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DISCUSSION

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This paper comprises results of two distinct experimental efforts: 5-ball life tests at high (750 ksi) maximum Hertz stress and ball bearing life tests at more normal (300–347 ksi) maximum Hertz stress.

1 With respect to the 5-ball fatigue tests, the results showing an inverse 12th power relation between stress and life seem well substantiated. One can compare these results with those quoted in reference [7] of the present paper, and which reports irregularly changing load/life relationships for the maximum Hertz stress range 600 ~ 800 ksi. Certainly, the present results do not show irregularities in the *same direction* as [7]. One must thus agree with the authors that irregularities in load/life relationship above 500 ksi maximum Hertz stress do not arise *under all conditions.* Unfortunately, this is cold comfort to the future experimenter. Unless he can be assured that irregular load/life relations will not arise in *his* tests, he is in danger of false extrapolation from high-stress rolling contact fatigue results to normal stress levels. It is felt that much more data in the high stress regime is needed before this danger can be considered overcome.

The authors devote much attention to the interpretation of the finding that the stress life exponent in their 5-ball tests is 12 rather than 9. This discusser does not feel that an exponent of 12 (or any other reasonable value) at stress levels above 500 ksi needs much justification. Since the tests run so obviously in the macroplastic range, one would demand justification for a claim that the stress/life exponent is the *same* as at lower, nonplastic stresses, but the finding of a *different* exponent is quite acceptable. Likewise, this discusser would willingly accept findings of *different* stress/life exponents for *different* tests run at maximum Hertz stress >500 ksi, since the plastic phenomena occurring in this range must depend on many factors: hardness, alloy, inclusion content of steel, lubricant properties, EHD condition, etc. The existence of greater nonmetallic inclusion content in airmelt specimens is hardly the sole responsible factor.

Moreover, the inference should not be made that different levels of nonmetallics influence the stress/life exponent in the practical stress range <500 ksi. Considering that vacuum *degassed* steels have been universal in rolling bearings for almost ten years and consumable electrode vacuum melted steels universal in aircraft mainshaft bearings for at least that long, any major systematic deviation from the standard load/life law should have manifested itself in observed misprediction of lives in service.

If this deviation were toward an exponent >9, service life at lower loads would be over-predicted and found to fall short in practice. This is definitely not the case, according to this discussor's information. A deviated exponent <9 could go unobserved since service lives *exceeding* prediction are no cause for complaint. However, the fact remains that this discusser has learned of no systematic field observations suggesting such a deviation.

2 Turning to the full-scale bearing tests: the most salient results to this discusser are these:

(a) The bearings have performed as expected and failed by spalling fatigue, at lives comparable to those predicted on the basis of low-temperature results.

(b) The Weibull dispersion parameters (slope) are in all cases high (>1.5) and highest (>3) for the heaviest load.

(c) There is insufficient data to derive or confirm a load/life relationship.

Findings *(a)* and *(b)* are important to turbine designers since they promise reliable predictions of expected life to first failure. Finding *(c)* is, of course, the curse of the student of rolling contact fatigue laws. Long test series are needed to obtain load/life laws and, using full-scale mainshaft bearings, neither facilities nor funds ever suffice to obtain them. This discusser has consistently suggested the use of *subscale* bearing tests (*not* element tests) to produce fatigue test series of the required length within economic feasibility.

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Authors' Closure

The authors would like to thank Mr. Tallian for his thorough and provocative discussion. It is the authors' opinion that the so-called "irregular load/life relation" does not occur if a sufficient number of fatigue failures are obtained at each stress level. The 5-ball fatigue tests reported herein were planned in order to obtain a large number of failures. It took approximately four years and approximately 35,000 test hours to accumulate these data. The text of (7) implied a possible deviation in the stress-life relation at different stress levels in the range of 610 to 800 ksi. However, a least-square analysis of the fatigue data of (7) would substantiate a 12th power relation for CVM AISI 52100 in this stress range.

The authors' Table 1 is a summary of published bench-type rig data obtained in a stress range from 526 to 1300 ksi. The single major difference between those data exhibiting an approximate 9th power relation and those with an approximate 12th power relation was the steel-melting process used for the specimens. Air-melted steel exhibited a 9th power relation while the vacuum-processed specimens exhibited a 12th power relation. While "the existence of greater nonmetallic inclusion content in airmelt specimens is hardly the sole responsible factor" for this phenomenon, the authors are hard-pressed to determine any other variable which may significantly contribute to it.

Current bearing operating experience indicates a much higher

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life than would normally be expected based upon standard life prediction methods [3]. Most, if not all, of the improvement in life over predicted values can be accounted for by the material, material processing, and lubrication factors [33]. And, as Mr. Tallian implies, were there a significant deviation in the stress-life exponent; e.g., the exponent >9, the experimental life would greatly exceed the prediction. The data reported herein for the CVM AISI M-50, 120-mm bore angular-contact ball bearings at 500 deg F appear, within reason, to approximate a 9th power stress-life relation. Hence, it must be concluded that the designer and user of rolling-element bearings can continue to use the 9th power exponent to predict bearing life within reasonable limits.

Additional Reference

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