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DISCUSSION

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As the authors have implied in their paper, a "life study" is more than a study of pitting, but also of tooth fracture and wear. Tooth fracture is a unique gear failure mode, which, although it occurs rarely with proper material selection and design, cannot be obtained with the disk, 4-ball, or conventional rolling-sliding testers. Wear varies along the tooth profile due to the variations of load and sum and sliding velocities in the mesh; these conditions cannot be simulated in a cyclic fashion in the conventional rolling-sliding testers. It can be argued that the three failure modes should be separately followed up in basic studies. Nevertheless, despite its shortcomings, there is a definite place for actual gear testing in a life study. I am aware of only one prior publication in the open literature [14], which was concerned with the effect of lubricants on gear pitting life. The authors' work deals primarily with materials and is concerned with all three failure modes and is thus particularly welcome.

The tooth fracture of M-50 gears is not surprising, as explained by the authors. In fact, we have occasionally encountered tooth fracture on M-50 gears, even in the relatively short-duration scuffing tests, at high loads due to bending alone, i.e., without pitting. We have found that M-50 gears give a much higher scuff failure load than Nitralloy N gears, depending on the lubricant [15]. But the tooth fracture problem makes M-50 steel an unacceptable gear material. Our unpublished results have shown that Super-Nitralloy N gears (with white layers) give excellent scuff failure loads; these results together with the authors' pitting results appear to show that it is a promising gear material. There are, of course, other steels that permit a hard case and softer core that are also worthy of consideration.

One of the strong incentives for conducting life testing of gears is to study wear, in addition to pitting and tooth fracture. The wear results reported here, with time, are not easy to explain. It is hoped that the work will be continued, with more attention directed to wear.

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D. J. Fessett[4]

This paper presents the gear fatigue properites of two materials under specific test conditions. Since the objective of these tests is to produce data that can be used by the gear manufacturers, the following suggestions and comments apply.

The use of AISI M-50 and Super-Nitralloy in aircraft gear transmission is very limited. At present AISI 9310 and Vasco X-2 are more likely to be used for the case-hardened materials, and chrome molybdenum and maraging steels for the through-hardened gear materials.

The face width of the test gears of 0.10 in. is thought to be too narrow for an eight-pitch gear. Face width of 1 to 5 times the circular pitch (0.4 to 2.0 face width) is more common. Can the data published in this paper be extrapolated to wider face gears?

The use of super-refined naphthenic mineral-oil lubricant having proprietary additives combined with an inert cover gas is not paractical for present-day gear transmission. A better choice of common lubricants such as MIL-L-7808 or MIL-L-23699 would allow a closer correlation of the authors' data with present aircraft transmission designs.

The test procedure of offsetting the gears is questionable due to extraneous tooth deflection. Would gears correctly in line produce the same results?

The fatigue data indicated a 90 percent survival (t_{10} life) was approximately 25×10^6 cycles with a Hertz load of 275,000 psi. An S–N curve showing the life at various stress levels would be more beneficial for gear designers, since their stress levels might be lower or higher.

Tip relief is primarily placed on gears to reduce scoring due to inaccurate gears or tooth defections. Tip relieving is generally not related to fatigue properties unless the tip relief is excessive. When the relief affects the majority of the addendum of the gear the contact ratio or load sharing of a tooth is affected resulting in higher bending stresses along with greater scoring potential. This fact is borne out by the authors in Fig. 8 and is the reason that the M-50 gears failed in bending rather than pitting. A proper tip relief should only be on the edge of the top land of the gear and should not extend any more than necessary into the involute of the gear.

Tip relief should not affect the Hertz compressive stress at the pitch line where pitting occurred. The difference in the fatigue results of the tip-relieved Nitralloy gears might be attributed to processing, since the gears that lasted longer were ground after heat treating while the gears that pitted sooner were tested with the nitride white layer on them. Also, was the involute of both gears identical, since nitriding (especially a thick coat of 0.020 in.) does cause growth?

In general, the work performed by the authors is commendable; however, further testing or additional data are needed to allow the paper to be more useful for the gear designer.

Authors' Closure

The authors would like to express their appreciation to Messrs. P. M. Ku and D. J. Fessett for their discussions. The authors

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agree with Mr. Ku's comment that there is a definite need for a life study of gear materials. While it is true that the AISI M-50 material is subject to tooth fracture, there are applications for AISI M-50 where increased temperature capability is necessary and where tooth bending stresses are not critical.

With regard to Mr. Fessett's comments, the authors agree that other materials such as AISI 9310 and Vasco X-2 need to be investigated. What is surprising however, to the authors, is the lack of pitting fatigue data for common gear materials used by gear manufacturers.

Offset testing of gears should not have an appreciable effect on the surface fatigue life of the gear tooth unless there is misalignment. Misalignment would cause edge loading and, hence, early failures. The authors have not seen any failures due to edge loading in their test results. The offset gear loading does, however, cause some twisting of the tooth and will increase the bending stress on the loaded side. This effect can influence the bending fatigue life of the gears.

The lubricant used in the authors' tests was selected because of its good storage life. A single batch of lubricant can be used over several years. As a result, comparative results can be obtained for several steels. Rolling-element bearing experience has shown that when comparing the pitting fatigue life of different steels, the ranking of the steels should be the same with different lubricants if the mode of failure is the same.

The distribution of surface fatigue failures of gears is represented by the Weibull plots shown in Figs. 5 and 9. As is obvious from these data, there can be considerable life scatter from the first failure in a group of test gears to the last failure. The life at a 90 percent probability of survival, or the L_{10} life (10 percent failure probability), can be taken as an estimate of early fatigue life. In general, $L_{10} \propto (1/\text{stress})^n$ where n can be assumed to be 9 based upon rolling-element fatigue data [16, 17]. Hence, these data can be extrapolated into a lower or higher stress range. However, for gears of different pitch diameter, tooth geometry or face width, the stress volume must be statistically considered in order to extrapolate these data for life predictions.

The authors agree with Mr. Fessett that tip relief should not affect fatigue life except where excessive tip relief produces increased dynamic loading. The data for super nitralloy (Fig. 9) showing the effect of tip relief on surface fatigue life indicate that the lives are nearly identical. The small difference in the L_{10} life is not statistically significant.

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