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THERMO-ELECTRIC MEASURING PROCESS FOR COMPARATIVE FRICTION TESTS ON LUBRICANTS WITH BOUNDARY LUBRICATION

Summary: A measuring process is described, in which the heating effect at the sliding surface of a lubricated pair of materials is used as a measure for the friction power. The experimental conditions are selected so that pure boundary lubrication exists. The process is distinguished by its great accuracy of measurement. This is demonstrated in a few typical examples.

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The fundamentals of lubricant friction and lubricating ability

Research into lubricant friction has already a long history. Progress has led from Coulomb's law via Newton's axiom to the theories and laws of hydrodynamic lubrication and finally to the extraordinarily varied investigations into lubricating ability. As a general rule, with lubricated surfaces, a distinction is made between the conditions of boundary lubrication, partial lubrication and full fluid lubrication. In the same way we speak of limiting friction, mixed friction and fluid friction. In this connection, partial lubrication does not really represent a new condition; indeed, with partial lubrication, limiting friction and liquid friction exist side by side.

Boundary lubrication and full fluid lubrication differ fundamentally from each other as regards the laws that are valid. The difference is most clearly expressed by the fact that the load in the condition of boundary lubrication is transmitted to the sliding surfaces by boundary layers with molecular dimensions, while in the state of full fluid lubrication, it is in equilibrium with the hydrodynamically formed pressures. Accordingly, in the condition of full fluid lubrication, only the correct choice of lubricant viscosity and the correct construction of the bearing are decisive for the lubricating process. In the condition of boundary lubrication, however, the viscosity has no effect; instead, the surface action between the material of the bearing and the lubricant is primarily important. All these influences are included in the term lubricating ability.

For many years research workers and engineers have striven to establish this conception both theoretically and practically. The most varied proposals have been made for measuring the lubricating ability (V. Vieweg, Die Schmierfahigkeit und ihre Messung. Ringbuch der Luftfahrttechnik IV C 13).

Experiments to evaluate lubricating ability solely on the basis of physico-chemical or pure chemical measurements have not, so far, produced any satisfactory results, because it is not possible to make allowance for all the influences that occur in the lubricating process. Thus, for example, in research on surface tension, heat of adsorption, adhesion etc. the investigations concern only a single surface moistened by the lubricant and not, as in the lubricating process, a pair of materials. Furthermore, such experiments ignore the sheer stress brought about by the sliding process.

In order to do justice to the actual conditions occurring in the lubricating process, various attempts have been made to ascertain the lubricating ability by measuring the friction and temperature on special test bearings or test machines with different sliding arrangements. The many years of experience of the Reichsanstalt have led to the conclusion that in a bearing, or even in other sliding devices that have been proposed, there is no homogeneous condition of lubrication. Indeed, even with high stresses and low speeds, we are chiefly concerned here with measurements in the state of partial lubrication. On the other hand, in such experimental arrangements as work allegedly in the state of boundary lubrication, no proof of this being the case has been adduced. In almost all the cases, particularly in a bearing, part of the load is taken by hydrodynamic pressures, so that the measurements are affected by viscosity. This is shown, among other things, by the fact that in such measurements an extremely low coefficient of friction (0.01 and below) was obtained (V. Vieweg, elsewhere, G. Vogelpohl: Zur Klarung des Gleitreibungsvorganges. Oel und Kohle 37, 1931, p. 720-728). According to measurements by the Reichsanstalt, which will be discussed later, however, the coefficient of friction in the state of boundary lubrication is 0.1 to 0.3. With measurements on bearings etc. in addition to the effects of viscosity, only great differences in the lubricating ability have any influence in the optimum case, as, for example, in the comparison of a fatty oil with a pure mineral oil. Moreover the lubricating state, e.g. in a bearing, is subjected in running to continual variations, so that it is not possible to obtain reproducible measurements. In any case it must be stated as a fundamental principle that friction measurements in the state of partial lubrication, do not permit of an evaluation of the lubricating ability owing to the overriding viscosity influence. Only in the condition of pure boundary lubrication can satisfactory investigations into the lubricating ability be carried out, and only here can the measured friction or temperature be used for assessing the lubricating ability.

In order to meet the demand for a satisfactory measuring process to investigate lubricating ability, the Reichsanstalt, on the basis of many years experience in oil and bearing research, first of all produced a testing device which enables a state of pure boundary lubrication to be created, and which permits exactly reproducible measurements. In addition to the special choice of the sliding arrangement, the careful mechanical construction of this device, coupled with the selected method of treatment of the sliding surfaces, determine its satisfactory functioning.

The method described in the present report assesses the lubricating ability by measuring the friction power and the temperature. The temperature and the heating effect at the surface is obtained directly. This process was evolved as far back as 1936. (In 1936 the author filed a patent for the process), the research carried out simultaneously in England into the surface temperature of sliding metals (F.P.Bowden and K.E.W.Ridler, Physical Properties of Surfaces, III. The surface temperature of sliding metals. The temperature of lubricated surfaces. Proc. Roy. Soc. London, A154, 1936 pp. 640-656), served more for general investigation into the surface processes with sliding friction. A quantitative evaluation of the lubricating ability was obviously out of the question, as the necessary conditions for a correspondingly good repeat ability, as discussed in the present report, could not be satisfied, especially with regard to the treatment of the sliding surfaces.

We will now discuss in detail the measurements of the Reichsanstalt, since the method described has stood the test of a considerable time. Furthermore, these measurements furnished fundamental conclusions regarding the lubricating process, for which, owing to their novelty, a further confirmation by a direct measurement of friction and wear is awaited. A further method of measuring the friction and wear in the state of boundary lubrication has recently been evolved by the Reichsanstalt, and will be reported subsequently.

2. Description of the Method

The fundamental method of operation of the said process is based on the fact that a thermo-electric potential is produced between sliding metal surfaces on heating. As the sliding surfaces make good electrical contact with boundary lubrication, the temperature rise produced in this way by friction on the sliding surface can be ascertained. Indeed, the thermo-electric potential increases linearly with the heating at the rubbing surface. It depends on both the friction and on the sliding speed and is proportional to the friction power. As will be seen from the experimental results included in this report, the method described reveals beyond doubt the influence of the lubricating ability of a lubricant in its friction behaviour. It is accordingly possible to make use of the friction power or the heating of the rubbing surface and the associated thermo-electric potential between the sliding surfaces, for a comparative evaluation of lubricants as regards their lubricating ability. As in earlier experiments of the Reichsanstalt the thermo-electric potential between the sliding surfaces of a bearing was used for investigating boundary lubrication (V.Vieweg & J.Kluge Arch. Eisenhuttenwes. 2. 1929, p. 808. Ueber Messungen der Schmierfähigkeit von Oelen in Lagern), there were some prospects of applying such thermo-electric measurements to other sliding arrangements. By the most precise and the simplest possible construction of the sliding arrangement, a correspondingly increased accuracy of measurement was to be expected.

The fundamental arrangement in this method is a rotating plane disc and a stationary pin-shaped test piece which is pressed with adjustable pressure against the disc. The lubricant to be examined is spread in a thin layer on the flat disc. The temperature change (heating) which occurs directly as a result of the friction at the rubbing surfaces of the sliding bodies is then measured. This heating is a measure for the friction power. If the temperature rise is divided by the sliding speed, the value obtained is a comparative measure for the friction power. Owing to the small dimensions of the pin, the degree of heating corresponding to the relevant sliding conditions will be set up almost immediately, which results in a short duration of test. The state of finish of the sliding surface is thus but little changed during measurement. As will be shown later this slight alteration in the surface is without effect on the friction measurements. The heating effect itself only amounts to a few degrees Centigrade, so that the test temperature remains practically unchanged. It is thus, for example, possible to investigate the friction under otherwise similar conditions as a function of the sliding speed, without the effect of temperature (as in a test bearing) being introduced as a further important factor influencing the lubrication.

If the pin-shaped test piece only is of metal, the degree of heating at the rubbing surface of the sliding bodies can no longer be determined by the method described above. The possibility however exists of ascertaining this temperature from the temperature gradient along the pin. In the case of comparative measurements on the same pair of materials, it is sufficient to measure the temperature at any determined point of the pin. For indirect measurements of this type, a Constantan wire is soldered to the side of the pin, so that it forms a thermo-couple together with the metal pin. In principle, the exact temperature rise at the surface of any pair of materials can be calculated from the temperature rise of two measuring points on the pin. Allowance must only be made for the fact that the temperature variations along the pin is exponential. The heating $(\Delta t)_x$ at any point x of the pin-shaped body is given by the equation:

$$(\Delta t)_x = (\Delta t)_0 \; c \; -cx$$

Here $(\Delta)_0$ is the required temperature rise at the surface c a constant. Now if $(\Delta t)_1$ is the heating at the point x = 1 and $(\Delta t)_2$, the heating at the point x = 2 1, the calculation is especially simple.
We have

$$(\Delta t)_0 = \frac{(\Delta t)_1}{(\Delta t)_2}$$

It is certainly not easy to arrange two measuring points in such an exact manner. Indirect determination of the heating effect at the surface from the temperature rise at one or two points of the pin should be used especially when, for example, the disc consists of synthetic material, or if the thermo-electric calibration constant for the pair of materials acting as thermo-element alters owing to the transposition of metal during the sliding process.

According to whether the degree of heating at the rubbing surface is obtained from the thermo-potential occurring there or from the temperature gradient along the pin, a distinction will be made between the direct or the indirect thermo-electric method for determining the friction power. In both cases the thermo-electric potential is of the order of 10^{-5}V. It is measured by a mirror-galvanometer of low period. By using a current recorder with a photo-electric amplifier (Ludwig Merz; Messung und Aufzeichnung kleinster Spannungen mit einem lichtelektrischen Kompensator VDE Fachber. 1938, p. 134-137), even this small voltage can be continuously recorded, and this is important for observing the running-in process etc. This photo-electric amplifier has, moreover, the important property that it automatically compensates the voltage to be measured. Contact resistances between the sliding bodies, which occur even in the state of boundary lubrication, are thus eliminated in the direct method using this automatic compensation. On the other hand, by means of a comparative voltage measurement on the thermo-element formed by the sliding bodies, with a parallel resistance, the contact resistance may be ascertained. If, for instance, the parallel resistance is adjusted to that the measured voltage drops to half the value, the contact resistance is equal to this parallel resistance. Thus the direct thermo-electric process also permits of investigating the smallest film thicknesses with molecular dimensions, such as occur in boundary lubrication. It is noteworthy that this electrical film investigation is not effected by the use of an outside source of potential, as is customary in other proposed methods, where, for example, conclusions are drawn concerning film thickness from resistance measurements.

3. Treating the sliding surfaces

As mentioned above, the treatment of the sliding surfaces is of paramount importance for ideal friction tests. In the method evolved by the Reichsanstalt, the rotating disc is lapped directly in the experimental apparatus, the opposing disc consisting generally of the same material, while artificial carborundum is used as the abrasive proper; this is stirred into a grinding paste with a determined quantity of petroleum. Furthermore, the duration of grinding process is rigidly specified. As was ascertained by check measurements of roughness, a surface condition that can be exactly repeated is thus ensured. In this way, the most finely finished surfaces may be prepared, whose roughness amounts to only 1 u, which is on the margin of accuracy of the usual roughness measuring instruments.

A surface of this nature has always a dull appearance. A gloss can only be seen under certain conditions of light. In appearance, it resembles surfaces which are treated by the "Superfinish process". It is, however, worthy of note that the surfaces prepared by the method of the Reichsanstalt show no traces of the finishing treatment. In this connection, the term unregulated roughness characterises such surfaces. As against this, a surface that has been finely polished in the usual way shows a regular roughness in the form of the finishing marks.

The treatment process of the Reichsanstalt represents to some extent a refinement of the "Superfinish Process". In the latter method an abrasive is used, which carries out an abrasive movement with as many degrees of freedom as possible. In the method of the Reichsanstalt, on the other hand, the grinding granules between the discs correspond in their action to a grinding system with an infinite number of degrees of freedom. Every individual granule goes through a rolling and sliding movement between the discs. In order to clarify this, Fig. 1 shows various micro-photographs of very finely finished surfaces. The surfaces treated by the Reichsanstalt method present a uniform appearance. A honed or polished surface, on the other hand, shows even with the slightest roughness, clear traces of treatment in a definite direction. The photographs in Fig. 1 also reveal that the wear on the rotating disc is extremely low. In oblique lighting, the sliding track can scarcely be distinguished. Clearly, only the highest points are polished by the sliding process, and these are the points which appear glossy with lighting at right angles to the surface.

It is furthermore important that the crystalline structure of the material is retained with treatment in the Reichsanstalt method. As opposed to this, in polishing a surface, an amorphous layer will form (Beilby layer), Ein Neues Feinstbearbeitungsverfahren (Superfinish), Automobiltechnische Aeitschrift, 1940, p. 596., which lies over the crystalline material. In the sliding process, individual parts of this layer will flake off, and this will bring about a relatively great change in the sliding surface. This rather jeopardises exact and repeatable friction tests. Surfaces that have been treated by the Reichsanstalt process, on the other hand, show a gradual but uniform wear of the material in the sliding process.

In all the friction tests hitherto known for evaluating lubricants, polished surfaces are used, or else the surfaces used have regular roughness in the above sense (finishing marks). In addition to the difficulties already described in bringing about a state of boundary lubrication, this is the main reason why the friction tests hitherto in use have not always given satisfaction as regards their repeatability and it has been impossible to arrive at an exact evaluation of lubricants on the basis of friction tests.

4. Mechanical Construction of the sliding device

The mechanical construction of the sliding device will be seen from Fig.2. The pin-shaped testpiece is fastened by means of pliers, as in usual workshop practice, to a single-armed lever. The tapered bearing of this lever ensures the maintenance of the setting of the pin in respect to the rotating disc. The load may be adjusted by adding weights to the lever. In order to secure uniform pressure distribution on the sliding surfaces, the latter must be ground together in a suitable manner. This is effected on the device itself by means of a special test. In order that the position of the sliding surfaces in respect of each other may be the same for all positions of rotation of the disc, when this disc rotates through the measuring point, it must not deflect in an axial direction. The revolving disc is therefore attached to a particularly well positioned spindle.

Furthermore, the measuring disc can be finely adjusted by means of a setting device. For this purpose, the setting device is fitted with a diaphragm-supported threaded journal and several set-screws. By this means the impact on the measuring point with a diameter of the sliding path of 120 mm, may be restricted to 1 u and below. The aforementioned mechanical structure also ensures the maintenance of the reciprocal position of the sliding surfaces, when the pin is removed for cleaning the sliding surfaces or for the fresh treatment of the disc. Even with hard materials such as steel and cast iron, it suffices to run-in for only about 10 minutes, and thus to avoid any minute displacement of the sliding surfaces.

5. Test Procedure and Results

After treating the rotating disc, the abrasive is carefully removed and the surface cleansed with residue-free benzine. The lubricant to be investigated is applied to the disc in a thin layer and while running is distributed evenly by a fragment of leather (previously cleaned) pressed lightly against the disc.

As already stated in the previous paragraph, the rod soon grinds itself in (a matter of a few minutes) on the surface of the disc. The measuring state thus produced in the case of the pair of materials steel-cast iron remains unaltered even for a prolonged test of about 2 hours. Fig.3 records such a test. If allowance is duly made for the fact that in the tests proper for adjusting a measurement value, and for its reading, only a few seconds are required, the measuring state is maintained for a sufficient length of time even for several tests carried out on the same sliding track. When kept running for still longer, however, a more marked polishing of the surface of the disc will be observed, so that the state of boundary lubrication gradually passes into the state of partial lubrication. This becomes noticeable in a reduction of the measured deflection; this reduction may be attributed partly to an actual reduction of friction owing to the formation of a film and partly to the contact resistance due to the film of lubricant.

The aforementioned brief measuring period for setting and reading off a measured value indicates the equivalent inertia free operation of the method described. In proof of this, Fig.4 shows the recording of the friction power by means of a recording instrument, the surface of the disc being coated with a very thin layer of oil (mineral oil), and at a small point of the sliding track some oleic acid is applied. The experiment gives a periodicity of the friction power corresponding to the speed of rotation. Each time the point moistened with oleic acid on the surface of the disc passes beneath the pin, the friction power at once drops, only to mount again just as quickly when this point has been passed. For this experiment the aforementioned fragment of leather was of course removed. The gradual drop of the mean deflection is due to the fact that the pin gradually conveys som of the oleic acid to other points of the disc surface.

Of the numerous measurements carried out on the most varie lubricants, we shall now describe a few of the more striking examples. Fig.5 shows first of all two series of measurements, affording proof of good reproducability of the method. The friction power is here, as in subsequent measurements, plotted in arbitrary figures. However, only one comparison of the experimental results assembled in one diagram is possible as the sensitivity was differently adjusted in other cases. The agreement of the two series of measurements in Fig. 5 is extremely satisfactory and shows that the finish of the sliding surface during the brief measuring period is scarcely altered, or else such alteration has no effect on the accuracy of measurements. Here it is noteworthy that between the two measurements, various other measurements were carried out on the same sliding track of the rotating disc, without the disc being freshly treated between tests. The same accuracy of measurements and repeatability are, however, obtained if the surface of the disc is freshly treated before each experiment. New treatment of this type is especially recommended when, as a result of the lubricant examined, a chemical attack on the sliding surface is to be feared. Fig.5 also shows the temperature rises at the sliding surface. They were obtained by a special calibration and confirmed the previous statement, that the temperature of the experiment is practically unaltered by the friction test itself.

As further stated in the description, the method works in the state of boundary lubrication. It must thus be possible to compare lubricants of different viscosity, without such comparative measurements being influenced by the effect of the viscosity. Fig. 6 gives the measurements of two oils, whose viscosities are approximately in the ratio of 1 to 30. These are, moreover, synthetic oils, which in regard to their surface effects behave in the same way, so that with measurements in the state of boundary lubrication, no discrepancy was to be expected in the matter of friction. Measurements confirmed this expectation and did not show, even slightly, any influence of viscosity. According to the experience of the Reichsanstalt, such an effect would make itself felt in a further reduction of friction, and this would be all the more noticeable the greater the viscosity. For in each case the friction is reduced on passing from the state of boundary lubrication to that of partial lubrication. It only increases again if a state of full fluid lubrication sets in, but never reaches the values of boundary lubrication.

Since the method works in the state of boundary lubrication, effects of the composition of the lubricant on the friction must become very noticeable during the measurements. Fig. 7 shows comparative measurements with cetane and with cetane containing different additions of palmitic acid. The well-known friction reducing action of the acid will at once be perceived. Very small additions at first cause a considerable drop in friction, but with larger quantities, the familiar end state as regards friction sets in. A further increase of the additive no longer affects the friction.

A further proof of the utility of the method will be seen in the measurements reproduced in Fig.8. In agreement with practical experience, the fatty oil shows a very much smaller coefficient compared with the mineral oil. The synthetically produced oil behaves even more unfavourably than the mineral oil investigated. These observations also coincide with practical experience, as the synthetic oil is a raw material that is expected to behave somewhat like a pure mineral oil. This result is important in so far as the measurements in Fig.8 might permit of the conclusion that synthetic oils are not suitable for lubrication

The experience of the Reichsanstalt with synthetic oils of various origins and spheres of application has shown that it is possible to-day to produce synthetic oils with excellent lubricating qualities. This, however, is a matter that will be left for future discussion.

6. Conclusions

The method described for the thermo-electric measurement of friction power has proved itself in the examination of lubricants with regard to their friction behaviour in the state of boundary lubrication. The measurements reveal quite clearly the effect of the composition of the lubricant on the friction. By eliminating all hydrodynamic film formation, comparative measurements are also possible between lubricants with great differences in viscosity.

In principle the thermo-electric method can only be used for comparative measurements. A quantitative measurement of friction, in particular exact indication of the coefficient of friction, is not possible by the method described. For such friction measurements another special method has been evolved and will be described in a subsequent report.

Diagrams

3rd April, 1945.