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Sliding tests on metals in a state of boundary lubrication.

The object of lubricating sliding surfaces is, on the one hand to reduce friction losses, and on the other hand to reduce wear and tear to sliding surfaces. Reduction of friction is specially important for instruments, electrical calculators, watches, and so on. In large bearings and in power machines, such as engines etc. it plays a subordinate part. But the wear behaviour of sliding parts is very important in any case, as it decides the accuracy of many devices and machines, and above all their length of life.

In the lubrication of sliding parts in practice we always take as our objective working conditions free of wear and tear. This is achieved when the whole load is transferred by way of a hydro-dynamically formed film of lubricant, which at the same time prevents the sliding surfaces from coming into direct contact with each other. In this condition, known as full fluid lubrication or fluid friction, lubrication is influenced by a single property, the viscosity of the lubricant. In full fluid lubrication, the bearing material has no influence. A characteristic of full fluid lubrication is, that friction assumes generally the lowest value attainable; the exceptions are bearings with very high shaft speeds such as spinning spindles.

In the lubrication process connected with wear, the load is taken up in a greater or less degree by actual contact, as the film of lubricant is broken down locally, either through overloading or too low sliding speed.

At points of direct contact we do not, as is commonly believed, normally get dry friction; rather, the lubricant is in the form of an adsorbed layer. In such a layer the lubricant no longer has the properties of a liquid, and hydrodynamic lubrication is not possible. Rather, at the points of direct contact the surface forces at work between the bearing material and the lubricant take effect, and influence the friction and wear accordingly.

The condition characterised by the effect of the adsorbed layer of lubricant is known as boundary lubrication or limit friction.

As already stated, under full lubrication the only property to take effect is the viscosity of the lubricant. As viscosity can be measured separately, with full fluid lubrication it is seldom necessary to make investigations. In surface lubrication, on the other hand viscosity is not important, and apart from the properties of the bearing material itself the interaction between the bearing material and the lubricant take effect. In most lubrication processes these two conditions occur together. We accordingly speak of a condition of partial lubrication or mixed friction. So far it has proved impossible in measuring partial lubrication to determine the proportion as between boundary lubrication and full lubrication. This difficulty occurs, for instance, with the well known bearing metal test machines, which work for the most part in a condition of partial lubrication. In any case, it is necessary, when investigating lubrication, to consider the boundary surface and conditions between the lubrication and the bearing material, in addition to the viscosity of the lubricant. Therefore, to determine this surface behaviour, we have to investigate the bearing material as well as the lubricant under conditions of boundary-surface lubrication.

The researches of the Reich Institute have shown that the behaviour at the surface between the bearing material and the lubricant results under boundary lubrication in wear of the bearing material. These researches further led to the conclusion that the best lubricant for partial lubrication is that one which causes the greatest wear to the bearing material under boundary lubrication. This is explained by the following consideration. In partial lubrication, as already stated, areas under boundary lubrication and areas under hydrodynamic lubrication exist side by side. The wear will be less, the greater the area where hydrodynamic lubrication prevails. It follows that the wear on a point where partial lubrication prevails can be reduced by certain working conditions, for instance, by using a lubricant of greater viscosity. We also know, from other tests by the Reich Institute, that those properties of a lubricant which cause greater wear on a material under boundary lubrication lead to a smoothing of the sliding surfaces under partial lubrication. But this increases the area under hydrodynamic lubrication, and accordingly reduces wear. This offers an explanation, why a lubricant, which causes wear to the bearing material under boundary lubrication, behaves better under partial lubrication.

We may assume that the different behaviour of bearing materials under partial lubrication can likewise be explained by measurements of the wear of material under boundary lubrication. The investigations under discussion are a contribution to this end.

The above considerations indicate that the material wear under boundary lubrication is of decisive significance for the behaviour of a lubricant, and probably also of a bearing material, under partial lubrication. In this connection it must be borne in mind, that the friction of a sliding part under conditions of partial lubrication is influenced in the same way as wear by the proportion of full lubrication to boundary lubrication. That is, as the proportion under hydrodynamic lubrication increases, both wear and friction are reduced. In addition, the Reich Institute found that by taking friction measurements they could decide whether a point was under partial or boundary lubrication. Also, earlier investigations by the Reich Institute had shown that the friction coefficient under boundary lubrication is independent of the pressure. If the friction coefficient falls when pressure is reduced, this is a sign that part of the load is being taken up hydrodynamically, i.e. that partial lubrication prevails. The reduction of friction through a corresponding gain in hydrodynamic lubrication is important in cases where the expenditure of power caused by friction is to be kept as low as possible. The friction arising from boundary lubrication (boundary friction) is, however, of secondary importance in practical lubrication.

In any case the tests described below, show that the wear to material under boundary lubrication is much more influenced both by lubricant and material than is the boundary friction.

Test procedure.

The tests were carried out at room temperature by a method developed at the Reich Institute. A pin-shaped piece of the metal under test is pressed against a smooth rotating disc of hardened steel; the pressure being adjustable. The surface of the disc is finely finished by a process similar to lapping. The result was a surface similar to a sand-clasted surface, the roughness peaks standing out about 0.002 mm. In view of the boundary lubrication conditions, the measurements were made at sliding speeds of a few cms/sse. For the same reasons the pressure should not fall below a certain minimum. The low rigidity of tin and lead, for example, necessitate an upper limit for pressure. After initial tests, we finally selected a pressure of 70 kg/cm². With lead it was impossible to obtain a measurement without lubrication under the test conditions selected. In the tests without lubrication, the surfaces cleaned with gasoline are considered for practical purposes to be dry, that is, it is still possible for layers of adsorbed gas or moisture, or even of oxide, to form.

The tests were carried out on various pure metals. Some of the metals used were available in the form of wire of 1 mm. diameter. The remaining metals were so ductile that they could easily be drawn out to form a wire.

For the surface lubrication investigations we used a pure hydro-carbon oil without additives and a fatty oil. Since fatty oils, in contrast to pure hydro-carbon oils, have good lubricating properties, the tests demonstrate the behaviour of the metals under test when treated with lubricants of various lubricating properties.

Results.

In figure 1 are shown the friction coefficients obtained for the different metals at a sliding speed of 7 cm/s. These make it clear that the influence of the bearing material on friction is comparatively small under boundary lubrication conditions. Comparing the most extreme cases the friction coefficients under boundary lubrication are in the ratio of 1 : 2. Tin has the lowest and nickel the highest value. The lubricant has even less influence. The boundary friction coefficient is less for fatty oil than for hydro-carbon oil in all cases except those of magnesium and copper. In every case the friction coefficients without lubrication are considerably greater than with lubrication, without a parellelism to the boundary lubrication measurements being established. In the tests on steel, cast iron, and electrolytic iron the degree of error in measurement was about 4 per cent. For other metals it has been considerably greater up to the present, especially in tests without lubrication. Nevertheless, the results of these tests may be confidently relied on.

Fig. 2 shows the figures for bearing material wear, obtained with a sliding distance of 25 m under boundary lubrication conditions. Above all, it is noteworthy that the influence of the bearing material and lubricant is very great, in contrast to the friction measurements. Thus the wear of lead and tungsten under boundary lubrication with hydro-carbon oil are in the ratio of about 80:1. Also, fatty oil generally gives a greater wear than hydro-carbon oil. This ratio is reversed for certain metals, such as gold, bismuth, tin and lead. Another remarkable fact is that the material wear without lubrication is generally lower than the wear under boundary lubrication. Some metals do, however, show higher values without lubrication, such as zinc, cadmium and tin. For magnesium and bismuth the wear without lubrication lies between the values which recorded for boundary lubrication with hydro-carbon oil and fatty oil. The low material wear without lubrication may be explained in part by the very adhesive layers of oxide which protect the surface against wear (e.g. copper). On the other hand, loosely adhering oxide layers can act as abrasives if sufficiently hard, and can increase the wear. Also, the structure of the crystals appears to have an influence. For the material wear without lubrication is only greater than wear under boundary lubrication in the case of magensium, zinc, cadmium, bismuth and tin, which do not form cubic crystals.

The main conclusion to be drawn from figures 1 and 2 is that the individual materials and the lubricants vary much more in their influence on material wear under boundary lubrication than on boundary friction. This fact allows for the view set out above, that the material wear observed under boundary lubrication leads to a smoothing of the sliding surface under partial lubrication. This increases the proportion of hydrodynamic lubrication, and so improves the behaviour of the lubricant or material as regards friction and wear, in as far as these are not determined purely by hydrodynamic conditions.

Also, the measurements given in fig, 2 show that the material wear under boundary lubrication, and thus also the smoothing effect mentioned above, are influenced considerably more by the bearing material than by the lubricant. This means that the practical lubrication behaviour of a bearing is determined to a much greater extent by the material of the bearing than by the type of lubricant. A bad choice of bearing material can only partly be made good by the lubricant. Even then it is assumed that the sliding surfaces are in every respect structurally perfect, e.g. as regards pressure at the edges (KANTENPRESSUNG). Structural faults can only in part be compensated for by the choice of a suitable bearing material, and by the lubricant practically not at all.

To explain the process of material abrasion more exactly, we tried to relate it to other physical properties of the metal in question. Of interest here is the hardness and the melting point of the metal. Figures 3 and 4 show that such a relationship exists, although one cannot speak of dependence on a law. We made the striking observation that the metals which do not form cubic crystals are the most difficult to bring into any relationship with the melting point. Important basic conclusions can be drawn from the dependence of material abrasion on the hardness or the melting point, as to the demands on the bearing material or lubricant in the lubricating process. with reference to the effective pressure and temperature. In the view of R. Holm, the effective pressure of a sliding surface is considerably greater than the pressure as recorded by geometrical measurement at the pressure surface; actually, the upper limit of the effective pressure is the hardness of the softer of the two metals in question. This means, however, that in the lubrication process we have to reckon in extreme cases with actual pressures of some 10,000's of kg/cm^2. This effective pressure is of course more or less reduced by a proportion of hydrodynamic lubrication, and this again demonstrates the special importance of the smoothing effect under partial lubrication. It follows from the interdependence of effective pressure and hardness, that the surface of contact is the smaller the greater the degree of hardness; to put it another way, hard surfaces will have fewer roughness peaks of contact than softer surfaces; whence it is apparent that the harder body suffers less wear than the softer one.

We may make the same study of the effective heating of the surface as we made of effective pressure, and on the basis of the interdependence of material abrasion and melting point we may suppose that heating directly on the sliding surface can be equal at its maximum to the melting point of one of the two metals of the sliding surface which has the lower melting point. But here, in contrast to considerations of the effective pressure, the sliding speed is a decisive factor. Thus, we can show by thermo-electric measurements, that the heating of the sliding surface of a low melting metal at first increases in linear relationship to the sliding speed, until finally, when the melting point is reached it no longer rises, in spite of further increase in the sliding speed. This observation has a more general application, though so far this has not been demonstrated for high-melting metals. At any rate, the thermal effect on the material and the lubricant in bearing materials with high melting points is considerably greater than in those with lower melting points. Here, of course, the cooling conditions of the sliding surface must also be taken into account. Thus, the lubricant itself, to take an example, may have some effect, especially if the proportion of hydrodynamic lubrication increases.

As was stated above, the material wear occasioned by boundary lubrication under conditions of partial lubrication is favourably affected by the additional smoothing of the sliding surface. We also observed that with most metals the bearing wear is greater with a fatty oil than with a mineral oil. Similar observations were made with several metals, using other lubricants with different lubricating qualities. It can be assumed, in agreement with investigations reported earlier, that the different abrasion of the bearings during lubrication with individual oils is assisted by chemical interaction between the lubricant and the bearing material, especially when we remember that the lubricant, in view of the considerations already referred to, is exposed to considerable pressures and heating. We will take another opportunity to discuss these more accurate investigations in more detail. It is only intended to show here that there is frequently evidence of an interdependence between the influence of the lubricant on bearing wear and the normal potential of the metals. Figure 5 shows the relationship between material wear under boundary lubrication with fatty oil and the corresponding value with mineral oil as functions of the normal potential. We observe that with precious metals such as silver and gold this ratio is practically equal to 1. That is, under lubrication with a pure hydro-carbon oil and with a fatty oil there is no chemical action.

Summary.

This is a report on investigations into the sliding behaviour of metallic materials under boundary lubrication. It can be shown that the abrasion of the bearing under boundary lubrication conditions is specially important as regards the practical lubrication process involving wear. On the basis of such measurements, for instance, we can predict the behaviour of the lubricant under partial lubrication as well as with regard to friction (power consumption), and also as regards wear (life and safety

factor). In any case that lubricant is preferable which produces the greatest material wear under boundary lubrication conditions. In the same way we may use the difference in material wear to estimate the sliding behaviour of bearing materials. Other properties also have to be considered, such as the sensitivity of the bearing material to pressure at the edges. The investigations also show that this sliding behaviour bears a certain relationship to the hardness and the melting point of the metal. It follows that extremely high pressures and temperatures can occur at the contact surface, leading to an additional chemical reaction between the lubricant and the material. It is therefore quite understandable that, for instance, a fatty oil under boundary lubrication conditions causes a greater degree of material wear than a mineral oil, or that the chemical influence of the lubricant is specially high in base metals. The further conclusions which can be drawn from this are fully discussed elsewhere. It is also the intention to complete the tests, which began on precious metals, with others on alloys and normal bearing metals.

Fig. 1 - Friction coefficients of metals sliding on a steel surface.

Fig. 2 - Material wear of metals sliding on a steel surface.

Fig. 3 - Material wear under surface lubrication as a function of the Brinell hardness of the metals.

Fig. 4 - Material wear under surface lubrication as a function of the melting point of the metals.

Fig. 5 - Material wear under surface lubrication as a function of the normal potential of the metals.

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