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Tests on a four-ball oil test machine

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Survey:

Boerlage evolved a four-ball oil test apparatus for testing extreme pressure lubricants. This apparatus was copied by DVL; the tests here described were intended to test its usefulness and range of application.

The seizing time and the coefficients of wear for a pure mineral oil, a fatty oil, and of a mineral oil treated with sulphur additive, were found, and showed definite and striking differences.

Contents:

I. Object of the tests

Most of the many known oil test rigs test lubricants under assumptions which are not qualified to give reproducible and undoubted results. This is mainly due to the innumerable factors which influence the state of lubrication, whose importance has not yet been assessed, or cannot be eliminated with the means at present available.

The four-ball apparatus (1) which was developed by Boerlage at the Bataafsche Petroleum Maatschappij in Delft for testing extreme pressure lubrication is distinguished by the fact that the problem of providing constant, i.e. interchangeable test materials is pretty well solved by the use of precision ball bearings. Moreover, the costs of producing these test pieces could hardly be less. Also, by having a rotating ball above three fixed ones a reasonably reproducible geometrical pattern of the point of lubrication can be secured.

Because of these properties, and for other reasons, DVL undertook to construct a copy of this four-ball apparatus, which was to be tested for its practicability and range of application in testing lubricants. It was also intended to investigate lubricating oils without extreme pressure additives, although from work elsewhere it was known that hitherto outstanding and clear differences were only apparent when testing oils which contained high pressure or extreme pressure additives.

II. Test method

a. Test apparatus and test material

The four-ball oil test apparatus which was built and used by DVL uses the contact points or surfaces of four balls as test material for lubrication tests. Three of these four balls, which are arranged in the shape of a pyramid (fig. 1), are held in a conical clamp by a screw-on cap in a test-cup, which also holds the lubricant which is to be tested. The fourth ball is clamped in a liner, which is connected by means of a spindle with the shaft of the electric driving motor (normal speed 1400 r.p.m.). Fig.2 shows the main components of the four-ball apparatus.

The motor casing has mounted on its lower end a guide for a piston shaped bolt, which can be loaded from below by a lever system. This transmits the load upwards to a base plate, which carries the test cup with the three fixed balls. The loading lever can be used to apply different constant loads by varying the length of the lever arm at which the weight is hung, and also allowing a continuously varying load to be applied by adding a loading tank which is equipped for receiving a flow of water.

The topmost ball, which, during the test run slides on the fixed balls, gives rise to a friction torque, which has a tendency to turn the test vessel and the lever arm which is attached to it. The latter transfers the torque to an indicator spring. The alteration in the length of the spring can be recorded on a time-base indicator during the test runs.

An adjustable switch on the casing is operated by a pin on the test vessel when the friction, and thus the turning moment, has reached a certain figure. The driving motor is thus switched off and the test concluded at this point.

The first tentative tests, with the four-ball apparatus constructed by DVL showed that the problem of centring the upper ball on the three fixed balls is of decisive importance. This is chiefly a problem of allowing as much free play as possible to the driving spindle, which must run completely smoothly, and the best possible centreing of the fixed balls, i.e. the ball-base, or the base-plate. The first requirement was fulfilled by suitable development of the spindle bearing. In the endeavour to satisfy the second requirement, a series of tests was made, which led to the conclusion that neither by any form of construction of the guide, nor by any choice of components, can centreing be accurately done. Therefore, the form chosen was such that the ball-base was allowed as much lateral play as possible.

It should be noted here, that the same problems were met with elsewhere, and their importance was likewise realised, and they were completely solved by other means (2).

The test material in these tests consisted of precision balls of 12.0 mm. diameter of hardened roller bearing chromium steel, their Rockwell hardness being about 65 (3). Fig. 3 shows the four-ball apparatus constructed at DVL before the commencement of a test run.

b. Test method

In the opinion of its inventor, the four-ball apparatus should be suitable for testing extremom pressure lubricants. Since these lubricants are intended above all to inhibit seizing, the standard of comparison selected was the load at which a violent and sudden increase in friction and wear, i.e. seizing, first occurred within one minute. This process is improved by plotting the friction-time graph during the one-minute run, and extracting from it the time taken to the rise in the friction coefficient. This seizing time, when plotted as a function of the load, gives a curve which is characteristic of the lubricant under test.

Also, after the run, the size of the wear pits is observed, and assessed in relation to the load.

It is to be noted also that in making the tests the order of events is as follows:- the load is first imposed, and the motor is then brought up to speed, and then switched off after one minute.

The similar tests made by DVL showed great variations. Since it was assumed that this was in part due to the poor reproducibility of the process at starting, that is, the initially almost jerky sliding motion of the steel balls deformed by surface pressure, a series of tests was made during which the load was imposed with the balls running. The resulting spread was somewhat narrower, and this method was therefore retained in all the tests described here.

Also, when the wear pits were measured after one-minute runs, the values varied so much that it was impossible to plot curves through them. Therefore at DVL the run was only continued until seizure took place, using the above-mentioned switch, which through the gripping of the ball-cup as the result of increased friction, was worked automatically by the test apparatus. To save time, a graph was not generally plotted, but the time simply measured from the application of the load till the increase in friction and wear, which was clearly indicated by the automatic disconnection.

The difference between the test method of the DVL and the methods used in other quarters, is that an attempt was made, by the choice of a suitable indicator spring and contact setting, to end the test run at the first definite rise in friction. This was done in view of the following considerations :-

When the run was broken off before the so-called seizing began, the wear pits consisted of small abrasions about the size of a Hertz flat. Its surface condition shows that up to the present it has been a question of even abrasion of particles of material. On the other hand, the wear pits of runs which are concluded at the slightest increase in friction have a very different appearance. Apart from the great difference in the size of the pits, these test balls are very unevenly worn, and have pronounced grooves and much burring. This condition is more typical of what happens to metals when they are turned or milled.

Therefore the beginning of these wear processes was considered as the beginning of seizing, for they cannot be described as "normal" wear. But if this point is intentionally overstepped, in some cases or with certain lubricants there is a reduction in friction, until after a certain time, another pronounced rise in friction occurs. Very often at this moment the balls fuse. In no case was this observed in the test process in which the run is ended at the first slight rise in friction.

The length and breadth of the wear pits was measured, under a measuring microscope.

c. Lubricants investigated.

To discover whether the four-ball machine is also suitable for bringing out differences between lubricants which contain no high- or extreme-pressure additives, two oils were tested which contained no such additives. Because it was assumed that the clearest difference would be that between a pure mineral lubricating oil and a pure fatty oil, the pure mineral aero-engine lubricating oil "Rotring D" (4) was selected as the normal and reference oil, along with the almost pure fatty oil (saponification value 155.6 mg.KOH/gm.) motor oil "Kompressol white" (8). Tests by I.G. Farbenindustrie showed that the process in the four-ball apparatus is not to be considered as pure boundary lubrication, but takes place in the region of partial lubrication. Here the viscosity of the substance under investigation is a factor in the result. In the case of the two oils selected, viscosity as a factor is to a large extent excluded, since the viscosities of Rotring D, of 18.0°E at 50°C, and of Kompressol white of 17.9°E at 50°C are very close to each other.

To test the effect of an additive on the straight lubricating oil, Rotring D was given an addition of sulphur and was then tested. To isolate the effect of the sulphur, the powdered sulphur, in concentration of about 5% (vol.) of the oil was pounded with the oil in a mortar at room temperature, instead of being dissolved in fatty oil at higher temperatures, as is usually done. As was to be expected, a large part of the suspended sulphur was deposited again, so that nothing can be exactly stated about the effect of the sulphur additive. In addition, a slight increase in viscosity had to be taken into account.

III. Results of the Tests

a. Seizing delay values

Initial experiments had already shown that the reproducibility of the seizing delay times is only moderate. Since it was impossible to bring about an improvement by any means, several tests were made at each load, so as to find the average value. At least 5 runs were necessary on each occasion, in order to obtain an even curve of the arithmetical mean values. Fig.4 shows the individual values of a series of 5 test runs made with the reference oil Rotring D.

The range of variation, which is hatched in between the two limit curves, is not always as wide as it is with this lubricant, but in the range of small loads the reproducibility is particularly poor.

Fig.5 shows the mean values for the test runs of the three lubricants which were investigated.

b. Wear values

The wear values were determined by measuring the wear-pits on the three fixed balls. Since in by far the greater number of runs these are not circular, but elliptical, the DVL did not take the average diameter (6), but the product of greatest length by greatest breadth, and the average value for the three balls was found.

Fig.6 shows the values obtained in the tests on Rotring D. In spite of the variation, the average values of 5 runs in each case show a fairly continuous curve.

Fig.7 shows the values for Kompressol white and Rotring D plus sulphur compared with those for Rotring D. The connected points show the results of several series of tests.

Since for every lubricant which is investigated there is a certain relationship between the amount of wear and the load, as also between the delay in seizing and the load, there must also be a fixed relationship between the wear and the delay in seizing. This is presented in Fig.8, together with the results of further test runs which confirm the correctness of the curve as it was found.

c. Interpretation of the Results

Fig.5 shows that the tests made on the three lubricants with the four-ball apparatus gave unambiguous results. Thus the fatty oil Kompressol white has a much better behaviour as regards seizing times than the pure mineral oil. Unfortunately, the differences are less in just that region in which the reproducibility is comparatively good. On the other hand the values for Rotring D plus sulphur are well above those for pure Rotring D, even at high loads, being almost ten times as great at nearly all loads.

In order to rate the curves quantitatively Boerlage and his colleagues selected the so-called $2\frac{1}{2}$ second seizing load. Fig.5 shows that this choice was judicious since in the range of $2\frac{1}{2}$ seconds the differences are comparatively large, yet they are still fairly reproducible. The tests on the four-ball machine of the DVL gave:

for Rotring D 83 kg. seizing load (cf. arrows in Fig.5)
for Kompressol white 128 kg. seizing load
for Rotring D plus sulphur 200 kg. seizing load

It should be noted here that when Rotring D was tested in the Dutch Proefstation Delft the average figure for three series of tests at $2\frac{1}{2}$ seconds loading was 78 kg. But it must be taken into account here, that the Delft tests were made with $\frac{1}{2}$ inch steel balls, quite apart from the fact that there may have been considerable differences in the way in which the tests were carried out.

The curves of Fig.7 are very interesting for here the order of rating is the same as in the seizing time measurements. But as a contrast to these measurements the picture as presented by the course of the wear curves is not in agreement. It is true that Rotring D and Kompressol white have a similar course, showing a rise in wear with increasing load, but Rotring D plus sulphur behaves quite differently, the wear being almost constant, irrespective of the load.

Fig.8 shows even more plainly that the addition of sulphur can completely change the process of wear, as it occurs with pure mineral oil. Whereas the pits with Rotring D plus sulphur are almost constant in size, Rotring D shows smaller pits when the seizing delay is increased, i.e. the load is reduced, and vice versa.

It is a striking fact that the values for the fatty oil, Kompressol white, are also on the curve of Rotring D, and that this is also true of all the oils, of the most varied origins, with or without a fat content, but without other additives. This means that these lubricants make pits of a quite definite size with a definite seizing delay. The differences between the oils are expressed only in the fact that this seizing time is found to occur with quite different loads, which are characteristic of the oils. Putting it another way, over a certain range of loads the wear coefficients are on the lower, flat part of the curve with good oils, while with oils which cause less delay in seizing they are on the steep left-hand branch of the curve, with its higher wear coefficients.

The excellent and much smaller wear values which result from the testing of Rotring D with a sulphur additive must have a totally different reason than that which accounted for the good behaviour of the fatty oil Kompressol white. The proof of this statement is that the pits with Rotring D plus sulphur had a distinctive characteristic, which was that they formed a dark compound, probably iron sulphide, chiefly at the edges of the pits, but also in the form of a thin coating.

It is also worth mentioning that the wear values and the course of the resulting curve are very much dependent on the test balls which are used. Individual tests with 12.7 mm. balls from another source gave results which were in no way comparable.

Much valuable knowledge could be gained from further research into these conditions. At all events, the significance of the results obtained with the four-ball machine is still not completely correlated with practical lubrication.

IV. Summary

A report has been made on tests on a four-ball oil test apparatus constructed at DVL. The results of tests made with a pure mineral oil, an almost pure fattyoil, and with a mineral oil with a sulphur additive were very much at variance. Still averages taken of 5 results in each case showed clear and reproducible differences in the wear delay times and the wear values.

It can be seen from the wear measurements that the favourable effect of using a sulphur additive is derived from basically different causes than the superior behaviour of fatty oil compared to pure mineral oil.

The significance and the transferability of the test results requires further elucidation.

FOOTNOTES

(1) G.D. Boerlage, Four-ball testing apparatus for extreme pressure lubricants, Engineering, Vol.136 (1933) 14 July, pp. 46/47.

(2) By the firm of Rhenania-Ossag, Hamburg.

(3) By the firm of Kugelfischer, Schweinfurt.

(4) Of Intava, Hamburg.

(5) Of the firm of Arens, Cologne.

(6) H. Blok, "Seizure delay" method for determining the seizure protection of E.P. lubricants, SAE Journ. Vol. 44 (1939) No.5 p.193.

FIGURES