TABLE 3 COEFFICIENT OF FRICTION AS A FUNCTION OF SPEED AT CONSTANT BEARING PRESSURE 884 PSI, FOR BEARINGS A, B, AND C, WITH READINGS TAKEN AT 45 C, USING LUBRICANTS NO. 1 AND NO. 4

| Rpm | Lubricant No. 1 | | | Lubricant No. 4 | | |
|---|---|---|---|---|---|---|
| | Bearing A | Bearing B | Bearing C | Bearing A | Bearing B | Bearing C |
| 1250 | 0.0218 | 0.0075 | 0.00160 | 0.0218 | 0.0075 | 0.0014 |
| 2140 | 0.0236 | 0.0106 | 0.00180 | 0.0180 | 0.0062 | 0.0011 |
| 2750 | 0.0247 | 0.0110 | 0.00240 | 0.0160 | 0.0051 | 0.0022 |
| 3875 | 0.0192 | 0.0089 | 0.00213 | 0.0089 | 0.0046 | 0.0019 |

contact between the irregularities of the bearing and the shaft.

### Time Required for the Bearings to Reach Temperature 50 C From 35 C at Constant Speed 2750 Rpm and Constant Pressure 1768 Psi

In the tests, it was observed that the temperature rise was rapid for relatively rough-finished bearings A and B, and slow for bearing C. For this reason it was decided to take readings of time required for the bearing to reach temperature 50 C from 35 C when room temperature was 23 C, at constant speed 2750 rpm and 1768 psi bearing pressure, using oil No. 4 as the lubricant. Volume of oil in the bearing reservoir was 22 cc in each case. Data obtained are given in Table 4. These data plotted surface of bearing finish versus time required to reach temperature 50 C from 35 C give Fig. 4. This graph indicates that the time required for the bearing to generate a certain amount of heat to increase the temperature of the oil bath in which the bearing is tested is a function of bearing finish.

TABLE 4 TIME IN MINUTES REQUIRED TO REACH TEMPERATURE 50 C FROM 35 C IN TESTS OF BEARINGS A, B, AND C UNDER CONSTANT LOAD 1768 PSI AT 2750 RPM USING 22 CC LUBRICANT NO. 4

| Bearing | Average bearing surface roughness, rms | Average journal surface roughness, rms | Time to reach 50 C |
|---|---|---|---|
| A | 22 | 42 | 2 |
| B | 15 | 27 | 10 |
| C | 8 | 10 | 37 |

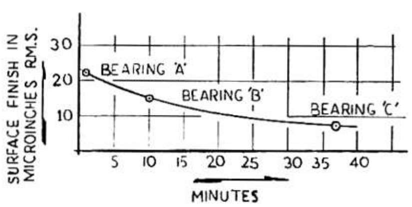


Fig. 4 Time in Minutes for Temperature to Rise From 35 C to 50 C at 1768 Psi and 2750 Rpm

### Conclusions

Test data given in Table 2 and curves in Fig. 1 indicate that for bearings made of cemented tungsten carbide with journals also made of the same material, at constant speed of 2750 rpm, using oil No. 4 as the lubricant, the coefficient of friction is nearly the same for the three bearings up to a bearing pressure of 500 psi regardless of surface finish, provided that the surfaces are reasonably smooth. Above 500 psi bearing A develops frictional losses at an accelerated rate due primarily to some metal-to-metal contacts between the irregularities of the bearing and the journal. Bearing C which has a fine finished surface develops the smallest frictional losses and these are nearly constant up to the highest pressure used in the test. Bearing B having a rougher surface finish than bearing C develops higher frictional losses than bearing C but not as high as bearing A.

The coefficient of friction of the three bearings plotted as a function of the operating variable $ZN/P$ shows a straight line for bearing C, while there is a reversal of the trend in the thin-film region for bearing A and B at approximate value of $ZN/P$ equals 60. In the thick-film region, the friction lines almost coincide, and for practical reasons can be considered to be the same.

As shown in Fig. 1, tests on bearing A were discontinued when the temperature of 115 C or 239 F was reached as it was assumed that this temperature was too high for operation of the bearings, using oil No. 4 as the lubricant.

Tests of cemented tungsten-carbide bearings at constant pressure 884 psi at variable speeds, taking readings at 45 C, indicate within the limits of this investigation a decrease in coefficient of friction for bearings with rougher than 10 microinches of finish and approximately constant coefficient of friction for bearing 8 to 10 microinches of finish. Fig. 3 also indicates the beneficial effect of the EP base additive on bearing performance particularly for bearings with rougher finish.

Tests of cemented tungsten-carbide bearings to determine the time required for the bearing to develop enough heat to raise 22 cc of oil No. 4 as the lubricant from 35 C to 50 C at constant speed and constant pressure is inversely proportional to bearing roughness.

## Discussion

E. M. Kipp.[6] The authors are to be congratulated for their contributions to a better understanding of the problems of friction and wear of bearing materials, particularly for the unorthodox combination which they have investigated. The use of bearing materials involving a shaft and journal of the same material is not common, and has been generally avoided because of the general rule that like materials are more apt to have poor bearing characteristics than are selected combinations of unlike materials.

We are somewhat concerned by the relatively wide spreads in the surface-finish values for the individual test specimens as presented in Table 1 of the paper. The spread in surface-finish data is such as to indicate a definite possibility that, for at least appreciable portions of the areas involved, the finishes of journals and bearings of the A-series could well have overlapped those of the B-series. It would be interesting to know whether the reported surface-finish values represent measurements made on an appreciable percentage of the total areas or whether they were confined to only a few such areas.

In the authors' discussion of the relationships between the effectiveness of extreme-pressure additives in the performance of the relatively coarsely finished bearings as compared to the smoother bearings, they suggest that the greater effectiveness of the extreme-pressure additives on the rougher surfaces is due to the lesser degree of metal-to-metal contact between the bearing and the shaft in the case of the rougher surfaces. It is implied that the "stronger" film of lubricant associated with the EP additives is more effective in preventing metal-to-metal contact in the rougher bearings.

We would like to suggest that a more fundamental explanation can be derived from the often-observed and well-known fact that as the surface finish of a bearing surface becomes smoother, it is possible to maintain full fluid lubrication with increasingly thinner oil films. Indeed, the curves of the authors' Fig. 2 clearly illustrate the shift of the minimum point in the $ZN/P$

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diagram to the left as the surface finishes of the bearing materials are made smoother. Therefore it is suggested that the existence of, or approach to, essentially full fluid lubrication in the bearings with the smoothest finish would tend to minimize the occurrence of unstable or boundary friction and hence would tend to minimize the effect of the extreme-pressure-type lubricants. The coarser bearing elements present conditions of boundary friction under which the extreme-pressure agents would be expected to be most noticeable in their effects.

The authors present valuable data to indicate that with suitable lubrication bearing elements of like materials and manufactured from hard materials such as cemented tungsten carbides may have attractive advantages. However, it would be interesting to know whether the authors have any data on the frictional properties of the cemented-tungsten-carbide bearing materials in the inadvertent or temporary absence of effective lubrication such as is bound to occur from time to time in most practical applications. This contingency, of course, is one of the reasons why most bearing assemblies involve the use of a softer material such as a babbit rubbing against a harder material. In the event of failure in such a case, more often than not only one of the bearing elements is damaged. We would be interested to know what would happen with the cemented-tungsten-carbide materials in such a case.

R. G. Moyer.[7] The authors are to be complimented on their pioneering work in the study of lubrication of cemented-tungsten-carbide bearings.

In the problem of lubrication of steel against steel, it has been theorized that sulphur, chlorine, and/or phosphorus in the EP lubricant react with the metal, under conditions of heavy loading, to produce films of sulphides, chlorides, and/or phosphides which preferentially rupture to protect the metal from damage. It is not easy to understand how the same theory may be applied to cemented tungsten-carbide bearings since the carbide is quite inert, but the authors indicate a substantial reduction in friction in some cases when EP base is added to the mineral oil. Is it possible that the EP additives react with the cobalt matrix in the cemented tungsten-carbide bearings or is the improvement due to the oiliness of the fatty material in the lubricant? If the former were true, one would expect eventual disintegration of the bearings. If the latter were true, equivalent performance might be expected from a mineral oil-fatty oil blend without EP additives.

Perhaps the authors have investigated a sufficient variety of lubricants to be in a position to advance a theory covering the action of EP lubricants on cemented-tungsten-carbide bearings.

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## Authors' Closure

The authors appreciate the effort and interest shown by Dr. Kipp and Mr. Moyer for their comments. We tend to narrow our field of vision as we become more engrossed with our own problem and it is through discussion that we again can attain the proper perspective to benefit the greatest number concerned.

Our problem began with the specific request for performance data on running similar materials as journal and bearing. It is true that dissimilar materials are usually selected for bearings; however, as mentioned, in the absence of specific data the experiment was carried out to determine some of the limitations involved.

Considerable time and effort were expended in the preparation of the bearing components, and values of surface finish are the results over appreciable areas. Perhaps the choice of the word "stronger" to explain the behavior of the EP additives was inadvertent. Some may say that there was full fluid lubrication, others a metallic sulphide and/or chloride having certain shear properties. We have tried to steer clear of these controversies. Fortunately we are able to use and take advantage of these desirable characteristics even though we are not able to explain precisely what takes place. In this connection it is difficult to believe that sufficient pressures are built up within a bearing, as has been described elsewhere, while both ends of the bearing itself are open and allow leakage. It is possible on the other hand that the pressure indications we observe may be due to the inertia effect of the moving liquid similar to the velocity pressure of air in respect to the static pressure. Thus far we have not attempted to destroy the bearing, either by lack of lubrication or by loading, until additional data for a third paper has been completed. In that event perhaps we can shed some light as to what happens because of lubrication failure or whether the EP additives react with the cobalt matrix as Mr. Moyer suggests.