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## Testing of Lubricants by Measurement of Wear.

by.

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**Synopsis:**
It is shown that the rating, of a lubricant based on measurement of wear depends largely on the metal. Variation in the pairing of the metals is liable to cause considerable changes in the order of merit in which the lubricants are arranged.

A strict distinction must be made between metal abrasion and wear accompanied by seizing of the metal. It appears that high abrasion affords a certain safeguard against the destruction of the surfaces of metal parts in rubbing contact, by tearing action. Thus it follows that to some extent, metal abrasion is an advantage.

The purpose of using a lubricant is to avoid losses in energy and material, or at any rate to reduce them. The power loss can be cut down to some extent by choosing a lubricant of definite viscosity. Only rarely is it necessary, as far as the power loss is concerned, to consider the conduct of the oil under conditions of boundary lubrication. On the other hand, loss of material ocurs with boundary, or partial lubrication so that conscientious tests must concern themselves with the loss of material under these conditions of lubrication.

For a number of years the Technical Research Station has been engaged on experiments the purpose of which was to investigate the events leading up to the failure of lubrication (i.e. leading to commencement of wear). The following is a brief survey of the present position regarding these tests.

Diag.No.1. is a schematic representation of the instrument employed for the experiments. Two drums fitted on a shaft are set in rotation by a motor equipped with reduction gear and connecting rod mechanism. The drums are lined with polished strips of hardened steel which act as friction surfaces. The wear elements, consisting of cylindrical pins made of various materials, are held against the underside of the drums, the load being submitted by a lever. Both rubbing surface and wear elements are immersed in the lubricant tested, and the latter in its turn is surrounded by an oil bath kept at constant temperature by electrical heatingcoils. The amount by which the pins shorten is measured by a dial gauge attached to the lever. The crank rotates at 81 r.p.m. resulting in 162 strokes per minute or a mean velocity of 22.3 cms/sec at the circumference. It may be assumed that with that type of motion, a state of limiting friction exists at the end of each stroke (where the motion suffers a reversal in direction) while fluid or semi-fluid lubrication exists at the mid-point. This assumption is based on measurements made of the (electrical) contact resistance set up, with the aid of an oscillograph. They showed that at the dead centre positions the system was short circuited while the resistance at the mid-point of travel is subject to violent fluctuations and reaches infinity for a short time. A number of oils were tested in this apparatus, using two different materials. Diag.2.(1402) shows some results obtained with smooth hardened steel strips and wear elements made of Aeterna VL 22. the latter consists mainly of copper (51%) and zinc (42%) and contains small quantities of manganese, aluminium iron, tin, silicon, lead and nickel. The diagrame shows that sulphur-containing products result in high abrasion on this metal, while entirely different conditions prevail if a different metal is used, such as iron ( in the form of iron wire as used for welding). Here, rape oil produces by far the highest abrasio viz above 2m/m in 20 hours, Castor oil produces an amount of abrasion which is of equally high order , but only with temperatures above 65°C. On the other hand, E426 in direct contrast to these two oils, produces high abrasion at low temperatures and little abrasion at high temperatures. It is interesting to note that S-ester and E.515 behave similarly while a mixture of the two has entirely different results, this is evidently an effect due to mixing. The wear curve relating to S-ester is here drawn according to the values recorded by the diag gauge: in actual fact it was found that hardly any wear had been produced on the soft iron pin while at temperatures above 100°C the hard steel strip which had been 0.2 m/m thick, had been worn down to the thickness of paper, this observation was made, to that extent, only in the case of S-ester, and this point will be dealt with again, later on. Diag 3 again shows results obtained with the same metals under the same conditions, as in the previous case. The four oils tested belong to the group of aero-engine oils, as regards their viscosity. K.7 is a mineral oil, SS 902 F 25 is a synthetic aero-engine oil with additions of ester, L.K.2200 and M.620 are experimental oils both insoluble in mineral oils. The diagram shows that with K.7 and M.620 there is very little effect when one metal is replaced by another, while in the case of the other two there is a reversal of wearing properties. All these trials were carried out with smooth polished steel strips, i.e. under conditions of practically constant roughness. In order to investigate the effect produced by rough surfaces, the smooth strips were replaced by steel strips which had been subjected to sand blasting, thus obtaining a roughness of about 10 µ. Measurement of the resistance showed that the system was short-circuited throughout, so that a state of limiting friction may be assumed. As had been expected, the amount of abrasion was large and the duration of the test was reduced to 20 minutes. The results obtained with these 4 oils are less dependent on the temperature and consequently more reliable (diag.4-1404): also, compared with the results obtained with smooth surfaces, the order of the oils is considerably re-arranged, above all it is interesting to note that K.7. which is pure hydrocarbon, is distinguished from the other three oils, all of which contain oxygen by very low abrasion. When, smooth strips were used, K.7. had produced a comparatively large amount of abrasion. This re-arrangement is probably due to the fact that with rough strips the machine works more in the region of limiting friction than with smooth strips: while with the latter, at least when the speed approaches a maximum value, partial lubrication, and to some extent, complete lubrication, takes place.

In order to investigate metal abrasion more closely we have built a piece of apparatus, which though it is not an original instrument has not often before been used for lubricant tests (Skoda-Sawin machine). As shown in diag.5. (1414), a stationary cylinder is held against a rotating hard metal disc, lubrication being provided by an oil drop-feed. After a certain time interval, usually 10 minutes, the disc will grind a out of certain length in the cylinder which differs for each oil. The number of revolutions made by, and the load on the disc can be varied at will. The cuts are measured with a measuring microscope, the volume ground out being calculated from a knowledge of the length. Some of the results obtained with this instrument are shown in diag.6.(1412) 14 oils of varying composition were tested, using a speed of 210 r.p.m. (peripheral speed = 33 cms/sec) and a load of 20 kg for tests of 10 minutes duration each, and cylinders made of different materials. The lubricants were arranged in the order of the results obtained with a steel cylinder, rape oil, which produced the largest cut, occupying the last place. If the same tests are performed with cast iron, considerable re-arrangement of the order results, with rape oil still at the bottom of the list, but with S-ester in the first place. Use of bronze results in B.H.4. producing the greatest, cut in direct contrast to the result obtained with a steel cylinder. Castor oil, too, and again rape oil, produce a strikingly large amount of wear, while LK.2200 occupies the first place, having produced the smallest cut. The greatest differences in the behaviour of each oil take place with a light metal cylinder. L.K.2200 and M.620 produce very deep cuts, followed by S-ester and SS.902 F.25. With the use of a tin and lead alloy used in bearings, the sulphur content in particular, appears to increase wear, the lowest values being obtained here, with M.620 and L.K.2200. This diagram clearly demonstrates, therefore, how differently the lubricants can act when used in conjunction with different metals. It should be mentioned, in that connection, that the appearance of the cuts is not, in every case, one of metallic brightness, but that they are frequently of reddish colour, or one ranging from grey to black. It seem reasonable to deduce from this that metal abrasion is, in part, due to chemical processes. Exactly how far tests of this kind can be exploited for actual practice, is a matter for further investigation. One might imagine, for instance, that the size of the cuts would be a key to the suitability of a lubricant for use as cutting oil. Accordingly, rape oil would be an excellent cutting oil for steel and cast iron, which of course it actually is. In these tests importance is attached to the fact that the solubility is very considerable and that the differences, contained on measurement, are considerably greater than in the case of friction measurements. These investigations of the abrasion of a lubricated metal are not without connection with the factors usually measured when lubricants are investigated, such as the coefficient of friction. During tests on numerous synthetic esters at the Leuna works it was observed that the values of $\mu$ as measured in a friction indicator (chain apparatus), bore a certain relation to the size of the cuts in the steel cylinder. Diag.7.(1407) shows the results obtained with 35 synthetic esters as well as rape oil and bone oil, each represented by a point on the graph. It is seen that all these points fall within a definite area which is narrow and long in shape, stretching from the region of high friction coefficients and little abrasion, to that denoting low friction coefficients and high abrasion. Probably the apparent, agreement would be still closer if both tests could be carried out with the same materials and under the same conditions.

The two instruments just described cover only one form of wear, viz. the gradual removal of minute particles of the material. A form which occurs chiefly in the case where the materials are widely different with regard to hardness. If, on the other hand, the materials used are identical, or at any rate are of similar hardness, a far more dangerous type of wear is met with, viz, seizing of the metal surface (cf. S Anton Eichinger: "wear of Metals: Report of the KWI for Iron Research in Duesseldorf") In routine tests on several lubricants in different instruments it was observed again and again that a connection existed between these two types of wear. This relationship will be explained in some detail for the case of 3 lubricants, those chosen comprise rape oil, the above Sulphur ester, i.e. two oils vastly different in behaviour, and a third a neutral lubricant, K.7. which is a mineral oil.

Particularly careful tests were carried out on these three lubricants with regard to their abrasive qualities. Diag.8.(1420- shows the relation between the abrasion produced on a soft iron pin, and time , using rough hardened steel strips at two different temperatures. In this case the curve relating to rape oil is almost straight and rises steeply, i.e. the abrasion of the soft iron is very great and at an almost uniform rate throughout the test, the roughness of the steel strip being hardly diminished. On the other hand, with S-ester the rate at which the pin is being shortened decreases rapidly, leading to the conclusion that the strip is being smoothed down considerably- an effect which is actually visible to the naked eye. K.7. produces neither great abrasion of the iron pin nor any particular smoothing effect on the steel strip. On the left hand side of diag.9.(1418) the results obtained with these 3 lubricants during tests lasting 20 hours, are again shown (cf,diags 2 & 3) using smooth strips at various temperatures. Under conditions of what is chiefly semi-fluid friction rape oil again produces high abrasion on soft iron, while that caused by K.7. and S-ester is very small. The latter again demonstrates its high abrasive powers when used with hardened steel, particularly at high temperatures. As already mentioned, at temperatures above 100°C the steel strip 0.2 m/m thick was almost completely worn through, showing that the wear on the hard steel strip is disproportionately greater than that on the soft iron pin. To afford a check on this result, and hardened pin was brought to bear on an unhardened strip, and as had been expected, the greater amount of wear was that produced on the pin.

The results of the test in the grinding machine are illustrated on the right hand side of diag.9.(1418). The metal employed was unhardened carbon steel, resulting in the same order as that obtained in tests on the wear machine, using rough strips (cf.diag.8.-1420); it applied, however, only to the first 10 mins. of the test, i.e. as long as the strips approximately retain their original degree of roughness and are not smoothed down, as in the case of S-ester.

General speaking, then, the abrasion tests enable the following statements to be made about the three lubricants:

With unhardened steel and soft iron, rape oil produces by far the greatest wear at all temperatures, while when used on hardened steel, this abrasive power decreases considerably. In the case of S-ester, the picture is completely reversed, particularly at high temperatures the abrasion of hardened steel is considerably greater than that of soft iron. While K.7. appears to affect all types of steel and iron in very much the same way. Now it is interesting to study the conduct of the oils thus classified, with regard to seizing, as observed in the various test instruments used: these comprised the Almen-Wieland machine , the Falex oil testing apparatus and the "Four-Ball" machine. Test conditions in these instruments are so arranged that with most oils seizure will be produced on the materials of the test elements. The Almen-Wieland machine employs soft steel (as used for the lining of bearings.- Vickers Hardness No about 150) in its bearing, and unhardened tool steel (Vickers Hardness No about 170) for the shaft (see diag.10-1415). This pairing of materials tends to produce seizure rather easily, so that only relatively small loads are required in the Almen-Wieland machine. Higher surface pressures are required in the Falex test which employs two varieties of steel with more widely different hardness numbers. The greatest load per unit area occurs in the "Four-Ball" machine: it should be noted here that this pressure, obtained from Hertz's formula, presumably does not really exist, as it exceeds the crushing limit. Further more the rubbing speed employed here is very high so that high thermal effects may be expected to occur at the points requiring lubrication.

The three above-mentioned lubricants were tested in these three instruments. In the Almen-Wieland machine the load is raised step by step until seizure commences. In the case of rape oil seizure was not produced within the maximum loading limits of the machine (diag 11-1416) while, on the other hand, early seizure effects were observed with S-ester and K.7. So that the lubricant which produces very high abrasion with unhardened steel and soft iron, is capable of preventing seizure within the limits of the demands set up by the Almen-Wieland machine. It would appear that here the similarity between the materials used is the deciding factor. If the same procedure is adopted in the Falex apparatus, the greater hardness of the test materials comes into play, causing a re-arrangement of the results in favour of S-ester and against rape oil, the latter producing seizure, while the former does not. Also, in the case of S-ester, it can be seen from the test elements that remain intact that the wear on the hard test sockets is considerably in excess of that on the shaft: this is in agreement with the results already obtained on the wear machine. The investigation was then continued with the "Four-Ball" machine employing the method adopted by the Army for tests on gear oils. This consists of finding out the amount of material torn away, rather than establishing the load under which seizure commences. For, this purose test runs of 1 min. duration are made at different loads, and the diameters of the worn parts of the 3 bottom balls are measured, In excess of a certain load the temperature at the points of contact may rise so high that welding of the balls occurs, the diameter of the worn portions and the "welding load" are adopted as standards for the suitability (or otherwise) of a high pressure oil (diag.12-1417). According to that system, S-ester possesses excellent qualities while rape oil is far inferior behaving only slightly more satisfactorily than K.7. Again it can be observed that high abrasive powers imply satisfactory conduct as regards seizure.

One might after all this, adopt the point of view that the judgement passed on the three lubricants, based on tests in the three machines, is not influenced by facts relating to the use of different materials, but by the variation in test conditions such as rubbing speed and surface pressure, the latter resulting in variations in temperature. To some extent this point of view is justified, but the experiments described below will show ~~that the~~ influence exercised by the material is the greater one; these tests were carried out under uniform mechanical conditions, the material employed being the only variable.

If the tests in "Four-Ball" machine just described, are carried out with balls of 400 kg/sq m/m (Vickers Hardness) instead of the normal commercial type (800 kg/sq m/m VH) ( a type produced for us by the "Deutsche Kugellagan Sabriken").it may be expected from what has been said that a re-arrangement will take place in favour of rape oil diag.12(1417) shows that this is what actually happens-at least below loads of 150 kg, the effect being even more pronounced with the use of cast iron balls where rape oil is superior even at loads up to 400 kg. Measurement of the diameters of the worn parts, made after 1 minute tests, does not result in a particularly clear understanding of what really happens. For that purpose it is advisable to consult the friction curves, from which interesting conclusions may be drawn (diag.13-1419). From the top left hand diagram, for instance it is seen that with K.7. used on normal bearing balls at a temperature of 20°C, the coefficient of friction increases sharply after barely 1 second an indication that seizure has started. This state of affairs lasts for about 20 seconds at the end of which period the value of the coefficient falls rapidly, and from there on runs without further change along a line parallel to the abscissa. Rape oil produces a similar diagram, but the time taken for seizure to commence is a trifle longer, the actual duration of the seizing action being shorter. With sulphur ester actual seizure effects are barely perceptible, the high coefficient of friction obtained for this oil with other instruments being again recorded. The frictional conditions can be explained as follows; semi-fluid friction takes place at the start of the trial but cannot be maintained. The actual duration of this condition depends on the boundary activity of the lubricant, as well as on the viscosity (cf.I Report No.486).

With the start of seizure the temperature at the lubricated surfaces will rise rapidly, leading to

a) an increase in chemical activity.
b) a change inside the working substances, or at any rate on their respective surfaces.
c) a change within the lubricant.

These 3 factors act collectively and simultaneously, leading up to a cessation of seizure and paving the way for steady abrasion. In the case of K.7 this period is comparatively long, i.e. the temperatures required are considerably higher than in the case of rape oil. This is made evident by the fact that with rape oil the balls show no sign of blue coloration, as they do with K.7. With rape oil a slight temperature rise suffices to produce a state of lubrication which if not ideal, is nevertheless capable of enabling the surfaces to bear loads again. With the chemically active S-ester the short period of 1 second is enough to produce the temperature necessary for steady abrasion, the latter probably being to a large extent due to chemical action.

The rise in temperature produced by seizure and the subsequent change in both materials and lubricants can be simulated i.e. by starting off with a different material and at a high temperature. For instance, the balls of 400kg/mm$^2$ Vh give a period of seizing action with K.7, which is 33,1/3% shorter. With rape oil no seizure takes place, creating the favourable impression illustrated in diag.12(1417). A similar effect is created by higher starting temperatures. Though the start of seizure is less delayed its duration is reduced to a considerable extent. These tests on different apparatus show therefore that the connection between metal abrasion and wear accompanied by seizure, is an actual fact. As long as the combination of metal and lubricant allows sufficient metal abrasion to take place under the prevailing conditions, seizure of the sliding surfaces will be prevented. This process may perhaps be explained as follows.

As already hinted, abrasion appears to be due, chiefly to chemical action. At the temperatures produced by friction and through the influence of the oil a protective film is formed on the sliding surfaces, which while it is easily and quickly removed, is reformed just as easily and quickly. As long as this process can be kept up, seizure of the metal surfaces will be avoided. A large amount of metal abrasion must thus be considered a good sign, but the existence of a certain limit, an optimum amount, must be assumed. This optimum is probably that state of affairs where under all service conditions met with, the abrasion produced is just sufficient to ensure sliding without seizure occurring.

The trials show also that in any case of wear the metal plays a very important part. Test conditions like rubbing speed, surface pressure and temperature no doubt possess some influence, but that of the metal is at least equally great. Consequently it appears inadmissible to compare the results obtained with different pieces of apparatus and to regard the respective test conditions, e.g. surface pressure and temperature as the only factors that may influence the relative evaluation lubricants. A comparison of test apparatus may be made only if the materials employed are similar.

As in the long run all test equipment serves to investigate the behaviour of the lubricants in actual practice the test materials at least must be as nearly as possible those which are used in that practice. It would doubtlessly be wrong, for instance to test machine oils on soft steel or iron, no matter how well the remaining conditions are adapted to the practical case.

Furthermore, the trials have shown that a relationship between the separate sets of results, as obtained with various instruments, can be established. It is our intention to proceed still further in that field as we are hoping to obtain a fuller understanding of the processes of lubrication. When once it is possible to "tune in" two instruments to such an extent that it is possible to predict the results obtainable with all other equipment from those of the first two, the step from experimental equipment to actual practice will no longer be difficult.

| Illustration No. | Title. | |
|---|---|---|
| 1. | Wear Machine (see Report 537) | |
| 2. | Wear/Temperature curves for various metals | |
| 3. | " " " " " | |
| | (abscissa: oil temp. ordin; shortening of pin | |
| | left: polished 20 hours test | |
| | right: iron " " " | |
| 4. | Wear using different degrees of surface roughness. | |
| | (left: polished 20hours test | |
| | right: rough, 20 mins test) | |
| 5. | Grinding machine (see Report No537) | |
| 6. | Wear of different metals, using various oils (see537) | |
| 7. | Coefficient of Friction/Wear Relationship | |
| 8. | Wear, based on duration of test and temperature | |
| 9. | Wear tests | |
| 10. | Comparison of 3 machines used for Testing of High Pressure Lubricants | |
| | Conditions of Test | unit |
| | No of revs | rpm. |
| | Rubbing speed | cms/sec |
| | Test Materials | |
| | Vickers Hardness of stationary parts | kg/mm$^2$ |
| | Vickers Hardness of moving parts | |
| | Average Surface Pressure | Kg/cm$^2$ |
| 11. | Comparison of Two Oil Testing Machines | |
| | left: ordinate: friction force | |
| | abscissa: no. of plates (load) | |
| | right: ordinate: friction torque | |
| | abscissa load | |
| 12. | Tests in the "Four Ball" Machine using different Balls | |
| | steel steel ordinate: dia of worn part | |
| | cast iron abscossa: load | |
| 13. | Seizure effects, Using different materials and temperatures. | |