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The Falex Oil Testing Apparatus - a comparison with the "Four Ball" and Almen-Wieland machines.

Synopsis: The Falex Oil Tester is used for testing extreme pressure lubricants. The test conditions are less severe than those of the "Four Ball" machine, but more so than those applying to the Almen-Wieland apparatus. The test procedure laid down demands that the oil should react in a certain manner under conditions of minimum high pressure so that the apparatus may not be used for every oil. Apart from the original method, experiments are carried out with two other test methods of which one allows any lubricant to be tested. The results obtained are similar to those given by the Almen-Wieland machine, but are in contrast to those of the "Four Ball" machine. Preference should really be given to the latter since here the materials used for the test pieces are the most similar to those of which gear wheels are made.

A. Object of the Test.

The "Heereswaffenamt" supplied the Technical Research Station at Oppau with a Falex Oil Tester for the purpose of finding out the relationship of the results obtained with it, to those obtained with recognised apparatus used for tests on extreme pressure lubricants.

B. Description of Apparatus and Test Procedure.

1.) The Falex apparatus is an exact copy of an American instrument, the Faville-Levally Oil Tester and was built by the "Laboratory for the Production of Machine Tools" at the Technical College at Aix-la-Chapelle. This institution prepared an exact description and test procedure, a short account of which is given below:

A rectangular vessel containing the test elements (described more closely below) as well as the oil to be tested, can be electrically heated. The vertical test shaft is driven at the top end by a motor operating a gear wheel drive (diag.1.). The test b ushes held against the shaft are fixed in two movable brackets connected to two load-transmitting levers (diag.2.). The ends of these levers are forced towards each other by the loading mechanism (diags. 3,4,5,&6), operated by the pressure of a spring inside a casing. Compression of the spring is procured by turning a wheel fixed on a shaft with threaded ends (using a right hand thread at one end, and a left hand thread at the other). The force of compression is indicated on a gauge and from it the magnitude of the force transmitted, can be obtained.

The torque on the test sockets is measured by hydraulic means; the parts which are capable of rotating about the shaft are connected through a lever to an oil dash-pot and the oil pressure produced is indicated by a monometer. This oil pressure is a measure of the torque produced. The test peices are shown in diag. 4. and consist of a shaft (6mm. dia. and 31mm. long) and two b ushes. The shaft to be tested is fixed to the driving shaft with a brass pin: when a sufficiently high torque is reached (especially with seizure) the pin will shear. The b ushes are cylinderical in shape but the face in contact with the shaft is cut so as to form two planes at right-angles: so that the shaft runs between four of these planes, all at right-angles. The shafts used are made of unhardened drawn steel rods, while the sockets are hardened and ground along the plane surfaces: both shafts and sockets were obtained from Messrs. Voigt & Co., of Deutsch-Ossig. The distribution of the forces acting on the load-transmitting levers and the test gear is shown in diags. 5&6. The transmission ratio being 23:207 = 1:9, a force F exerted by the spring produces a force Q = 9F, where Q is the force acting on one socket. The normal pressure at each part of contact with the shaft then becomes $S = \frac{Q}{2}\sqrt{2}$, enabling the friction force and torque to be calculated. In the instructions given regarding use of the apparatus, a force P = 2S has been employed in all load tables and calibration curves. This force is not really brought into action as it was obtained by adding the actual values of the normal pressures S_1 and S_2, and S_3 and S_4 respectively, instead of being determined by vector addition. This idea has been taken by the Technical School from the instructions relating to the American apparatus and was adhered to for the sake of simpler comparison. Below, the factor $S = \frac{P}{2}$ is introduced instead of the force P, which has the advantage of being the actual force i.e. the load on one point of contact. Comparison with the American original is easily made by doubling the figures.

In the test the American method was employed first of all. A preliminary trial of 15 mins. duration is here carried out, the purpose of which is to raise the temperature of the machine to the level at which actual trials can be carried out. New test peices are then fitted and fresh oil is put in the vessel. The trial proper starts with a load of S = 112.5kg. for a period of 3 mins. (diag. 7); the load is then raised at intervals of 1 minute until a maximum of 340kg. is reached. From then onwards the load remains constant, measurements being made at 6 minute intervals, of oil temperature, number of revs, torque and amount of wear. The latter is measured as follows:

Wear results in a smaller load acting on the test peices so that in order to keep the pressure exerted by the spring, constant, it is necessary to keep on turning the loading wheel. The amount of turning required is in direct relation to the wear produced so that it offers a means of measuring wear during running. The test ends after 63 mins. at the end of which the test pieces are dismantled, the length "1" being measured (see diag.6). The amount by which this dimension is reduced compared with the (Δl) length at the beginning of run is the exact quantity of wear and affords a control on the measurements taken during the test. The test procedure introduced by the Americans and laid down in their service manual assumes, of course, that at these high loads the lubricant will stand up to a non-stop test of one hours duration without causing seizure of the test pieces. Since it became evident that the majority of the gear oils used in Germany cannot live up to the demands made, the test was modified accordingly. The constant load of S = 340kg. was replaced by one of 150kg. built up, as specified, within the first 6 minutes (diag.7). This method, again was not satisfactory so that a third method had to be adopted in which the load was increased step by step. The test was started with 50kg. load, the load being increased at a rate of about 12.5kg. per minute corresponding to a dial gauge reading of 0.05mm. In this manner one obtains the load at which seizure occurs. The torque is read off with each load and the coefficient of friction calculated from it. It was found that an evaluation of each oil could be obtained by this method.

2). The "Four Ball" Machine.

This is made by the Rhenania-Ossag Works, and their service manual contains fuller details about its construction and operation. In this method tests of one minute duration are carried out at different loads, and the diameters of the wear scars on the three bottom balls are then measured. Welding action takes place on the balls above a certain load, and this load is ascertained for each oil.

3). The Almen-Wieland machine.

This uses a bearing of mild case-hardened steel with a shaft of unhardened tool steel (o.3mm. dia). Tolerance in the bearing amounts to O.2mm. and the bearings are forced hydraulically against the shaft which is rotating at 200r.p.m. Loading takes place by the addition of weights at intervals of ½ minute until either the maximum load for the machine is reached or seizure of the bearings takes place. With the addition of each new weight the frictional force at the shaft perimeter is measured and from it the coefficient of friction is calculated. A closer description of the Almen-Wieland Apparatus will be found in the publications of the Optimol Co., and in several books (e.g. Kadmer: "Lubricants and Lubrication").

4). Comparison of the three machines.

The tests carried out on the three machines were made on a comparative basis, and the characteristics of the machines are clearly illustrated in diag. 8. From it it is seen that the Falex Tester falls in every respect somewhere between the Almen-Wieland and "Four Ball" machines. The Almen works with the lowest rubbing speeds, the softest materials and the lowest pressures per unit area. The conditions applying to the "Four Ball" machine are in complete contrast to this. This strong contrast leads to very little agreement between the two instruments and the fact that the conditions applying to the Falex Test lie in between the two may enable us to find the missing link in the explanation of the bad agreement.

C). Results.

Tests were carried out with the following oils:

Lubricant	Viscosity 38°C.	99°C.	V.I.
Valvoline Hypoid gear oil No.362	256.5	17.2	73
Veedol Hypoid gear oil No.363	561	42.5	119
Army Stan'd oil No.1057+10% (Chlophen)No.A.30	96	8.8	43
Army(Winter) gear Oil No.1032	132.0	10.6	48
"Red Band" Standard oil No.891	245.3	18.7	92
Rape Oil	56.9	10.6	144

The six oils were first of all tested according to the procedure laid down in the service manual, but this method could be applied to 3 oils only, the remainder producing seizure of the test peices before the required test load had been applied. The results illustrated in diags. 9,10,11 and 12 show that satisfactory differentiation between the three lubricants is possible and the experimental points are not scattered more widely on the graph than is the case with the results given by other machines of a similar type. The temperature of the oil shows considerable increase even after the start of the test proper (diag.9), indicating that despite the trial run of 18 minutes conditions are not yet constant, and this is probably the reason for the decrease in friction torque. In all cases the amount of wear on the test pieces indicated by the number of teeth on the wheel (Diag.11) is less than that indicated by direct measurement (diag.12). This is due to the fact that some wear has occurred before measurements were taken (i.e. during the first 18 mins.), and this is not taken into account. As only certain lubricants could be tested in that manner trials were carried out with the lower continuous load, i.e. S = 150kg. on four oils one of which, (Army (Winter) gear drive oil No. 1032) proved deficient through permature seizure. The results are shown in diags. 13,14 and 15 and are particularly interesting because of the conclusions to be reached regarding the lubricants. It is seen, for instance, that "Red Band oil, an ordinary aero-engine oil, behaves more efficiently with respect to friction, wear and temperature, than Valvoline Hypoid Gear Oil. Also, it seems strange that Army (Winter) Gear Oil should fail at all. It seems in order, therefore, to compare this method, as well as the original one, with the results of other test apparatus: diag. 17 shows how these six oils fared in the "Four Ball" machine. According to that instrument, Valvoline gear oil is the best high pressure lubricant being slightly superior to Veedol Hypoid gear oil, while Army Standard oil + 10% Chlophen A30 shows no properties at all which might enable it to work at high pressures. According to the results of the Falex test, employing the original method these oils should arrange themselves in exactly the reverse order (diags. 9-12). Much the same applies to the oils tested under the lower load. While Army gear oil (Winter) fails completely in the Falex test, it stands up rather well to high pressures when tested in the "Four Ball" machine, being superior to both "Red Band" and rape oil.

It is also seen that the oil which possesses the best properties under high pressure. Valvoline Hypoid gear oil, when tested according to this method in the Falex apparatus again does rather badly with respect to temperature, friction and wear. Consequently as there is too much contradiction between the Falex and "Four Ball" results, attempts were made to improve matters by altering the test conditions in the Falex apparatus.

Accordingly, the method adopted was not based on a constant load, but as in the Almen-Wieland machine, on a gradually increasing load (diag 7.) giving the results illustrated in diags 18 and 19: the advantage of this method lies in the fact that the test can be carried out on every oil. The oil is judged on the measured coefficient of friction and particularly the load at which seizure commences. The results, however, when plotted are rather widely scattered which is a factor that must always be reckoned with in such tests. The coefficients of friction are remarkably low and in the case of Valvoline Hypoid gear oil there are violent fluctuations of the friction readings. Presumably this is due to the periodic abrasion of small metal particles. No seizure took place with that method, during the tests on Hypoid gear oils and Army Standard oil + additive. With respect to the coefficient of friction, Veedol Hypoid gear oil and Army Standard oil + 10% (see note A) A30 occupy the first place, followed by Valvoline Hypoid gear oil, rape oil, "Red Band" Standard oil and Army gear oil (Winter), in that order.

It is clear then, that even this method produces no similarity of results with those on the "Four Ball" machine. On the other hand, good agreement exists with the results of the test, as shown in diags. 20 and 21, the order of merit remaining the same with the exception of rape oil which shows up most favourably in the Almen test.

D). Conclusion

The following rule may be accepted as correct: under the conditions of the Almen-Wieland test, "mild" high pressure oils e.g. vegetable oils, react very well. High pressure and extreme pressure lubricants are inclined to cause seizure or at least exhibit high coefficients of friction, in other words they are not outstanding. In the Falex method last described the good properties of the Hypoid oils become a little more evident, while rape oil, producing seizure shows up less favourably. While the step from the Almen to the Falex apparatus is small that from the Falex to the "Four Ball" apparatus shifts considerably the positions in the scale of values of each oil. It is only then that the extreme pressure additives produce their full effect, as seen in the excellent results obtained with the two Hypoid oils and the fact that the Army gear oil takes a leading place in the scale. "Mild" E.P. lubricants like rape oil or Chlophen lose their efficiency here, while additive-free mineral oils, e.g. "Red Band" Standard Oil, as expected do not produce particularly good results in any of the three machines. The reason for these large discrepancies lies not only in the varying conditions, like sliding velocity, pressure per unit area etc., but in the use of different materials. As shown in Report No. 548 it is particularly in the case of extreme pressure additives (e.g. sulphur compounds) that the question of whether hardened or unhardened steel be used, becomes important. "Mild" additives e.g. vegetable oils, behave satisfactorily even at maximum loads if the working substances are unhardened steel, cast iron and similar materials, while they fail if used on hardened steel. With Hypoids the state of affairs is completely reversed so that the differences in materials used for the test pieces in the three machines are of great importance in their evaluation.

To form an opinion as to which one of the three machines is the most suitable for the imvestigation of gear lubricants one must be clear regarding the type of wear that occurs on gear wheels: three different manifestations of wear can be expected viz. formation of grooves, abrasion and seizure. Groove formation will not be considered here as the three test machines deal only with pure sliding action and so do not produce this type of effect. Abrasion is slow and continuous leaving the surfaces smooth and in a technical useable condition. Wear through seizure is definitely more dangerous, it will occur under excessive load on the driving gear, leaving the edges of the toothed wheels badly torn and pitted and will lead to rapid destruction of the wheels. Seizure, therefore is by far the more unpleasant form of wear and one takes pains to avoid it by the use of extreme pressure lubricants. The latter probably react chemically when in contact with the metal, under the conditions of high temperature at the points of lubrication. Metallic salts are probably formed removed by friction, and immediately reformed. The protective layer thus formed though it prevents seizure, must necessarily lead to increased abrasion. In other words, wear through seizure being the greater of two evils, will be replaced by wear through continual abrasion. Metal abrasion also occurs when the load on the driving gear is small. With low loads extreme pressure lubricants, such as Hypoid gear oils, will therefore behave less satisfactorily as regards abrasion than lubricants not containing such additives. That is why the very oils considered unsatisfactory when tested according to the original Falex method are exactly the ones that show good high pressure properties in the "Four Ball" machine. A reciprocal relationship can almost be established here: in its original form the Falex method assumes an ability to withstand a certain minimum high pressure. Of the lubricants fulfilling the required conditions, on account of the duration of the test that oil is considered the best which produces the lowest temperature, coefficient of friction and amount of wear. No objection will be made to this method as long as it can be proved that this performance under a minimum high pressure corresponds to the conditions in an actual gear wheel drive. Great differences exist even on comparison of the "Four Ball" and

Falex machines, so that it may be assumed that great differences will exist also between the evaluation based on the Falex machine and that given by actual ~~practical~~ conditions. This assumption is based directly on the fact that the test pieces in the Falex machine are not made of the same material as toothed wheels. So that the "Four Ball" apparatus appears to be a far more suitable test for high pressure lubricants, the Almen-Wieland machine being completely out of the running in this respect. Another advantage of the "Four Ball" machine is its availability and the reproducability of the test pieces. The claim that this machine employs excessively high loads is perhaps justified in the case of the method of the Rhenania-Ossag Works adopted here but it is quite possible to reduce the thermal and mechanical attack at the lubricated surfaces by altering the speed of rotation and the load.

Illustration No.	Title.
1 and 2.	View of the Falex Apparatus. top: revolution counter electrical heater test pieces oil container bottom: load transmission levers calibrated loading wheel and load mechanism oil dashpot
3.	Loading mechanism
4.	Test pieces.
5.	Distribution of load on the levers
6.	Distribution of load on the test pieces. forces perpendicular to shaft at point of contact. friction forces total torque ($\Sigma T = M_{ges}$)
7.	Methods of loading used in the Falex apparatus: ord: dial gauge readings absc: time. ———— method laid down in service manual — · — loading increased step by step — — — method actually employed small load.
8.	Characteristics of the three machines No. of revolutions Rubbing speed Vickers hardness of stationary parts " " " moving " Max. load - Q max. Average load - Q_{mean} Mean pressure - p Mean pressure based on Q_{mean}

(Footnote under diagram): The tolerance in the bearing is 0.2mm. with a shaft dia. of 6.3mm. It is doubtful whether with so great a tolerance the breadth of the shaft is actually 6mm. (the value assumed in the directions for the Almen-Wieland machine. The figures in brackets calculated by Hertz's method, probably approximate more closely to practice).

Illustration No.	Title.
9 - 12.	Tests in the Falex machine according to the procedure originally laid down
9.	Oil temperature/Time graph
10.	Torque/Time graph
11.	Wear/Time graph
12.	Wear as measured: Δd wear on shaft Δl total wear
13 - 16.	Tests in the Falex machine with low continuous load:
13.	Oil temperature/Time graph
14.	Torque/Time graph
15.	Wear as read off the wheel calibration
16.	Wear as actually measured: Δl as Δd above
17.	Tests in the "Four Ball" machine (Rhenania-Ossag method) Wear diameter/load graph o end of test through welding effects
18 and 19.	Tests in the Falex apparatus with increasing load. Torque/load graph(o end of tests through seizure)
20 and 21.	Tests in the Wieland machine Friction force/load graph: (No. of plates surface pressure) o end of test through seizure.