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New knowledge on lubricating properties and their measurement

by Johannes Kluge, Berlin.

The problems of lubrication have existed as long as technical devices have been known: in all cases losses by friction and losses of material are required to be reduced by lubrication. Loss by friction here signifies loss of energy and is a considerable factor in lubricating instruments. Loss of material (wear), on the other hand, is mainly connected with the lubrication of machinery. It results in the destruction of the bearing surface and jeopardises the machinery.

It should be borne in mind as a matter of principle that lubrication does not depend only on the lubricant, but also on the material of the bearings and the properties of the point of lubrication (construction and conditions of working of the bearing). For solving problems connected therewith, the collaboration of the oil chemist, materials expert and designer is therefore essential. The Physikalisch-Technische Reichsanstalt has always endeavoured to offer its services and aid towards such collaboration. In this connection, reference will merely be made to the hydrodynamic work on the formation of films on journal and anti-friction bearings. This work was able to furnish, among other things, valuable knowledge regarding the design of journal bearings: in addition, the conceptions and deductions of the hydrodynamic lubrication of bearings were to a great extent confirmed by this work. The hydrodynamic theory of bearings was of great importance inasmuch as the evaluation of lubricants for the processes of pure fluid friction could thereby be referred to a measurement of the viscosity.

For lubricating highly stressed sliding surfaces, however, the mere choice of a lubricant on the basis of its viscosity is not sufficient. The fundamentally different behaviour of a fatty oil and a pure mineral oil for engine and gear lubrication should be noted in this connection. This may be attributed to the fact that when heavily loaded or insufficiently lubricated, (e.g. lubrication of piston rings), the bearing surfaces slide on each other so that they are either wholly or partially in permanent contact. Molecular contact surface forces act here between the lubricant and the material of the bearing and are not expressed in terms of viscosity. Modern research on lubricants comprises the action of those contact surface forces in the term lubricating property, but this does not make possible an immediate solution of the problems in question. In most cases the correct choice of a lubricant could still only be made after costly running tests. There was thus an urgent need for establishing reliable measuring methods and evaluation data for the selection of a lubricant with regard to the aforementioned contact surface behaviour and therefore with regard to its lubricating properties. Recent work of the Reichsanstalt, which was carried out primarily on the pair of materials steel/cast-iron with regard to the special significance of piston ring lubrication, provides an important contribution in this respect.

Before discussing this matter in greater detail, it must be mentioned by way of elucidation that a number of running conditions are to be distinguished in lubricated sliding surfaces. If, for instance, the sliding surfaces are separated by a hydrodynamically formed film, this is termed hydrodynamic or complete lubrication, to which allusion has already been made. The load is in a state of equilibrium with hydrodynamically formed pressures, and viscosity is the only determining characteristic of the lubricant. If the load is too great or the speed of rotation too low, so that a hydrodynamic film cannot form, the lubricant only acts in thin layers adhering to the contact surfaces, and this condition is accordingly termed boundary lubrication (Grenzschmierung). In this case, lubrication is not affected by viscosity. On technical sliding surfaces, boundary lubrication and complete lubrication frequently exist side by side, and this is spoken of as partial lubrication. To elucidate these terms further, Fig. 1 shows the coefficient of friction of a friction bearing as a function of the speed w or of an undimensioned magnitude $\mu.w/p$. As will be seen, by way of example, from Fig. 1, the coefficient of friction for partial lubrication, in contrast to complete lubrication, is lower the higher the viscosity; likewise, dependence on speed for partial lubrication is fundamentally different for complete lubrication. It is therefore inadmissible to transfer measurements and experience simply from one lubricating condition to another. In future, therefore, one should speak of the suitability of complete lubrication, boundary lubrication etc., viscosity being the evaluation factor for the suitability of complete lubrication, while as regards the suitability of boundary lubrication, the boundary surface forces between the lubricant and the material of the bearing should be computed. The suitability of boundary lubrication is therefore to a great extent identical with the term hitherto known as the lubricating property. In this sense, the oil testing apparatus hitherto in use cannot be used for evaluating the lubricating property, since they worked more or less on partial lubrication, i.e. the measurements obtained with apparatus of this type for friction and wear are still affected by viscosity and only partially influenced by the boundary surface forces that are responsible for the lubricating properties. It must also be borne in mind that the hydrodynamic portion of the lubrication with these testing machines cannot be indicated. Indeed, it will be very different for the individual repetition and comparison tests, so that measurements in the state of partial lubrication will only be reproducible imperfectly; this precludes any evaluation of the lubricating properties on the basis of investigations in the state of partial lubrication.

(Fig.1 - Friction curve after Striebeck)

The new measuring methods developed at the Reichsanstalt, on the other hand, work strictly in the state of boundary lubrication, so that the sliding process can be investigated as a pure boundary surface process. The figures thus obtained for the coefficient of friction, heating and wear may therefore be used without reserve for the evaluation of the lubficating properties. As the measuring system has been partly described in great detail elsewhere, only its more important characteristics will be given here. The sliding system used is a flat, rotating disc, against which a rod-shaped test-piece is pressed; in addition, a defined and reproducible fine-lapping process is used for the sliding surfaces. By this means, the geometric ratios of the sliding system may be ascertained with accuracy, and moreover uniform pressure distribution is ensured. Measurements of friction and warming can be made under these conditions with a degree of accuracy of about 2%. The small dimensions of the rod-shaped test-piece moreover entail only a low degree of heating, which can be adjusted in a few seconds according to the respective sliding conditions. The measurement time is therefore short and the operating conditions originally present are scarcely altered during measurement. In contrast to this, a bearing, for example, exhibits a high degree of heating, i.e. the temperature of the experiment varies considerably with the respective measurements. Furthermore, a constant state of heating does not occur for a considerable time, and this involves continual variations in the operating conditions on the sliding surface.

For the actual measurement of the friction, heating and wear figures determining the sliding process, electric and electro-mechanical measuring methods of a fundamentally new type are used in the Reichsanstalt experiments. Special care is taken to prevent the measuring system from reacting on the sliding system itself. Thus the instrument for measuring force works with a gauge length of a few μ, i.e. the reciprocal position of the two sliding bodies scarcely alters during the measurement. The measuring device for wear works in a similar way, but with a measurement pressure of a few grammes that can be controlled with accuracy. It is also important that there should be no resonance between the sliding system and the measuring system. A further great advantage of the new measuring systems is that the relatively small measurements for friction, heating and wear can be magnified as desired by electrical amplification independently of mechanical conditions. It is possible to read off the measurements with an ordinary commercial galvanometer or electric recording instrument. A few measurements with the pair of materials steel/cast-iron will be described below, showing how it is possible to evaluate the lubricant by measuring the limit friction.

Evaluating lubricants by measuring limit friction

From the measurements shown in fig. 2, it is at once possible to see what conditions as regards pressure, roughness, etc., must be adhered ~~to so that the friction~~ is not affected by viscosity, even at the lowest sliding speeds, i.e. so that pure boundary lubrication occurs.

(Fig.2 - Coefficient of friction as a function of pressure and roughness)

Two pure hydrocarbon oils were investigated, showing great discrepancies between their viscosities. It is known that the coefficient of friction approaches a constant final value as the pressure increases. This final value for the coefficient of friction will hereafter be termed the coefficient of limit friction and is the same in both oils because the properties of their boundary surfaces are the same. In the case of lower pressures, on the other hand, a partially hydrodynamic formation of film takes place, and this reduces the coefficient of friction. It has also been ascertained that this hydrodynamic influence is the more powerful in action the greater the viscosity and the less the roughness. It is worthy of note that the coefficient of limit friction does not depend on viscosity or on pressure and roughness. As shown by the measurements in fig. 3, the coefficient of limit friction is also to a very large extent independent of the sliding speed. The coefficient of limit friction is therefore highly suited for evaluating a lubricant, inasmuch as it is only affected by temperature for a given pair of materials.

(Fig.3 - Coefficient of limit friction and heating with oils of different viscosities)

Comparative measurements of friction with a pure mineral oil and a fatty oil were able to prove that this evaluation coincides with practical experience. It will be seen from fig. 4 that the coefficient of limit friction for the fatty oil is very much lower than for the mineral oil. The varying friction behaviour at the lowest sliding speeds and for static friction is particularly clear. Indeed, static friction is greater than sliding friction for mineral oil, while for the fatty oil it is less than the sliding friction. Of considerable importance in this connection were the terms falling limit friction characteristic or rising limit friction characteristic; according to experience at the Reichsanstalt, the rising characteristic of the coefficient of limit friction, in research on the pair of materials steel/cast-iron, is always a special feature of a lubricant possessing good lubricating properties.

(Fig.4 - Coefficient of limit friction of mineral oil and fatty oil)

Among the many measurements carried out in this connection, mention will be made of comparative measurements with a vaseline and a wool-fat (lanoline). In agreement with the aforementioned considerations for vaseline, which corresponds to a pure mineral oil with regard to its boundary surface behaviour and lubricating properties, the measurements shown in fig. 5 exhibit a falling characteristic for limit friction, while the wool-fat, being a lubricant of animal origin, whose excellent lubricating properties are well known, shows a rising characteristic. In addition, the wool-fat has, on an average, a lower coefficient of friction than the vaseline.

(Fig.5 - Coefficient of limit friction for vaseline and lanoline)

It is furthermore worthy of note that with the experimental system of the Reichsanstalt, measurements of limit friction with non-fluid materials may also be carried out. To obtain further insight into the natural laws governing the connection between limit friction and lubricating properties of the influences determining lubricating properties, complete friction experiments were conducted with various chemically defined substances.

Limit friction and the constitution of the lubricant

It has long been known that the lubricating properties of a pure mineral lubricant can be improved by the addition of boundary surface active substances. Reference is made to the customary method in the "Germ process" of using traces of free oleic acid by way of additive. Fig. 6 shows by way of example the coefficients of limit friction for pure cetane and cetane with varying additions of oleic acid.

(Fig.6 - Coefficient of limit friction for cetane with additions of oleic acid)

In agreement with practical experience ("Germ Process"), even a very slight addition of oleic acid produces a very much lower coefficient of friction than pure cetane. Furthermore, as more acid is added, the limit friction characteristic passes from a falling to a rising curve. It is a noteworthy fact that even extraordinarily small quantities of oleic acid, e.g. 1 vol. %, bring about very different limit friction behaviour; in this connection it should be remembered that 1 vol. % free oleic acid corresponds to a neutralisation factor of only 0.2%. The great influence of the oleic acid is evidently to be attributed to the strong polarity of the end group. As a further proof of this, comparative experiments were carried out on homologous alcohols and acids. Fig. 7 shows for purposes of comparison the limit friction coefficients for homologous alcohols and acids.

(Fig.7 - Limit coefficient of friction for homologous alcohols and acids)

The rather strong polarity of the final acid group causes in each case, by comparison with the corresponding alcohol group, a rising limit friction characteristic with, on an average, a lower coefficient of friction. Moreover, in a homologous series, the coefficient of friction is lower the longer the chain. Generally speaking, alcohols possess practically the same limit friction behaviour (falling characteristic) as the saturated compounds.

The effect of the end group could be shown by friction experiments with various butyl derivatives. In fig. 8 limit friction figures are plotted for the halogen compounds of butyric acid. The iodide clearly exhibits a rising curve for the limit friction characteristic, which is obviously to be attributed to its greater polarity, while the chloride has a pronounced falling characteristic.

(Fig.8 - Limit friction coefficient for butyl derivatives)

To sum up, the conclusion is reached that the rising or falling limit friction characteristic of a lubricant, as observed on the pair of materials steel/cast-iron, is to be attributed to the degree of polarity of its components. The coefficient of limit friction at higher speeds, on the other hand, depends both on the polarity of these components and on the size of the molecule (length of chain). Since, on an average, all the technically usual lubricants have more or less the same molecular weight, the influence of polar groups on the coefficient of limit friction of technical lubricants will also prevail in the higher range of sliding speeds. In particular, the limit friction behaviour of a fatty oil, in contrast to a pure mineral oil, is principally conditioned by the polar molecules of free fatty acid or by other components of great polarity.

Evaluation of lubricants by measurements of wear in the state of boundary lubrication

As already mentioned, the behaviour of a lubricant is a decisive factor not only for friction but for the wear at the point of lubrication as well, but in the great majority of cases, the amount of wear should however be of major significance. On the basis of friction measurements, it was to be assumed that the wear in the various states of lubrication and likewise the friction, would show varying obedience to natural laws. Thus in the state of complete lubrication, there is no wear as the bearing surfaces are separated by a film of fluid. For determining wear, therefore, only the states of partial or of boundary lubrication can be used. However, as long as it is not possible to give the hydrodynamic portion in measurable values in partial lubrication experiments, only the state of boundary lubrication can be employed for accurate investigations into wear and for friction experiments.

As the Reichsanstalt experiments showed, abrasion of material that is generally termed "wear" (Verschleiss) is in fact so different with boundary lubrication and partial lubrication that in future the term "wear" will only be used for abrasion of material in the state of partial lubrication. This distinction was found to be particularly necessary for investigations with engine lubricants having a well-known wear behaviour. Fig. 9 shows the time curve for abrasion of material in the case of a fatty oil and a pure mineral oil, as obtained from the wear of the rod-shaped test-piece in the Reichsanstalt experimental system for pure boundary lubrication.

A fundamentally new observation is that the fatty oil of known good lubricating properties and particularly favourable deterioration behaviour in the engine, in the state of boundary lubrication produces practically twice the wear as with pure mineral oil. This result could also be obtained with numerous other lubricants having good lubricating properties.

(Fig.9 - Wear with boundary lubrication using mineral oil and fatty oil)

In each case a lubricant possessing good lubricating properties produced in the state of boundary lubrication greater wear than a lubricant with poorer lubricating properties. By way of a further example, fig. 10 shows corresponding comparative tests with a vaseline and the aforementioned wool-fat (lanoline).

(Fig.10 - Wear with boundary lubrication using vaseline and lanoline)

An explanation of the foregoing observation as to wear of material in the state of boundary lubrication and its transference to the state of partial lubrication prevailing in the engine is clearly furnished by the fact that for wear in the state of boundary lubrication, the lubricant has fairly good running-in behaviour. This is of the greatest importance for making and maintaining a good bearing surface and thus for the reliable running-in, e.g. of an aero-engine. In other words, the lubricant having good running-in behaviour, by its rapid but uniform wear of the material of the bearing points where high pressure stresses prevail, ensures smoothness at these points and a flattening of the pressure peaks which otherwise, if allowed to act permanently on the material, could entail the destrubtion of the bearing surfaces.

It is important to remember that the smoothing of the material in the state of partial lubrication is mainly brought about by excess stress of the material of the bearing at the points with high pressure peaks. In this connection alone is the further use of the term "wear" (Verschleiss) practical and admissible. On the other hand, in the state of pure boundary lubrication, the abrasion of the material corresponding to the running-in behaviour preponderates. It brings about an additional and very fine finish to the bearing surface, whereas wear involves the destruction of the bearing surfaces.

Both forms of removal of material occur side by side in the state of partial lubrication, where, however, the carrying away of the material through wear is greater than the corresponding abrasion for the running-in behaviour. The latter type nevertheless affects wear considerably since, as already mentioned, it smoothes the points endangered by wear and thus flattens the high pressure peaks.

The carrying away of material observed in the state of boundary lubrication, on the other hand, indicates the aforementioned running-in behaviour of the lubricant in its purest form, as the load is taken uniformly by all points of the sliding surface. The actual pressure stress is of the order of magnitude of the mean pressure calculated for the whole sliding surface. Pressure points which have high pressure peaks and are endangered by wear (these are particularly characteristic of partial lubrication), do not occur with pure boundary lubrication, or else may be avoided.

Summary

It has been shown that it is desirable to distinguish between lubricating properties of complete lubrication, boundary lubrication or partial lubrication. While the lubricating properties of complete lubrication are determined solely by the viscosity, in the case of boundary lubrication, they depend on the boundary surface forces between the layer of lubricant and the material of the bearing. They are independent of viscosity and on the whole identical with the term "lubricating properties" as hitherto used. In like manner, the state of boundary lubrication is not affected by hydrodynamic viscosity action, and is rather of the nature of a pure boundary surface process. In the case of partial lubrication, boundary surface forces and viscosity act side by side.

The measuring system that has been developed for investigations into lubricating properties works strictly in the state of boundary lubrication. The varying lubricating properties of a technical lubricant are expressed during sliding experiments with the pair of materials steel/cast-iron in the curve of the so-called characteristic of limit friction. By means of research on chemically defined substances, relationships obeying natural laws can be ascertained between the lubricating properties determining the quality of the lubricant and the boundary friction characteristic. The accuracy of measurements for complete friction investigations is relatively high - about 2%.

The lubricating properties are particularly clearly expressed when measuring wear in the state of boundary lubrication. In every case a lubricant with good lubricating properties produces greater wear in the state of boundary lubrication than a lubricant with poor lubricating properties. The point in question is that this more or less good running-in behaviour of the lubricant leads to an additional, very fine chemico-mechanical working of the bearing surface. It is shown how the carrying away of the material corresponding to the running-in behaviour must not be confused with wear. Between the two there is, however, an inner relationship.

On the basis of new knowledge regarding lubricating properties, it was possible to obtain valuable guidance for the practical selection of a lubricant and for building up a synthetic lubricant. Thus the experiments of the Reichsanstalt provided an explanation of the behaviour of high-grade military oils of synthetic origin. Problems of piston-ring wear could also be solved to a considerable extent. From experience so far available, a comparative assessment of lubricants in accordance with the new measuring processes of the Reichsanstalt has resulted in a classification in regard to lubricating properties which in every case coincides with technical experience. For further details, as to the new measurement methods of the Reichsanstalt, reference should be made to the reports and papers given in the bibliography.

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