Bearing Design and Failure

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IN THE broadest sense of the term, a bearing is any structural member of a machine that is so designed as to convert dry, wearing friction into wearless, fluid friction. The relative motion of the parts may involve a plain sliding motion (cross head, cylinder and piston) or an oscillatory motion (piston pin and bushing, spring shackle) or a rotating motion (crankshaft and connecting rod bearings). The member in which rotational or oscillatory motion is involved may be either a plain or sleeve bearing, or an anti-friction bearing. The purpose of this discussion is to consider some of the factors involved in the design of certain types of plain bearings.

Plain bearings consist of two units, the bearing proper, and the journal or axle. The bearing surface may be made of any one of a variety of materials, such as wood, plastics, cast iron, bronze, silver, alloys of lead, alloys of tin, etc. The alloys of lead or tin which are employed in bearings are commonly referred to as the soft bearing metals. The present discussion will be limited to this type of bearing material. Such a bearing usually consists of a highly rigid shell and a lining which is supposed to permit a certain amount of plastic flow and "embeddability" of dirt particles.

LUBRICATION

In order to convert dry friction to fluid friction, a lubricant is required for the proper operation of the bearing. The lubricant, preferably a moderately compressible and viscous fluid, supplies a complete fluid film between the journal and bearing. If some means could be provided to prevent the escape of the lubricant, any fluid, even air, probably would serve the purpose.

With regard to bearing performance, the principle of fluid lubrication is illustrated in *Fig. No. 1.* The bearing has a certain clearance with respect to the journal (greatly exaggerated in the sketch). On starting, the journal pumps the lubricant under itself and builds up a pressure which lifts the journal from the bearing. The escape of the lubricant is retarded by its viscosity. Higher viscosity, longer bearing, and smaller clearance act to decrease the escaping tendency. These variables are three of the factors to be considered in the design of bearings. With less lubricant escape the shaded peak shown in *Fig. No. 1* will be higher and the load capacity of the bearing will be increased. However, if the greater pressure is produced by higher viscosity, greater frictional heat may be developed which must be carried away by the journal, the bearing, and the flow of the lubricant.

It may be estimated from *Fig. No. 1* that the pressure established is far in excess of the feed pressure. It is obvious that the lubricant must not be fed into the area of high pressure from the lower pressure feed line, as this would decrease the pressure necessary for proper bearing operation. This presents another design factor which must be considered.

GROOVES AND DIMENSIONS

The dimensional characteristics of the bearing itself will play an important part in the operation of the bearing assembly. Oil grooves commonly employed in bearings present another factor to be considered in design. The effect of an oil groove placed in the high-pressure area of a bearing is shown in *Fig. No. 2.* The dashed curve indicates the pressure distribution when the groove is absent. The effect is to reduce the pressure to about that of the feed, and to prevent the unit from building up normal load capacity. On the other hand, some advantage may be derived from placing an oil distributory groove in the low-pressure area for a portion of the bearing length. Any grooving that crosses the high-pressure area is objectionable, except in those rare cases when fluid lubrication may be impossible under the particular operating conditions.

In general, circumferential oil grooves are objectionable, even though they may be the cheapest way of feed-

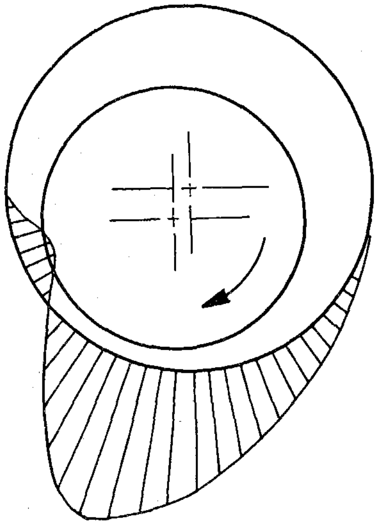


FIG. 1. Pressure distribution (shaded area) in lubricant film of plain bearing.

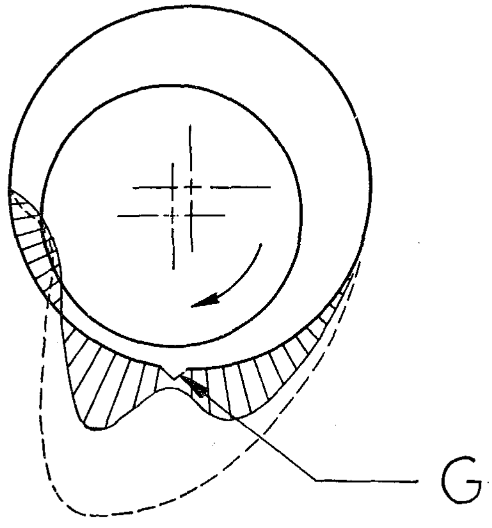


FIG. 2. Pressure distribution (shaded area) in lubricant film of plain bearing containing axial groove G.

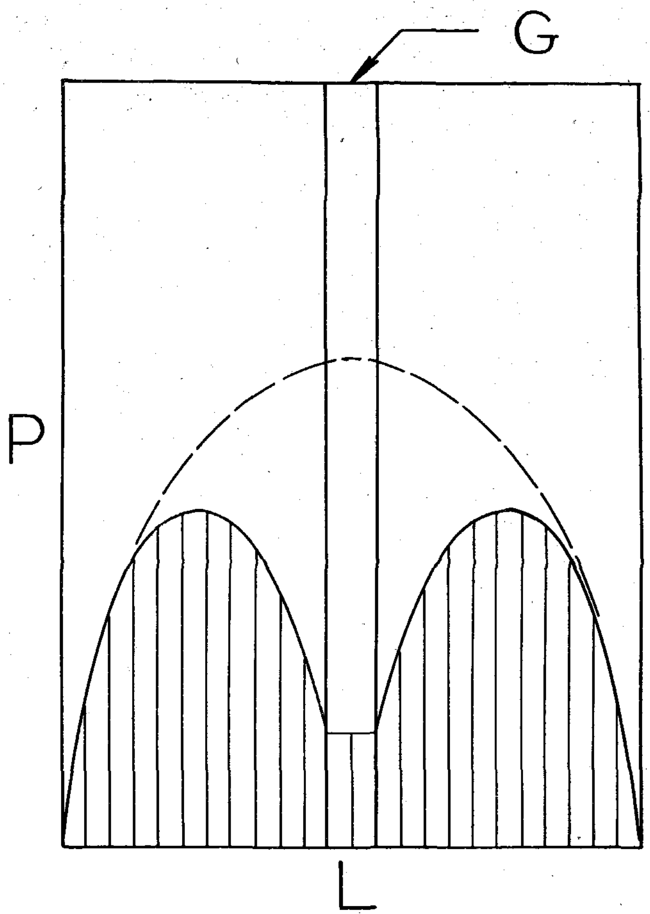


FIG. 3. Variation of oil film pressure *P* along the length *L* of a plain bearing due to its finite length. Pressure at ends equal to atmospheric pressure. Dashed curve outlines additional area without groove.

ing oil to the connecting rod bearings. *Fig. No. 3* illustrates the effect of such a groove on the pressure distribution along the length of a bearing. The dashed curve is the normal distribution, while the shaded area is the distribution which may be expected in the presence of the groove "G."

The basic factors in the design of a bearing are its dimensions and the oil viscosity. The dimensions refer to size, proportions, and clearance, which are usually the objects of compromise. The size and proportions may be dictated by available space and weight limitations, as in aircraft and automotive engines. The flexure of the shaft which passes through the bearing and the limits of accuracy in alignment are of great importance in modifying the ideal design. A misaligned journal leads to an axial pumping action. A small clearance is conducive to high load capacity, restricting oil escape, but it impairs oil flow and cooling as well as the beneficial damping effect of an otherwise thick oil film.

FACTORS LEADING TO FAILURE

Considering the factors of design and operation: What is a bearing failure and what is its course? Experience leads to the conclusion that the answer must be partly a result of speculation because the information is derived from postmortems and it is not possible to check all the factors which may have contributed to a particular failure. Discarding cases of gross neglect in operation and accidents, bearings fail by excessive wear and by fracture; both may be interconnected. A properly designed bearing with fluid lubrication should last forever, its whole projected area being hydrostatically loaded. Accidental or operational shocks are well damped by a thick oil film; surface asperities are small in comparison with the film thickness.

In case of accidental or occasional wear of the bearing surface or excessive temperature, or both, the clearance becomes greater or the oil becomes thinner and more oil escapes, thus decreasing the oil film thickness. Finally the oil film may become so thin that interlocking of the irregularities of the journal and bearing takes place, producing more wear and greater escape of oil and further deterioration of the bearing. Under these conditions any shocks or natural vibrations of the system are less damped and are taken up directly by a few points of contact. Under proper conditions these shocks are taken up by the hydrostatic pressure of the whole bearing. In the end the lining cracks, permitting pieces to fall out so that they become wedged between the moving parts, thus accelerating the destruction of the bearing. This is just one typical course of events.

In most cases of bearing failures inadequate or improper appraisal of operating conditions leads to inadequate bearing design, which in turn results in impaired lubrication and failure of the bearing. Thus, usually a bearing failure is ultimately a lubrication failure for which either design or operation or both are responsible.

While some failures occur because of failure of lubrication, this discussion will be concerned with the failure of reasonably well lubricated bearings. Referring to *Fig. No. 3,* if the designer computed the load capacity of the bearing on the basis of the ungrooved bearing and subsequently put in the groove, the bearing would be underdimensioned and shorter-lived. The effect is to replace the full-sized bearing with a twinned narrower one, with increased axial oil seepage. Great difficulties also are encountered in cases where the load on the bearing continuously changes its direction, as in connecting rod bearings, where the low-pressure area is not as large as in ordinary main bearings. Another source of difficulty lies in the flexure of journals and bearing shells. Such factors, combined with warranted or unwarranted compromises due to legitimate or illegitimate ignorance or neglect, are the main sources of bearing failures.

METALLURGICAL CONSIDERATIONS

There is no similarity between a small bearing such as is used in an automotive engine and a bearing 15 x 15 inches in dimensions, when made of the same alloy.

The conditions of solidification of the alloy which is poured in or onto the shell are different for the two cases because of the difference of the heat capacities of the shells. The grains in the alloy in the lining of the large bearing will be very much larger than those in the small bearing. Furthermore, the more or less inherently brittle intercrystalline substance is much more concentrated in the large bearing. There will also be a marked difference in the mixture ratio of the structural constituents in the two cases. Pouring and cooling conditions and workshop practice will produce marked differences in size and orientation of the grains in the alloy.

Consider the quality of the bond between the lining and the shell and the cooling of the lining with respect to internal stress. A smoothly machined bearing does not remain smooth at operating temperatures, because the structural constituents in the alloy do not expand uni-

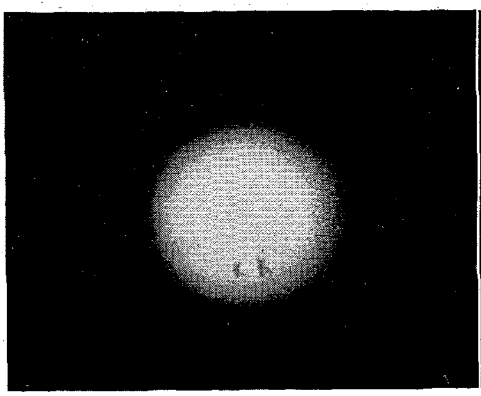


FIG. 4. Reflection image of polished tin babbitt specimen at 25 degrees C., surface smooth (actual size).

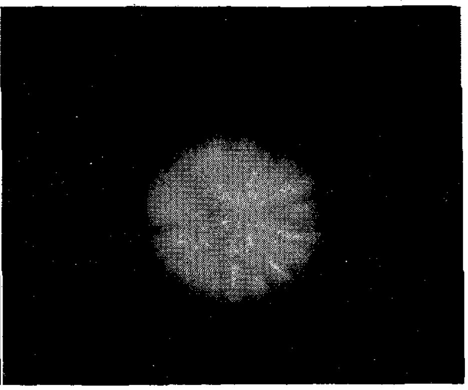


FIG. 5. Reflection image of polished tin babbitt specimen at 150 degrees C., surface irregular from anisotropic thermal expansion of crystallites (actual size).

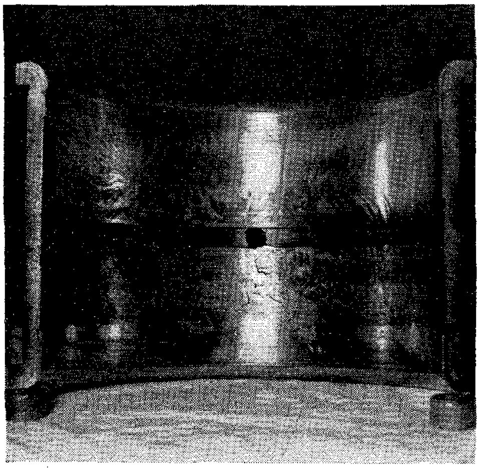
formly. As a matter of fact, the soft metals which practice considers indispensable for "matrices" of bearing alloys are those metals which have the highest thermal expansion. Thus, in the copper-lead alloy, widely used in Diesel and airplane engines, the lead expands almost twice as much as the copper and the shaft is supported solely by the soft lead and not by the copper under conditions of non-fluid lubrication. This is just the contrary of what the time-honored "bearing metal theory" maintains.

The constituents of the tin base alloys, the basis of "babbitt metals," are so anisotropic that the alloy composed of randomly oriented grains expands non-uniformly. Therefore, while the surface may be smooth at room temperature, it becomes quite irregular at higher temperatures because of the difference in expansion of the grains in different directions. This effect is illustrated in *Figs. No. 4 and 5* by the reflection images of a polished specimen of babbitt metal. The surface condition at room temperature is shown in *Fig. No. 4* and at 150 degrees C. in *Fig. No. 5.* The whole crystalline structure appears in bold relief on being heated and again becomes smooth when cooled to room temperature.

Recrystallization also plays a part in the performance of these materials. Letters were engraved into a babbitt metal specimen and then polished off until they entirely disappeared. Within a few days they reappeared because of recrystallization due to the cold working by engraving. The reappearance of the recrystallized area is shown in *Fig. No. 4.* This demonstrates the change in structure which may occur in these materials with cold work.

Not only may recrystallization occur, but also there may occur intercrystalline precipitation and diffusion. This takes place by virtue of the fact that as the alloy is cast it is not in a state of equilibrium. The precipitation and diffusion is the result of a tendency of the alloy to assume equilibrium conditions.

These changes in structure are more pronounced at operating temperatures which may double the rate for each 10-degree C. rise in temperature. *Fig. No 6* is a photograph of a large gas engine bearing of about 10 inches in diameter. It will be observed that a piece of the lining has fallen out and that several cracks appear on the surface of the bearing. The bright cloudy areas which take the shape of feathers and Arabian script and the cracks follow the grain boundaries of the alloy. The machining marks are barely visible in some areas between the bright clouds in the photograph. This condition is more clearly shown by visual examination of the bearing. The mechanism by which this appearance was produced may be outlined as follows: Under the shock loads to which the bearing was subjected the oil film became very thin; in time the high operating temperature facilitated the precipitation of the brittle compound *Sb-Sn* from the unstable *Sn-Sb* solid solution. The precipitate diffused to the grain boundaries and, because of its higher specific volume, formed raised ridges on which the shock loads were carried. The compound of which these ridges are composed is relatively brittle and thus with the shock loads, cracking is almost inevitable. With



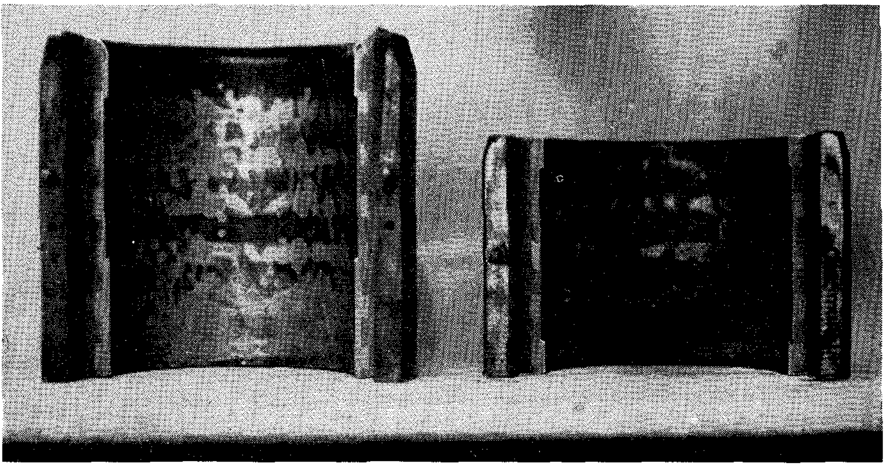


FIG. 6. Cracked bearing showing crystal structure due to intracrystalline precipitation and volume expansion.
FIG. 7. (Two views on right) Effect of dovetails on bearing performance due to greater expansion at dovetails (bright circumferential zones).

the load being carried on these protruding ridges, forming an area roughly 30 per cent of the intended area, the bearing was severely overloaded.

THERMAL EXPANSION

The non-uniform thermal expansion of the lining alloy may constitute an asset, even though the old concept of bearing operation would indicate otherwise. Under conditions in which an ideally smooth surface would only permit the maintenance of an extremely thin oil film, perhaps of molecular dimensions, a wavy and otherwise irregular surface may retain small pools of lubricant sufficient to maintain fluid lubrication to a greater extent. The duplex structure of a bearing alloy may constitute a safety factor rather than an indispensable requirement. In neglecting the benefits derived by non-uniform expansion the engine builder unwittingly sacrifices load carrying capacity. However, the different thermal expansion produces internal stresses within the lining which reduce fatigue life. It is therefore not surprising that modern aircraft engine bearings lined with pure silver have given excellent service, since they were designed with proper clearance and provided with a thin lead coating which lowers the occasional non-fluid friction. In this case the operating temperature is kept down and excessive growth of the lining which decreases clearance is prevented. An excess of growth would throttle down the oil flow, permit rise of temperature and eventual seizure of the shaft.

These phenomena are illustrated in *Fig. No. 7.* Here are two large compressor bearings in which the lining is anchored to the shell by circumferential dovetails. The lining is about twice as thick at the dovetails as at other places. It is clearly impossible to maintain proper clearance in the bearing unless the operating temperature corresponds to that at which the bearing was machined. In operation the temperature was higher and therefore the lining bulged at the dovetails to such an extent that the clearance between journal and bearing was decreased in these circumferential areas. Eventually there was space for only a very thin oil film which carried the whole load, while the spaces between the dovetails acted as wide shallow circumferential grooves. In this case actual seizure of the shaft and outright melting of the babbitt did not occur, because of the plastic flow of the babbitt and comparatively favorable operating conditions.

PRINCIPLES FOR DEVELOPMENT

Once the chain of events has been recognized—duplex structure (or anisotropic metal), uneven expansion, reduced area, overloading, cracking—the inherent limitations of the current bearing alloys become evident and the principles for a rational development of bearing alloys toward longer service appear clear. These principles, the outcome of research at the California Institute of Technology, involve the field of physicochemical analysis in engineering, analogous to previous physicochemical analysis of lubrication.

Accident Prevention

(*Continued from Page* 10)

MANPOWER CONSERVATION

In connection with safety prevention, and keeping the man on the job, recognition of manpower figures which indicate present-day demands are worth reviewing. This information could not be given by any better authority than that of Lawrence A. Appley, executive director of the War Manpower Commission. In the September issue of *Engineering and Science Monthly* he stated that "There are 22,000,000 men between the ages of 18 and 37 inclusive registered by Selective Service Boards. This includes all men regardless of physical, military, or occupational status. Approximately 14,000,000 of these men can meet the physical requirements for military service.

"The armed forces will require 10,800,000 of this 14,000,000 by the end of 1943. That leaves us a balance of 3,200,000. *Of this number 1,500,000 will be deferred for agriculture.*

"By simple arithmetic we now have 1,700,000 left for non-agricultural deferment. While that is more than are now occupationally deferred it must be realized that there are many men who have been deferred for dependency who, if they were not so deferred, would be for occupation.

"Before we jump to the conclusion that there are a possible 1,700,000 deferments of able-bodied men for non-agricultural occupations, we must realize that none of the above figures provides for any replacement which will be needed to maintain the armed forces at 10,800,000. That need will be determined by the human cost of the military campaigns that are ahead of us. Neither do they provide for personal hardship cases.

"This manpower arithmetic is another one of the 'dynamic factors' which influence the handling of the manpower problem."

In view of these figures one may ask, "What is industry doing to conserve and preserve manpower in this time of direct need?" It appears that not enough is being done in this direction. One of the most destructive attacks made on this nation last year was not made by a foreign enemy but by accidents. These accidents left 93,000 dead, 350,000 permanently disabled, 9,000,000 lesser casualties, and 450,000,000 man days of lost production. Putting it in a different way, the national economic loss was $5,200,000,000. It cost as many productive man days as would be required to build 72 battleships. All this destruction, this delay, this waste of manpower and materials was caused by accidents. Even though we recognize the seriousness of these figures, accidents are increasing. *Accidental industrial deaths increased five* per cent in 1942 over 1941. Approximately 200,000 more accidental injuries occurred last year than during the preceding year. There was a rise of 10 per cent in the number of man days lost to industry. In 12 states, deaths from occupational accidents showed increases ranging from 25 to 77 per cent.

With millions of employees being shifted into strange new jobs, with other millions of new untrained workers being drawn into plants, working under terrific pressure and at top speed, and with the strains of dislocations of wartime conditions multiplying hazards to life and property throughout the country, the accident toll will continue to increase, and certainly will not decrease until adequate preventive measures are taken.

The fact that off-the-job accidents far exceed the number and severity of occupational accidents must not be overlooked. It might be concluded that industry cannot control or influence off-the-job accidents in view of these figures, but such is not the case, for plants which have reduced work accidents have at the same time greatly reduced off-the-job accidents among their employees. This fact tends to substantiate the claim that accident prevention is mainly accomplished through education, training, and executive order. Therefore, one must accept the axiom that safety is a responsibility of management.

If really good practice in the elimination of preventable accidents is to be reached and held in any establishment, the top management must accept full and definite re-