DISCUSSION

W. M. Needelman[1]

By obtaining data under controlled conditions which for the first time give estimates of the relations between ball bearing wear and a number of lubricant contamination levels, the authors are to be commended. In actual operating recirculating lube systems, the particle contamination tends to stabilize at relatively constant levels for most of the system operating time. This level is strongly dependent on the type of filtration present in the system. It is also dependent on other factors, such as the system flow rate and the rate of contaminant particle introduction into the lubricant (including from wearing component surfaces and from the surrounding environment). The important relationships that need to be evaluated are between bearing wear and the level of lubricant contamination in which the bearing is operating.

The weight loss of suspended test bearings is an important example of a "progressive performance deterioration" of a component [21]. This class of failures is characterized by a continuous loss of component performance with a continuous attrition of surface material during operation. It is interesting to note that for the set of bearings studied, the rate of weight loss of operating (unfailed) bearings increased with the increase in the number of particles greater than 15 micrometers in Test Series I through V (the authors' Table 5). Thus the wear mechanism leading to bearing weight loss in this study appears to be abrasive wear by particles greater than 15 micrometers.

On the other hand, bearing fatigue life is a form of "cumulative performance deterioration." This group of component failures is characterized by a negligible loss of component performance over an extended period of operation, followed by a phase of rapid decline leading to failure. It is likely that in these modes of failure surface defects accumulate until a critical level is reached, followed by a gross and rapid loss of surface material. Recent evidence has indicated that in ball bearing fatigue failures, particles smaller than 5 micrometers make a major contribution by producing many of these surface defects [22]. This is not surprising since we frequently observe in actual field operation that the number of particles smaller than 5 micrometers is orders of magnitude greater than the sum of contaminant particles greater than 5 micrometers. The particles greater than 5 micrometers in size may have only a small influence on the fatigue life, and may be considered only a tailing off of the effect produced by the great number of smaller particles.

Unfortunately, it is believed that the differences in the concentration of these smaller particles, resulting from using different types of filters, was significantly less in the study than is found in field applications. There are a number of reasons for this:

1. The flow density (the liquid flow in gallons per minute divided by the filtration medium area in square feet) of 0.1 that existed during this study is much lower than flow densities of 10–30 typically found in operating systems, where constraints of size and weight dictate higher flows through smaller assemblies. Possible filtration mechanisms at a low flow density, such as particle removal by settling, filter cake formation, and adsorption, differ greatly from mechanisms occurring at higher flow densities. Laboratory [23] and field experience at higher flow densities and with continuous injection of particle contaminant, using the type of filtration present in Tests II and III, have shown that the use of the finer filter can reduce the number of particles by a factor of 100 as compared to the coarser filter.
2. The method of particle contaminant introduction used in this study was slugging in an aliquot of contamination every 10 minutes. Due to recirculation through the filter, the initially high contamination levels seen by the test bearings at the beginning of this interval would be expected to exponentially decay over the 10 minute period. Under the unusually low flow density conditions of the study, differently rated filters could clean the lubricant to nearly the same cleanliness level by the end of the 10 minute interval. This effect would be corrected by continuously injecting a well mixed slurry of contaminant, which would produce a steady-state lubricant contamination level more typical of operating systems. Then the bearing wear as a function of the lubricant contamination level in which the bearing is operating would be more readily measured.
3. According to the widely used contamination classification system of document NAS 1638, the contamination levels of Tests I–IV varied from Class 8 to about Class II. On the other hand, while some systems do operate at Class 11 and even Class 12, particle contamination control technology exists and in some instances has been applied to reduced operating contamination levels to Class 6 and better. Studies in which comparably large decreases in particle contamination levels have been accomplished have qualitatively shown large differences in the condition of bearing surfaces [24].

It therefore appears that the contribution to abrasive removal of bearing material by particles greater than 15 micrometers was observed. However, the contribution of smaller particles to the competing rolling contact fatigue mode was not as clearly measured. This was due in part to test conditions which did not produce the large differences in the concentration of small particles found to occur during field operation of lube systems when using different levels of filtration.

It is believed that future study on the relationships between lubricant particle contamination and bearing wear, and in particular on fatigue life, should incorporate the following recommendations in order to more closely simulate the variety of operating conditions found in the field.

1. Use flow densities of 10–30 (gallons per minute per square foot filtration area) through the filters of the test apparatus.
2. Constantly inject a well mixed suspension of test contaminant particles throughout each test.
3. Study wear over a wide range of contamination levels, especially in the direction of cleaner systems.
4. Measure the concentration of particles down to 0.1 micrometer in size (or to the size of the minimum film thickness of the contact region).

Additional References

21 Needelman, W. M., "Relations Between Fluid Particulate Contamination and Component Wear and Performance" *Proceedings of the First International Conference on the Fundamentals of Tribology,* June, 1978.

22 Dalal, et al. "Final Report on Progression of Surface Damage in Rolling Contact Fatigue", U.S. Navy Contract No. N00014-73-C-0461, 1974.

23 ANSI Specification B93.31—1973, Multi-Pass Method for Evaluating the Filtration Performance of a Fine Hydraulic Fluid Power Filter Element.

24 Final Report, Product Improvement Program Item 0012 Increased Service Life Sub-Item 0012A0 Transmission 3-Micron Filter, 7/72. Hughes Tool Company—Aircraft Division.

D. Lubrano[2]

An increasing awareness to contamination of lubricating oil systems has come about in the past few years with little understanding of the affects on component life and how to minimize them. A pragmatic approach such as the authors have taken was needed to define these efforts. To the best of the discusser's knowledge, the authors are the first researchers to gather quantitative data on the effects various levels of filtration can have on ball bearing life and condition in the contaminated lubricant.

The discusser has had a field evaluation underway for over two years to determine if the laboratory benefits addressed by the authors can be truly achieved in the field. Analytical teardown analysis of

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helicopter turbine engines operating with 3 micron absolute filtration clearly indicate the beneficial results of fine filtration obtained by the authors can be obtained under field conditions. For example, the analysis of an engine that was removed for a suspected bearing failure, which had operated for approximately 1000 hours with 3 micron absolute filtration, revealed that the engine had experienced extremely light wear. In addition, there was absolutely no secondary damage from the bearing failure that was present. This is in contrast to the normal occurrence of secondary damage leading to increased overhaul cost.

T. E. Tallian[3]

This discussion addresses the applicability of a theory of contaminant effects on life, proposed by the discussor (8), to the experimental results of the authors.

Qualitatively, applicability appears confirmed. The authors' test Series IV clearly shows shorter life than Series I and II. The contamination levels in the effluent lubricant, shown in Table 5 are clearly greater for Group IV than for I and II, when one considers particle sizes of 30 μm or less, which dominate in number. The SEM appearance of the ring surfaces shown in Fig. 3 shows dense debris denting for Group IV, none for Group I and a moderate level for Group II. Therefore, debris denting seems to follow lubricant contamination and life follows denting.

Also in accordance with theory is the increase in Weibull slope for the contaminated tests. Progressive denting should cause such an increase. It is embarrassing that the discussor's own test results (6) have failed to show this effect. However, the authors' good control of lubricant contamination levels with the test duration very likely provided for a more uniform dent accumulation rate than in (6) and this may explain the increased slopes in the authors' contaminated tests.

From the theorist's point of view, one regrets the omission of repeated SEM photos of the surfaces at various points in time during testing. If a history of dent accumulation were available, one could undertake a dent sizing and counting effort and then details of the theory could be checked, such as whether linear or quadratic damage accumulation models apply and whether the degree of life shortening corresponds to the degree of denting as predicted by the model.

A few interesting details can be highlighted as follows.

The SEM photos in Fig. 3 are quite revealing. They show significant levels of denting for *all* contaminated lubricants. Thus it is not surprising that loss of life (at high life quantiles) occurs already for Series II, inspite of a very fine filter. The count of 5–15 μm diameter particles in Series II is also much higher than in Series I, i.e. the filter cut-off was not "absolute" at 3 μm. The relatively small but numerous particles in the 5–15 μm category control denting, as seen in the SEM and apparently influence life.

Group III still shows areas of undented surface, but Group IV does not. It is saturated with dents. Thus, it is understandable that life declines progressively from Group I to Group IV.

The wear failures of Group V occurred in the presence of the only dramatic increase in *large* particles in the oil. The screen filter used allowed many more particles of all sizes to circulate, than any of the fiber filters. Thus massive abrasive wear set in, changing the failure mode. From the results, it appears that wire screen filters cannot prevent massive contamination of the lubricant and resultant wear failures.

Depth filters (e.g. fiber filters) are shown quite effective in keeping most of the contamination out and can prevent early catastrophic failure. When very fine, they succeed in reducing even the fine, 5–15 μm contaminants to the point where their influence on fatigue life is *moderated.* They do *not* prevent the ill-effects of contamination on life altogether. Thus, it appears that filtration alone is an unhappy answer to a dirty oil system.

One question this discussor finds puzzling is the disposition of the enormous amounts of contaminant that must have accumulated on the filters. In 800 test hours, *50* teaspoons of contaminant per bearing or a total of 400 teaspoons could have accumulated. It seems amazing that the filter continued to function!

Authors' Closure

The authors thank Messrs. Needelman, Lubrano, and Tallian for their comments and observations.

Mr. Needelman expresses concern that the bearing fatigue life differences observed in this study with changes in filtration level may not be as large as that anticipated in field applications. He attributes this to a relatively small variation in the concentration of small particles, less than 5 microns in size, with filter size compared to field experience. He contends that it is these sub-5 micron debris particles which dominate the surface fatigue process.

The accelerated contaminated lubricant conditions used in our tests may differ quantitatively from those in the field. However, it is unlikely that differences in the concentration of sub-5 micron particles had much of an effect on test bearing fatigue life.

The authors view the effects that particle size has on bearing fatigue life and wear in a far different way than Mr. Needelman. In the case of bearing wear, there is little question that all things being equal, a large particle, e.g., greater than 15 microns, will cause more surface distress than one that is smaller. However, it should be emphasized that the vast majority of particles smaller than 15 microns found in the test lubricant are still many times larger than the calculated elastohydrodynamic minimum film thickness of 0.38 microns. This, coupled with the observation that the sub-15 micron particles are a couple of orders of magnitude more numerous, strongly suggests that they are as important, if not more so, to the wear process.

The role played by small sub-5 micron size particles on surface fatigue initiation is not well understood. The authors were unable to find the "recent evidence" cited by Mr. Needelman in [22] which establishes that particles smaller than 5 micron in diameter make a significant contribution to bearing fatigue failure. In these bearing tests [22] no naturally generated sub-surface or debris related fatigue failures were obtained, due to the exceptionally clean nature of the lubrication system. All five bearing fatigue failures were artificially

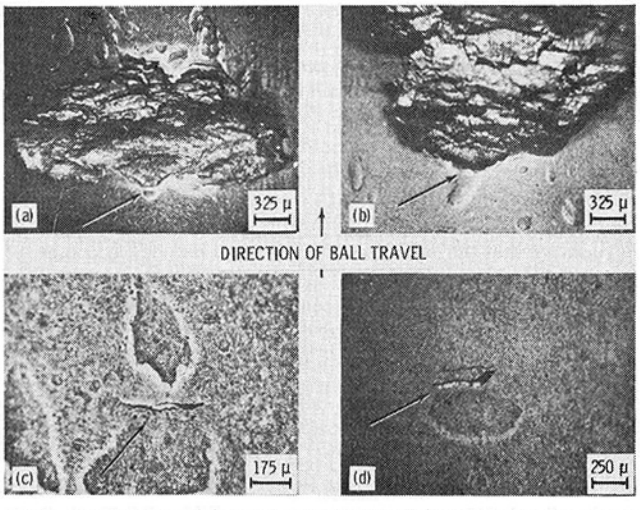

Fig. 5 Spalls (a) and (b) and prespall cracking (c) and (d) at surface dents. (Arrows indicate spall formation at trailing edge of dents.)

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induced by indenting the bearing inner race with either a Rockwell C or Vickers hardness indentor.

Although the number of debris dents undoubtedly contributes to the probability of spall initiation, the far more dominant effect, in our opinion, is the severity of the defect, that is, its size and depth. This view is evidently shared by Tallian [6], among others, whose "extreme value" type of contaminated lubricant fatigue model is predicted on the basis that the larger dents determine survival probabilities. Wedeven's optical EHD experiments [25] indicate that large dents substantially modify the EHD pressure profile which contributes to the stress concentration acting at the trailing edge of the dent. It is not uncommon to find bearing spalls emminating from the trailing edge of very large debris dents as illustrated in Fig. 5 taken from tests reported by Parker [26]. Thus, it can be concluded that it is unlikely that the small variation in the number of small particles, had much to do with unexpectedly small differences in fatigue lives of bearings tested with various size filters.

Another explanation for the relatively small differences in fatigue life with filter size is the influence that raceway wear may have on the fatigue process. It is probable that the gradual wearing away of the raceway surface, which increase progressively with coarser filtration, may delay the fatigue process. In simple terms, the wear process is physically removing some of the material at, or slightly below the bearing surface which is in the process of fatiguing, thereby exposing new material to the cyclic stresses. In addition, the wear process is also removing or smoothing over some of the potential spall initiating debris dents. This evident from the SEM photos of Fig. 3 where the well defined dents appearing on the surface of a bearing tested with 3 micron filtration become worn down to a more uniform textured surface on bearings tested with coarser filters. If the bearing race wear was the same or a greater rate than the rate of fatiguing then fatigue failure could, in principle, be indefinitely postponed. This is probably why no fatigue failures occurred on the 105 micron filter test bearings after 448 hours of testing. This absence of spalling is in contrast with bearings tested with 49 micron filtration in contaminated oil where 8 bearings fatigue failures occurred prior to 448 test hours. The implication of this, is that the accelerated wear process occurring in these tests relative to field service may have significantly narrowed the expected fatigue life variation obtained with filtration level. It is therefore conceivable that greater life differences than those demonstrated in this study could be expected in field application. Of course, purposely inducing bearing wear to postpone fatigue will lead to other problems.

Our test results do show a qualitative agreement with Mr. Tallian's theoretical Weibull slope variation, as we have already indicated. However, less confirmation exists with regard to the theoretical, detrimental effects that the level of contamination has on the bearing fatigue life. This may be due in part to the masking effects that wear may have on the fatigue process as previously discussed.

The riveted cage construction of our test bearings did not permit intermittent inspections of the bearing raceway surfaces. Hence, we could not keep a record of the dent accumulation rate.

In response to Tallian's comment that "the filter cut-off was not absolute at 3 microns." The particle count readings appearing in Table 5 can be somewhat misleading if taken in an absolute sense. These samples were taken downstream of the test bearings with an automatic sampling device installed at a point in the return line between the scavange pump and the sump. Consequently, the particle count readings include some secondary wear debris particles from the bearings and the scavange pump. This is why the particle count reading for test series II gave the impression that the 3 micron absolute filter was not "absolute" in removing the larger particles. Calibration tests conducted after the completion of this investigation with an electronic particle counter installed directly downstream of the test filter did verify that the filter element was essentially 100% efficient in capturing particles larger than its absolute removal rating.

Finally, with regard to Mr. Tallian's comment on the disposition of contaminants, the test filters had sufficient dirt capacity for an entire test sequence without the differential filter pressure ever reaching the clogging level.

Additional References

25 Wedeven, L. D., "Influence of Debris Dents on EHD Lubricating," *ASLE Trans.*, Vol. 21, No. 1, 1977, pp. 41–52.

26 Parker, R. J., "Correlation of Magnetic Perturbation Inspection Data with Rolling Element Bearing Fatigue Results," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 97, No. 2, Apr. 1975, pp. 151–158.