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**DISCUSSION**

P. B. Macpherson

A considerable amount of interest is currently being displayed in machinery filtration and this particularly applies to the Aerospace industry. It now seems generally to be accepted that worthwhile bonuses in improved reliability and overhaul lives are to be attained through the introduction of finer filtration. How fine depends upon surface roughness characteristics and thickness of oil film generated within lubricated contacts, because these, combined with debris size, govern rolling fatigue life in the present context. The paper provides further information to add to all too scanty a collection and, for this reason alone, the paper is particularly welcome.

To the discusser, the only unexpected result is the relatively large increase in B_{90} life between 49 and 30 /μm filter ratings when used with contaminated oil. It is not immediately obvious why this should be so. Previous work has suggested that changes in surface roughness dominate over other features such as pressure relaxation and localised increase in contact stress. In the present case surface roughness considerations alone would suggest a B_{90} life of about 630 hours as against 875 hours realised. Could it be that other considerations predominate in this instance? This is typical of the many questions that have to be answered before we can tackle seriously the important task of applying surface finishing techniques that are likely to minimise the generation of damaging sized debris. Comments by the authors would be helpful.

The lower limit of acceptable debris size is that which will pass through a contact without causing damage. The contact itself can be regarded as a filter and, in that context, an elementary model would be based on the maximum gap between surfaces when deep valleys in each surface coincide. A Gaussian topography would give a maximum local film of approximately 6 standard deviations of the composite roughness plus the e.h.d. film thickness. Applying this concept to the present results would suggest that filtering down to 1 /μm absolute rating would be beneficial. The trend in results for 3 /μm rating between ultra clean and contaminated oil tend to suggest that this would be so. Further work using finer filtration would be a useful extension to the present work.

In any work associated with particle size a problem arises over definition. There appear to be some 18 different definitions of particle size currently in use. Bearing wear particles mostly seem to be of platelet form and clearly, in this class of work, morphology is extremely important. A comment on shapes of particles used and how they compare with bearing wear particles and filter calibration particles would be informative.

It seems probable that small particles that form sharp edged indentations could be more damaging than many of the large particles. Are the authors able to form any judgement from post test examinations available on sizes below 5 /μm?

No matter how efficient a filtration system may be it cannot cater for the first pass of debris. Much debris is generated by the bearings themselves, especially during the early stages of running and this will tend to pass through the contacts before being filtered out. The authors very rightly draw attention to this problem. There would appear to be little point in the bearing manufacturers having expended so much effort and money on improving metal cleanliness when debris indentations can be every bit as damaging as the presence of nonmetallic inclusions. Does the authors’ work throw any light on the relative damaging potential of these two aspects?

As a concluding comment the discusser would like to congratulate the authors on their presentation and especially for having stated so clearly that a certain amount of debris was equivalent to a “level teaspoonful.” How refreshing it is today to be able to recognize a measurement so readily.

T. E. Tallian

The authors’ data on lubricant contamination versus rolling bearing life are most useful. Reliable information on contamination effects is scarce and the authors’ tests are well organized, well defined, and careful.

The ultra-clean test series is probably the most exacting of its kind reported to date. This discusser described a very clean test series in (8) but it did not achieve the level of cleanness of the author’s “Ultra-Clean” series.

The following comments apply to the life results.

1. The life degradation is relatively modest for all groups in Table 5. Life reductions of comparable order were observed in (8) as a result of contamination. A more severe life reduction was noted there only when lubrication became inadequate leading to surface distress microcracking. A similar situation probably existed in the author’s series with centrifugal filter and contaminated lubricant.

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2 Vice-President, Technology Services, SKF Industries, Inc., King of Prussia, Pa. 19406.
(2) One could conclude from the results that the benefit
from ultra-clean operating conditions is not very great. A
"reasonably" clean operating environment such as that in
the "baseline" series seems sufficient for good bearing life and
the bearing appears quite tolerant to contamination, even
beyond this "reasonably clean" level.

(3) The author's observation of surface damage in the
ultra-clean tests, and its interpretation as arising from self-
generated debris, raises the question whether the test bearings
were optimally designed for an ultra-clean environment.
ABEC 3 bearing rings are not necessarily ground on all
surfaces and metal cages can have sharp edges and burrs.
However, aircraft quality bearings are available with all
surfaces ground and all edges broken; and cages with all edges
carefully broken and deburred can be made. One could also
use polymer cages, which are by no means debris-free, but the
debris are soft. Finally, there are unusual bearing designs with
spacer balls instead of a cage. It may be interesting to attempt
further improvements of cleanliness in this direction.

(4) The very high Weibull slopes in all but one test are
remarkable. They are much more in keeping with this
discussor's theory (18) than my own results. The normal slope
of the "baseline" clean test suggests that the high slopes of
the other groups are not artifacts of the test system. However,
It remains difficult to understand why the ultra-clean test
shows such a very high slope and relatively low L₁₀₀ life.
Perhaps the author's suggestion of a random sampling error is
the best explanation.

The Xerox copies I have of the micrographs are illegible. In-
formation on quantitative damage rating of surfaces would be
of value in applying the theory in (8).

Finally, attention is called to recent experience of the SKF
European Research Centre where high speed, high-A ball
bearing life tests under meticulously clean conditions are
routinely run. Lives of the order of the author's best results
are obtained and the life-extending effect of clean en-
vironment is consistently observed.

Authors' Closure

The authors wish to thank Mr. Tallian and Dr. Macpherson
for their thoughtful comments. Mr. Tallian is basically
correct in his observation that there is not a particularly great
incentive to achieve ultra-clean lubrication conditions over
and above the "reasonably" clean levels obtained in the
baseline bearing test series. However to achieve even this level
of lubricant cleanliness, which roughly corresponds to that
found in a typical aerospace hydraulic system, would require
a relatively fine filter in practice. At higher contamination
levels, the wear rate and surface distress of the test bearings
appears to us to be quite sensitive to the debris level in the oil.

The authors are unable to explain why the experimental B₀⁵
life of the bearings tested with the 30 micron filter was higher
than Dr. Macpherson expected. No unusual circumstances
could be identified that would influence the test results.
Perhaps it was simply the statistical nature of the fatigue
process associated with a limited test bearing population.

With regard to Dr. Macpherson's question of test debris
size and shape, the composition of contaminants used, closely
represented that of debris found in the oil sump of actual
aircraft jet engines. A variety of particle shapes and sizes were
present, ranging from basically spherical in the case of the
carbon and Arizona test dust to thin slivers of stainless steel.
Of course, wear and spall fragment particles were added to
the system during operation. However no special attention
was given to controlling the shape of the debris particles.

As to Dr. Macpherson's question whether small or large
particles cause the most harm, it was difficult to decide on the
basis of post test bearing examination. Unfortunately a good
deal of information regarding particle indentation shape and
size was worn away with time and sharp edged indentations
were generally smoothed over. It is likely that the large
particles which generate large and relatively deep dents with
significant stress concentrations would have a dominant effect
on the fatigue process. On the other hand, small particles
which are orders of magnitude more numerous than large
particles and still large enough to breach the thin EHD film
would be expected to strongly influence the rate of wear and
degree of surface distress.

We concur with Dr. Macpherson's comment questioning
the incentive of using exceptionally high quality steels in those
situations where debris damage is a factor. As noted in the
paper, today's bearing steels tend to be so metallurgically
clean that inclusion related failures tend to be the exception
rather than the rule. The money and effort to arrive at this
point, however, was not ill spent. But future emphasis would
probably be more profitably directed toward better control of
the bearing's environment as elusive as that may be. Finer
filtration, bearing construction that minimizes break-in wear
and more corrosion resistant steels will contribute to a greater
utilization of the life potential of today's premium bearing steels.