DUCOM.

4. Conclusions

To determine the performances of a full synthetically oil designated for long running, tests were carried out on the four ball machine. The LNSL, ISL and WP were determined with accuracy.

The weld point corresponded to a mean pressure on the wear spot, expressed as contact load divided by the theoretical Hertz spot area, of about 4GPa. For the LSnl the Hertz pressure is 3.86 GPa, and for the ISL the value is 3.93 GPa. The oil film strength parameter (OFS) [1], expressed as the normal contact load divided by the mean experimental measured wear spot for each test, is 0.3 GPa for the WP, 1.4 GPa for the ISL and 1.9 GPa for the LNSL point. This proves once again the technical meaning of the OFS factor, which allows a clear differentiation of the specific tribological parameters of lubricants.

The computed minimum lubricant film thickness using combined Roelands-Barus equations [10] is around 58 nm for all the tests, with a very slow decrease from LNSL to WP, showing that at very high Hertz pressure the role of the additive is crucial.

The data acquisition system of a four ball machine was improved by tensometric measurements of the instantaneous friction torque and LabVIEW graphic and computational interface. The improved data acquisition system and the LabVIEW interface allow the detection of the scuffing initiation with a precision of one second (the maximum sampling frequency imposed by the Vishay P3 bridge) and a load step of 100 N.

Interpreting the statistical parameters as SNR, kurtosis and skewness of the acquisitioned data during tests prove the quality of the acquired signals during measurements and reveal the scuffing initiation and the weld point presence by skewing the data. The smooth running is characterised by uniform distribution and centred data.

The results regarding the values of the mean friction coefficient during test are the same order of magnitude with those reported in other prestigious scientific researches [11], obtained on modern ready-to-start four ball machine manufactured by DUCOM.

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