A. Beerbower[1]

The authors are to be congratulated on another fine contribution to the series of IRG reports. It is very gratifying to see that they are starting to quantify the change in roughness during running-in, since it is important to permit valid comparisons of the nonvirginal roughness to the EHD film thickness.

An especially interesting feature of this paper was the description of the transition delay, previously studied by Pike and Spillman [10]. At that time this delay was mysterious, but the discusser has come to believe that it is related to Bayer's [11] zero-wear period prior to high-transfer wear. It also appears that all these can be attributed to the results of low-cycle fatigue. This is defined by ASTM [12] as "characterized by the presence of macroscopic plastic strain." The definition further states "for common ductile structural materials, the low-cycle fatigue regime is generally limited to less than 50,000 cycles."

Some important distinctions from the high-cycle fatigue so familar in rolling element bearings are discussed in a recent paper [13]. What needs to be mentioned here is that the transition delay in low-cycle fatigue is entirely due to crack propagation, as initiation takes place in the first cycle. In high-cycle fatigue, delay is prolonged by the relatively long time required to initiate cracks. Initiation is well known to follow the Palmgren equation $t_d F_N^3$ = constant. Bayer apparently assumed that propagation follows the same rule, which did not matter since he strongly advised against designs that would result in high transfer failure. The "zero-wear" life in such cases is so short that most experimenters ignore it.

The Coffin-Manson equation for low-cycle fatigue can be put into similar form, but the exponent varies from 2/3 for purely elastic strain to infinity for materials so plastic as to have zero yield stress. This led the discusser to plot the present data (scaled from Fig. 7) and Pike's on log-log paper. The points form good, straight lines with a few exceptions, and the slopes cover the entire theoretical range as shown in Table 4. The mere fact that the lines are straight lends support to the fatigue theory. Furhter, the shorter lives with rougher surfaces are as would be predicted. The increased exponents with stearic acid can be attributed to the plasticizing "Rehbinder effect." In addition, the previous finding that steels with high retained austenite (4) show only the I to III transition can be attributed to the well-known plasticity of austenite.

However, this theory is far from solving all problems and raises a few new ones. First of these is that fatigue of either kind is essentially independent of velocity. That fits well to the right of S on Fig. 1, but is strongly contradicted by Pike's data in Table 4. Conceivably, velocities below v_s could be by adhesive wear and above by low cycle fatigue. In that case Bayer's transition, run at 5×10^{-5} m/s, would be adhesive. Some explanation is certainly required as to how he could experience transition at that speed and F_N of 40 N or less, on several hundred experiments, if Fig. 1 is to be considered universally valid.

An even worse dilemma arises on the implication that the authors never experienced transition delay except with Procedure B running-in. If that is indeed the case, the low cycle theory would be of little value, as that is hardly typical practice; but then, why is delay so common on the 4-ball machine? Most users have seen and heard it, though few report it.

Do the authors feel that the points raised above justify further investigation of the low-cycle fatigue theory?

Table 4 Slopes of load-life plots

Source	Lubricant	R_c (μm)	v (m/s)	Slope
Present	Mineral Oil	0.51	4.6	2.1
Present	Mineral Oil	0.31	4.6	4.6
Present	Mineral Oil	0.14	4.6	6.3
(A1)	Cetane	0.03	0.5	3. ± ?
(A1)	Cetane	0.03	0.8	2.1
(A1)	Cetane	0.03	1.2	0.7
(A1)	Cetane + Stearic	0.03	0.5	∞
(A1)	Cetane + Stearic	0.03	0.8	12.4
(A1)	Cetane + Stearic	0.03	1.2	6.2
(A1)	Cetane + Stearic	0.03	1.5	15.2

Additional References

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11 Bayer, R. G., and Schumaker, R. A., "On the Significance of Surface Fatigue in Sliding Friction," *Wear,* Vol. 12, 1968, p. 173.

12 "Definitions of Terms Relating to Constant-Amplitude Low-Cycle Fatigue Testing," ASTM Standard E 513-74, American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

13 Beerbower, A., "Wear Rate Prognosis Through Particle Size-Distribution," ASLE Preprint No. 80-AM-2D-1 (May 5–8, 1980).

H. Czichos[2]

In this paper, considerable changes in the surface roughness of lubricated sliding contacts during running-in are observed which have a pronounced influence on the load-carrying ability of the system studied.

In previous experiments we too studied the changes of surface roughness before the failure of thin-film lubricated concentrated contacts.[3] In these observations we observed that the interfacial asperity interaction processes preceding failure

(i) roughen very smooth surfaces, and
(ii) smooth relatively rough surfaces,

so that a narrow range of "dynamic" surface roughness data immediately before the break-down point results. My question is: have the authors in their investigation made a similar observation?

Authors' Closure

Dr. Beerbower's suggestion that the first transition may well be governed by a fatigue mechanism of the sort as described by Bayer, et al, certainly is attractive and thought-provoking. This is the more so as – indeed – also virginal surfaces show the phenomenon of collapse delay. There, however, delay times fall in the range of 0-10 s, which would mean a much higher value for the exponent β than Dr. Beerbower found for run-in surfaces. A problem, associated

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[3] Czichos, H., "Influence of Asperity Contact Conditions on the Failure of Sliding Elastohydrodynamic Contacts," *Wear,* Vol. 41, 1977, pp. 1–14.

with applying a fatigue theory, however, is that the transition from region I to region III as well as that from region I to region II is viscosity controlled (c.f references [10, 11]) and occurs at a well-defined value of the Hertzian contact pressure [12].

These facts seem difficult to reconcile with a fatigue mechanism. In fact in the authors' opinion, the most reasonable description of film collapse, still runs as follows:

Already at values of F_N, much below the transition value F_{N_C}, occasional solid-to-solid contacts occur. Upon increasing F_N, the number of contacts increases exponentially, i.e. for surfaces with normal distribution according to the Gaussian distribution curve. At $F_N < F_{N_C}$, rapid oxidation of damaged asperities prevents full-scale scuffing; at $F_N = F_{N_C}$ the influx of solid-to-solid contacts into the contact area becomes so large that oxidation cannot longer keep abreast of junction formation and full-scale scuffing developes.

This model accounts adequately for the effects of roughness, oxygen concentration and chemical reactivity of the lubricant, as reported on previous occasions [13, 14]. Also it does not exclude the possibility that, at $F_N = F_{N_C}$, it takes some time before full-scale scuffing occurs and the film collapses.

Notwithstanding the above we agree with Dr. Beerbower that it might be wise to investigate the fatigue idea somewhat more thoroughly. In this respect the comment should be made that any realistic collapse theory should account for the fact that the lower transition curve is continuous, point S merely being the intersection of this curve and the upper transition curve. This is made clear in reference [10].

Also it should be taken into account that the diagram given in Fig. 1 applies for values of $v_t > 0.01$ m/s. At still lower values of v_t the load carrying capacity of the EHD film *decreases*, in accordance with hydro-dynamic concepts [15].

In reply to Dr. Czichos' comment we would like to refer to Table 3, which shows that running-in at low speed and relatively high load invariably leads to a reduction in roughness of the stationary cylinder, while the roughness of the rotating cylinder remains constant.

Additional changes in roughness during subsequent performance of two minute tests (i.e. in the "delay period"), have not been recorded, but may nevertheless have occurred.

Additional References

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15 Begelinger, A., and de Gee, A.W.J., to be published.