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DISCUSSION

E. V. Zaretsky[2] and R. J. Parker[2]

The author presents a continuum of very interesting papers, of which the instant paper is but one, showing the lubricant's chemical effects on rolling-element fatigue. The discussers have been continuously critical of these papers because the credibility of the published results are placed in question by the extremely high maximum Hertz stress of 1.2×10^6 psi used by the author. The discussers have continually stated that these high Hertzian stresses mask any definitive conclusions because of gross plastic deformation and wear which occurs in the upper-ball, lower-ball contact (see discussion to [8]). Mr. Rounds has continually refused to recognize this factor in analyzing his results.

Based upon track width and depth measurements for the seven steels used in the instant investigation run with Oil C, the author concludes that, "there was little variation in track depth and only a limited variation in track width" with exception of those measured with the AM51100 and AM52100 steels. The veracity of this statement depends wholly on the effect of the track alteration due to plastic deformation and wear on the maximum Hertz stress. Track width and depth is a measure of this alteration. By the use of trigonometric relations, an effective ball radius R_p at the point of contact can be calculated [22, 23][3] in terms of track width W, track depth H, and original ball radius R where

$$R_p = \frac{W^2}{8\left[R - H - \frac{1}{2}\sqrt{4R^2 - W^2}\right]}$$

Using the foregoing formula the discussers calculated the effective ball radius R_p for two of the steels, AM51000 and 440-C although any one of the other materials could have been selected. The values of R_p were -0.338 and -0.272 inch, respectively. The radius of each of the running tracks changed from a convex profile prior to running to a concave profile after running. This would substantiate that gross wear and/or deformation occurred in the contact zone. Using R_p, the Hertzian stresses were recalculated for the AM51100 and 440-C. The recalculated stresses for these materials were 680,000 and 520,000 psi maximum Hertz. Interesting enough, the 440-C which had the lower stress produced twice the life of the AM51100. Surely, the amount of plastic deformation and wear in the contact zone could not be equal for all materials nor could the difference be insignificant.

Referring to Fig. 1, the discussers question whether the data justifies drawing any conclusion regarding the effect of viscosity. Out of seven lots of data presented, three may justify a conclusion of increasing fatigue life with increasing lubricant viscosity. However, the remaining lots would essentially indicate no viscosity effect. If the tests were run under conditions of boundary lubrication, no significant effect of viscosity would be expected. If, however, the stress was significantly decreased due to plastic deformation and/or wear, then an elastohydrodynamic film may be formed and an apparent viscosity effect would manifest itself.

Based upon Fig. 3 and considering the decreased "effective" maximum Hertz stress and the extremely low fifty percent lives which ranged from 11 to 553 minutes, it becomes questionable that any of the failures can be attributed to rolling element fatigue. Gross plastic deformation, wear, and severe surface pitting due to high surface tangential friction forces are the most probable modes of failure. In addition, the very short life failures may be due to fracture of the steel. As the author points out, "the data fall into two statistical populations." Generally, the slope of the Weibull lines should be approximately one for rolling-element fatigue distributions. For most of the data presented, this is not the case.

Referring to Fig. 4, it is the discussers' opinion that while the author presents a logical premise regarding the effect of surface coating on fatigue life, the data presented does not support nor refute the conclusions of the author. Much more data are required.

With regard to Fig. 6, oil oxidation tends to increase the viscosity of the lubricant under normal operating conditions. While increased acidity may decrease rolling-element fatigue life, the increase in viscosity of the lubricant may have the opposite effect. At an acid number above 0.3, there appears to be no statistical effect of acid number from the author's data.

In conclusion the discussers would like to ask the author if he would have come to the same or similar conclusions if the specimen ten percent lives were used for comparison purposes. In application, what is deemed important is the early failures in order to assure maximum system reliability. The ten percent life or the 90-percent probability of survival is a measure of this early life.

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R. S. Fein[4]

Mr. Rounds' excellent paper presents the clear challenge of a problem to the steel, bearing, lubricant and equipment manufacturers. Optimum utilization of rolling element bearings and gears in equipment requires predictability of surface-fatigue limited life. However, the paper demonstrates large variations of life with specific combinations of steel-lubricant chemistries. Thus, for example, Table 5 shows that a chlorinated wax additive increases the B_{50} life of M-50 and 440C steel but decreases the life of 52100 steel. Conversely, oleic acid decreases the B_{50} life of M-50 and 440C and increases the life of 52100. The specificity of these chemical interactions and those shown for lubricant viscosity and steel combinations suggest that other variables must determine the sensitivity of surface fatigue to lubricant-steel combinations.

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[3] Numbers [22–23] in brackets designate Additional References at end of discussion.

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The problem currently challenging the various industries is how to predict the circumstances under which surface fatigue life is sensitive to chemistry (steel, lubricant and atmosphere chemistry) Solution of this overall multi-disciplinary problem would provide each industry with knowledge required to develop tests for studying their individual problems of chemical effects on surface fatigue Knowing the circumstances which make surface fatigue sensitive to chemistry is the key to making the proprietary tests significant

The economic resources and multi-disciplinary know-how required to find the circumstances dictate cooperative research sponsorship with close guidance by experts in several fields Consequently, the ASME Research Committee on Lubrication, with the cooperation of ASLE and ASTM, has set up a research program which is being sponsored by sixteen organizations The program, which is currently getting underway, will be largely carried out with the exceptionally well-suited facilities of IIT Research Institute Close active guidance will be provided by an Advisory Board, including leading authorities on metallurgy, lubricant properties, lubrication chemistry, elastohydrodynamic lubrication, boundary lubrication, bearings, and gears Anyone wishing further information on the program or on how to become a sponsor should write or call Mr B W Kelley, the Advisory Board Chairman [5]

T. E. Tallian[6] and H. E. Mahncke[6]

The authors work on chemical effects in lubrication mechanisms has focused well deserved attention on a group of phenomena which have become more significant as research and development in this field continues The present paper is another step in this continuing work However other and more detailed studies have shown that the whole subject of rolling contact fatigue is a quite complex one and we should like at this point to pose a few precautions against a too simplistic interpretation and extrapolation of the observations

In the Introduction, the author states "How asperity contact leads to fatigue failure has not been satisfactorily explained"

While admitting that the satisfactory nature of an explanation is a matter of judgement, it is desired to cite references in which such an explanation has been offered In [24],[7] Tallian suggested that surface asperities, in contact, create micro-Hertzian stress fields leading to surface fatigue, which in turn paves the way for spalling This position is further explained in [25] In [26], Martin and Eberhardt show metallographic evidence of near-surface plastic flow associated with asperities In [27] Leonard shows, by scanning electron microscopy, the development of plastic flow, cracks and pits at surfaces, associated with surface asperities In [28], the concept of surface fatigue from microstresses at interaction asperities is used to sketch a method for mathematical prediction of spalling fatigue life as influenced by lubricant film thickness Finally, in [29], this mathematical model is presented as a quantitative theory

The last reference includes concepts suitable for taking account of the type of chemical lubricant-metal interactions described by the author and will be presented later in this program, where, it will be noted that a distinction is made between subsurface fatigue and surface fatigue

It is to the latter case that the present work applies since one would hardly expect "action at a distance" as a result of chemical effects Rather one would expect direct interaction on an atom to atom (or molecule) basis Detailed surface studies which have been made possible by the scanning electron microscope show that a great deal of microplastic deformation occurs during rolling contact under Hertzian maximum stress loadings of the order of 2-3 $\times$ 10^5 psi if the lubricant film is thin enough to admit of asperity contact These thru continued cyclic stress applications eventually lead to fatigue spalling at the surface

However we submit that the application of such excessive loads as those used by the author (1 2 $\times$ 10^6 psi max Hertz stress) lead to such gross and continued plastic deformation as to constitute a case of metal failure which by-passes the part played by continued micro-plastic reaction to cyclic stressing, or at least reduces it to insignificance If this is the case, then we are dealing with a different failure mechanism, and the author's observations, which we certainly have no reason to question are understandable in the sense that chemical interactions at contacting surfaces will serve to mitigate the potential effects of plastic deformation

We do suggest that, where the plastic deformation component of metal failure is not large relative to elastic stressing, these chemical effects may not be so significant a factor in what is regarded as fatigue failure in conventional bearing operation

We would also suggest however another area in which chemical and/or structural effects may play an important part in the failure process The advent of the methods of optical interferometry for the study of lubricating films, pioneered by Cameron, has presented evidence that there are considerable differences in the rheological characteristics of these lubricating films which seem to be related to their chemical nature A full realization of the significance of these effects is only just dawning and it will require a great deal more work in several directions to achieve a complete understanding of the complex mechanism of the lubrication of rolling contacts

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Authors' Closure

In their discussions, both Zaretsky and Parker, and Tallian and Mahncke raise doubts concerning the validity of the 4-ball fatigue data because of the high load used, 1,200,000 psi Hertz (nominal) The purpose of the high load was to reduce the test time to a manageable level so as to permit systematic screening of the potential variables in rolling contact fatigue The success of such an approach depends on how well the laboratory screening test, the rolling 4-ball machine, correlates with full-scale bearing experience For this reason, we have made correlation checks whenever suitable full-scale bearing data became available As with any accelerated test, there have been successes and failures, but the successes have substantially outnumbered the failures For example, the 4-ball test was able to correctly predict in both direction and magnitude (*a*) the difference between balls

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[7] Numbers [24–29] in brackets designate Additional References at end of discussion

made by two different manufacturers (~3 to 1 difference), (*b*) the effect of changing the steel melting practice from air-melt to carbon-vacuum deoxidizing (~2 to 1 difference), (*c*) the effect of increasing oil viscosity, (*d*) the detrimental effect of oil oxidation products, and (*e*) the ranking of a series of candidate traction-drive oils. Based on this experience, we believe that the rolling 4-ball fatigue test is a reasonable screening test. The final answer will always remain the full-scale bearings operating in the actual environment.

Tallian and Mahncke point out in their discussion that asperity contact can occur at loads as low as 200,000 psi. Limited capacitance measurements made on our rolling 4-ball machine have confirmed this observation. In addition, it was observed that a substantial fraction of the load was carried by an oil film even at 1,200,000 psi. Further, the effects of lubricant variables found in thrust ball-bearing friction experiments run at loads of 300,000 to 500,000 psi have generally been observed in the high-load fatigue tests as well. Thus, it is my belief that the difference between 300,000 psi (heavily loaded bearings) and 1,200,000 psi (4-ball fatigue tests) is one of degree only, and that these are not two unrelated regimes. However, Tallian and Mahncke are probably correct in their assumption that the high load tends to emphasize the chemical effects.

Zaretsky and Parker present a useful equation for calculating the effective ball radius on the upper ball in the contact region. If the effective unit loads in the contact region are calculated using this effective ball radius, differences among the various steels are observed. However, no correlation between the calculated effective unit loads and life was noted. The AM51100-440C comparison used by Zaretsky was fortuitous in this respect.

It is generally accepted in the bearing industry that increasing oil viscosity usually increases fatigue life. The purpose of including the viscosity study in the present paper was not only to point out that the viscosity effect recognized by the bearing industry can be detected with the 4-ball machine using some steels, but also to show that additive chemical effects can be substantially larger than the viscosity effect. The cooperative research program described by Fein should go a long way in defining the role of the lubricant in rolling contact fatigue.

Some other points were also raised by Zaretsky and Parker. Despite the short test times in our 4-ball fatigue tests, the 4-ball fatigue-test failures have the same appearance as actual bearing failures and show many of the same characteristics, such as life sensitivity to load, statistical nature of duplicate tests, damage progression with time, etc. Fig. 4 was a first attempt to show a relationship between surface chemical activity and fatigue life. We fully agree that more work is needed to better define this relationship. Although it is true that oil oxidation does cause the viscosity to increase, a significant viscosity increase in terms of fatigue generally cannot be detected until after the TAN has increased 0.5 or more. Thus, it is doubtful that changes in oil viscosity were a significant factor in Fig. 6. If B10 life rather than B50 life had been chosen as the basis for comparison, substantially the same conclusions would have been reached. However, many more tests would have been required to obtain comparable confidence in the numbers obtained.

We agree with Tallian and Mahncke that fatigue is a complex phenomenon and that the lubricant is only one of many factors involved. If the lubrication conditions are such that asperity contact occurs, surface chemical reactions will occur. Thus, it would appear that when asperity contacts occur, more than just the mechanical aspects of the situation need to be considered. This was the reason for the statement, "How asperity contacts lead to fatigue failure has not been satisfactorily explained."