contamination effect measured on the same basis as pre-existing defects is a heuristic feature which should prove useful in future work.

12 Conclusions

1) A broad review of contact fatigue life models in the open literature indicates a consensus that material fatigue susceptibility, Hertz pressure, stressed volume, and film thickness/composite roughness height ratio are variables with demonstrated strong effect on spalling life.

2) Additional variables recognized in a number of published models as having an effect on spalling life are: fatigue limit stress and defect severity.

3) Contact interface traction and a measure of asperity sharpness are postulated in some research models to be additional influences on life, but appear as input parameters in engineering models by this author only.

4) Published models vary widely in the predicted form of life distribution, and in the relation between the predicted measures of life scale (quantile) and life dispersion on one hand and the life-influencing variables on the other. Nonetheless, by weighing the strength of experimental support behind each published model, ranges of behavior can be identified, within which a credible new engineering model must lie.

5) A *new model* is proposed, which encompasses all major recognized life-influencing variables and can readily be fitted within the ranges of behavior made credible by published models, by adjusting disposable constants.

6) The *new model* is sufficiently flexible to adjust its life predictions to experimental data on spalling life of different contact components. Its predictions are readily calculable from closed-form expressions, if all needed input parameters are given.

7) The *new model* can be used to explore the behavior of several likely life-influencing variables which have not yet acquired consensus status in published engineering models.

8) Some plausible life-influencing variables, notably direction of sliding, asymmetrical (forward) crack growth directionality, residual stress and any material strength and surface geometry changes occurring during cycling, remain unrepresented as input parameters of the *new model*, as they are in all reviewed engineering models, indicating that, for engineering purposes, their inclusion would be premature.

9) The preferred way of validating the *new model* is by comparison with primary endurance data. It is well known that data with sufficient scope of operating and contact parameters to permit critical comparison with a life model are extraordinarily difficult to obtain from the open literature or any other source. The use of published models as comparisons was adopted as the only means of validation accessible to the author within a reasonable time frame.

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DISCUSSION

E. Ioannides, E. Beghini, B. O. Jacobson,[1] A. A. Lubrecht,[1] and J. H. Tripp[1]

The discussers would like to compliment the author on reviewing the extensive list of contact life models and also on the attempt to unify them. We feel, however, that in adopting the approach of developing numerical fits to existing models, the author has been too quick to abandon the alternative more integrated approach of constructing new physical models, such as the Ioannides-Harris model (1985). As the author himself points out, "the new model does not claim new insights into the physical failure process." The criterion for the new model is merely that it should be a successful life predictor. While both alternatives are driven, as they must be, by test results, the former runs the risk of violating physical sense by concentrating on parameters—consensus parameters—individually and ignoring possible inter-dependencies between them. Life reduction is not given by a product of independent correction factors.

As just one illustration of the kind of erroneous conclusion this leads to, take the effect of contamination, shown in Part II, Fig. 4, which indicates that the life correction factor is dependent only on defect depth, δ. In Lorosch (1985) and Lubrecht et al. (1990), experimental and theoretical evidence is given that life reduction arising from a given indentation depends also on bearing size. Whereas for a larger bearing the life is not influenced by a dent, a similar dent in a smaller bearing causes a drop in life of 100 times. Other work has shown dependence of dent-influence on load Lubrecht (1990). To describe such multi-parameter dependence of life reduction on defect size, it would be necessary to construct the corresponding multidimensional plot of δ.

SKF has taken a different approach to the problem, in which a model [1] of the failure process itself is used as a starting point, with all assumptions stated. Parameters entering this model are indeed evaluated by fits to experimental data but the physical foundation of the model allows a definite measure of confidence in its extrapolation to conditions beyond those under which the tests were carried out. Using this model, a unified description of many very different physical phenomena is now possible, including to date, the influence on life of: steel cleanliness (relation between load and contamination on Weibull slope) Lubrecht, Jacobson et al. (1990); surface roughness parameters: Tripp et al. (1990); hoop stresses: Ioannides et al. (1989); particulate contamination (dependence on bearing load, size, type, etc.) Lubrecht, Venner et al. (1990); Lubrecht, Dwyer-Joyce et al. (1991); film thickness Lubrecht, Venner et al. (1990); Ioannides, Jacobson et al. (1989); traction Ioannides, Jacobson et al. (1989); residual stresses: Beghini et al. (1991).

The author remarks (Part 1, Section 5.2) about the lack of published detail of what he terms the "SKF Bearing Model." Any bearing company, however, might normally be expected to maintain different levels of availability of information, for example: (*a*) the Catalogue Level—simplified models as they are published in a manufacturer's catalogue; (*b*) the Application Engineering Level—programs based on models developed for use by application engineers faced with problems under a wider range of conditions than is covered in the Catalogue; (*c*) the Research Level—physical models and the com-

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puter programs for evaluating them, together with results of tests.

While the computer programs associated with levels (*b*) and (*c*) are generally proprietary, the preceding discussion has clearly demonstrated that the models themselves and the assumptions built into them have been fully presented and are available in the open technical literature.

In closing, while continuing the search for simplified life prediction models, we feel there still remains much to be extracted from models based on a combination of experimental data and sound physical assumptions before it becomes necessary to resort to curve fitting, with its many inherent dangers.

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We read Dr. Tallian's contributions to contact fatigue life prediction models with a great deal of interest.

In Part I of his two-part paper, the author describes and compares most of the engineering and research life prediction models that are known and used today.

To the author's description of the FAG bearing life prediction model, we would like to make the following comments:

The author states that the FAG model is based on the assumption that "failures originate primarily, if not exclusively, at the surface." This statement is not right. Depending on the cleanliness and thickness of the lubricant film, the initiation of failure can be at the surface or below the surface. The FAG model takes care of this aspect through the a_{23}-factor.

In case the contacting surfaces are fully separated by a very clean lubricant, fatigue occurs due to initiation of cracks at weak points within the material. These weak points could for example be nonmetallic inclusions. The FAG model considers this failure mode through the *f*-factor, which leads to a_{23} values in the region I of the a_{23}-κ-diagram (Fig. 1a).

In the presence of a contaminated or unsuitable lubricant, failures originate at the surface of the material. Region III of the a_{23}-κ-diagram covers this mode of bearing failure.

Finally, the region II of the a_{23}-κ-diagram considers not only failures that originate at the surface but also fatigue due to the initiation of cracks under the surface. This region covers most of the practical applications in which bearings run in the presence of clean lubricants with additives.

The different modes of failure that are considered in the FAG model, have been explained in detail in numerous publications, for example in the references in this discussion.

The author describes the FAG life prediction model in which the fatigue limit of rolling element bearings has been integrated. Simultaneously he refers to some of our latest publications. Our initial publications regarding the existence and importance of the fatigue limit of rolling element bearings were presented in the 60's, as our references demonstrate.

In the second part of his paper the author presents a new fatigue life prediction model. This is a very remarkable model, since with a suitable choice of the different parameters, this new model covers the fatigue life predicting capability of all known engineering models. The new model needs to be matched to experimental data. Our references (1968–1985) contain a good selection of fatigue life experimental data for rolling element bearings. We hope that other bearing manufactures, as well as users, supply the author with more experimental and field data.

In deriving the new fatigue life model, the author had to make a few assumptions. This certainly has to be done in the first stage of development. The fatigue life prediction capability of the new model could be increased extensively if the author could do away with the following restrictions in the future:

—limitation of the model to line contacts
—constant traction coefficient within the contact area
—neglect of residual stresses

I Transition range to the endurance strength. Preconditions: utmost cleanliness in the lubricating gap, loads not too high.
II High degree of cleanliness in the lubricating gap, suitable additives in the lubricant
III Unfavourable operating conditions, contaminants in the lubricant, unsuitable lubricants

Attainable fatigue life L_{na}

$$\boxed{L_{na} = a_1 \cdot a_{23} \cdot f_t \cdot L}$$

a_1 = life adjustment factor for failure probability
$a_1 = 1$ for failure probility of 10 %
a_{23} = life adjustment factor for the material and operating conditions
f_t = temperature factor
L = rating life
ν = operating viscosity of the lubricant
ν_1 = rated viscosity

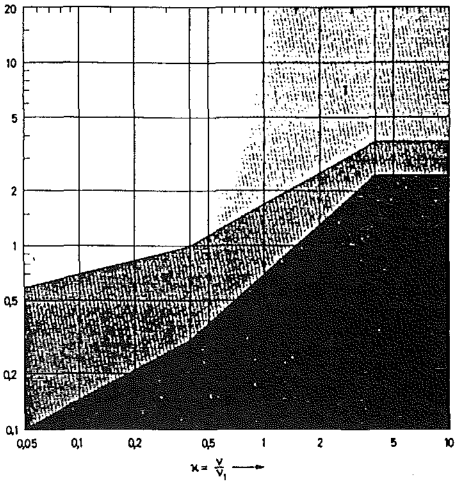

Fig. 5 a_{23}-κ diagram

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