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Effect of Lubricant Additives on the Surface Fatigue Performance of Gear Oils

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Abstract—The effect of additive chemistry on the serface fatigue of gears was investigated using the FZG gear tester and fluids based on an API GL-5 grade oil. Surface fatigue lives were determined as a function of load and additive chemistry. At 1.52 GPa, the removal of the primary extreme pressure additive (EP) from the fully formulated gear oil decreased the fatigue life of gears slightly (4%), however, the removal of the primary antiwear additive (AW) decreased the fatigue life of gears significantly (83%). At 1.86 GPa, the removal of the EP additive from the fully formulated gear oil decresed the gear fatigue life 27%, however, the removal of the primary AW additive decreased the fatigue life of gears significantly (75%). Micropitting was the dominant surface morphology in the dedendum of gears tested With two oils at load stage: one using the complete additive package, and a second where the EP additive has been removed. However, spalling is the primary failure mode of gears tested without an AW additive independent of whether an EP agent was present. Surface analysis of pinion gears showed the formation of a mixed phosphate/phosphite-oxide layer on the surface of gears tested with fluids containing an AW. Formation of this layer seems to be key to long fatigue life.

1. Introduction

The processes by which gears fail are complex and not well understood. Many factors, such as surface roughness, lubrication, impurities, and hardness can have an effect on the process. Gear failure mechanisms are generally divided into five broad classes [1-3]:

- *Wear (loss of materials by abrasive contact)*
- *Plastic flow (surface yielding and deformation due to heavy loads)*
- *Surface fatigue (failure of material due to repeated contact)*
- *Breakage*
- *Associated gear failures (e.g. lubricant starvation)*

These mechanisms are not necessarily independent. For example, severe wear can decrease tooth sterngth, thereby causing breakage.

Past research on gear metallurgy and surface finish have extended the life of gears significantly. Much of tody's attention is focused on the improvement of modeling and desingn processes of gears. Gear surface is currently considered a key limitation in component life due to the growing demand for extended drain intervals by original equipment manufacturers. Thus, a better understanding of gear surface is required. While the effect of lubricant on the surface life of gears has been studied , there is still little understanding on the effect of additives on the surface fatigue life of gears [4-9].

Lubricant oil consists of base oil (60-95%), viscosity modifier (0-30%), pour point depressant (0-2%) and performance package (5-10%). The performance package contains antiwear(AW) additive, extreme pressure (EP) additives, corrosion inhibitors, oxidation inhibitors, and foam inhibitors. The AW and EP additives are organic compounds that contain one or more elements such as sulfur, chlorine, and phosphorous and are intended to prevent or minimize wear and surface damage to gears. Antiwear additives either adsorb onto the surfaces or react with the gear surface to form protective films. EP additives react with metal surfaces under high temperatures and high pressures [10-15].

It has been reported that the surface fatigue of materials is sensitive to the combined physical and chemical nature of lubricants as well as operating variables indicating that the fatigue life of materials depends on the material-additive interaction [10,12]. The evaluation of additive effects is quite complex and should be conducted at the stress and slip levels of importance to the specific application. Additives are reported to increase or decrease the fatigue life of materials depending on the additive-material combinations [10,11].

There is a considerable amount of literature available in the field of surface fatigue, however, the effect of fully formulated lubricants has in the been widely studied. Townsend *et. al.* [13-14] reported that the addition of phosphate containing additive to a reference fluid (synthetic tetraester containing oxidation and corrosion inhibitors and an antiwear additive) increased the fatigue life of spur gears significantly. However, the addition of a sulfur containing EP to the reference fluid did not show a statistically significant improvement.

It has been reported that there is a relationship betting and micropitting [15]. An oil containing zinc dithiophosphate (ZDP) resulted in a better fatigue life than an oil containing gear oil additives. However, the analysis of tested gear surface by microscopy and profilometry showed the presence of significant micropitting and high wear on the gear teeth tested with the oil containing ZDP. In contrast the gear tested with the oil containing the gear oil additives showed the presence of minor micropitting and low wear.

In this study, the effect additives used in the formulation of API GL-5 grade (GL-5 grade) gear oils was evaluated using an DZG tester. Emphasis was placed on: 1) development of liad stage (contact stress) - surface life of gears curve, 2) evaluation of additive effects on the surface fatigue life and failure mode of gears, and 3) chemical analysis of the gear surfaces at the end-of-test.

2. Experimental Procedures

Table 1 details each fluid used in the study along with selected physical and analytical characteristics. Test Fluid 1 was prepared using a generic additive package capable of meeting API GL-5 performance reqirements. Test Fluids 2-4 were prepared by eliminating key components from the baseline formulation in order to isolate their effect in the pitting test. All fluids were blended in an SAE 90 viscosity grade oil made from conventional solvent refined neutral and bright stock components.

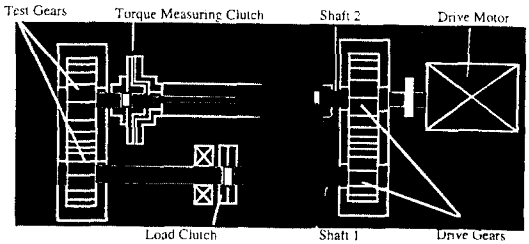

Fig. 1. Schematic drawing of FZG gear tester.

Evaluations to determine the surface fatigue properties of the oils presented in this paper were carried out with an FZG test rig as shown in Fig. 1. The FZG tester is a recirculating power, four-square configuration rig used to evaluate various lubricants and performance parameters [16-19]. The principal parts of the rig include a test gearbox, a slave gearbox, a load clutch, and a torsional shaft. The test gears used for the pitting evaluations discussed here were straight cut spur gear. These are typically referred to as Type "C" gears. The gears are made from 16 MnCr5 steel, case carburized to a surface hardness of 60 to 62 Rockwell C, and finished with a Maag 0° grind which typically produces a surface roughness, Ra, in the ranfe of 0.35 to 0.55 μm.

A break-in phase is conducted by running the gears at the standard speed (pitch line velocity of 8.3 m/s) for two houes at a Hertzian contact pressure of 1.02 GPa; which is equivalent to load stage 6. The oil is heated to 60°C before starting the motor. The

Table 1. Summary of test fluids and their physical and analytical characteristics

Test Fluid	SAE 90 Base Stock Containing	Physical and Analytical Characteristics			
		Kinematic Vis. at 100°C (cSt)	Kinematic Vis. at 40°C	% P (theo)	% S (theo)
1	API GL-5 formulation	17	189	0.11	2.1
2	GL-5 formulation less EP	18	204	0.11	0.2
3	GL-5 formulation less AW	17	185	0	1.9
4	GL-5 formulation less AW and EP	18	201	0	<0.1

oil temperature is controlled thereafter to a maximum of 90±2°C for the remainder of the test . Following break-in, the gears are inspected for any signs of abnormal wear or damage; also, the amount of mocropitting is noted at this time. The load (torque) is then set to the desired level for the loaded phase of the evaluation. In this case, several torques were used to establish the lubricant. Historically, a Hertzian contact pressure of 1.52 GPa (load stage nine) was used to evaluate lubricant performance. However, for these tests, Hertzian contact pressures of up to 1.86 GPa (load stage eleven) were used. The test gears are inspected at intervals during the course of the evaluation; the interval is chosen based on experience and the level of damage observed at the previous inspection.

Individual teeth were removed from the tested FZG gears for surface analysis. Scanning Electron Micrographs (SEM) and optical micrographs were taken of the drive side of each tooth[(a)]. In addition, the drive side of individual teeth was analyzed using a Scanning Auger Micropobe (SAM) to yield an elemental depth profile for selected areas on each gear surface[(b)]. X-ray Photoelectron Spectroscopy (XPS), also known as Electron Spectroscopy for Chemical Analysis (ESCA), was used to obtain functional group analysis as well as elemental depth profiles of selected gear surfaces[(c)]. SAM and XPS depth profiles were obtained by argon ion sputtering where the sputtering rate was calibrated using a tantalum oxide/tantalum standard; sputter depths listed below are not adjusted for differences in sputtering rate between the standard and the experimental samples.

3. Results and Discussion

3-1. Gear Test Results

Fig. 2 shows a load stage (or contact stress) - fatigue life of gears curve obtained from the pitting tests using a fully formulated gear oil at different load stages ranging from nine to twelve. This curve can provide a guideline selecting conditions. It can be seen from the curve that the fatigue life of gears is too short to study the effect of lubricants at load stage twelve. Therefore, subsequent pitting tests were done at load stage nine and eleven to study the additive component effect at different contact stress.

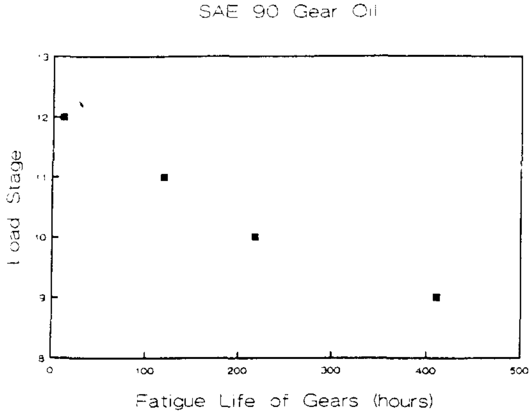

Fig. 2. Load stage-fatigue life of gear curve obtained from FZE tests.

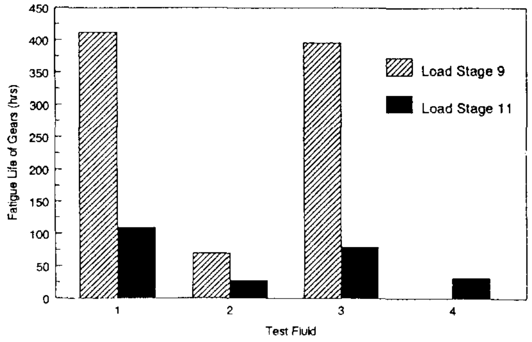

Fig. 3. FZG pitting test results at load stages 9 and 11.

Fig. 3 shows fatigue life of FZG gears tested with each oil at load stages nine and eleven. At load stage nine, the removal of EP additive from the fully formulated gear oil decreased the fatigue life of gears slightly (4%); howevre, the removal of primary antiwear additive decreased the fatigue life of gears significantly (83%).

Similarly at load stage eleven, the removal of EP additive from the fully formulated gear oil decreased

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(a) SEM analysis was performed using a LaB_6 cathode operated at 30 kV.

(b) SAM analyses were performed using a conventional scanning electron microscope with a LaB_6 cathode operating at 10 kV and nominal 400 nA current.

(c) XPS analyses were performed using a monochromate Al Kα source operated at 15 kV with a power of 350 W. The spectrometer was calibrated to the $^{4f}7/2$ peak of gold and all binding energies were referenced to the C-H peak at 284.6 eV.

the fatigue life of gears 25%; while, the removal of antiwear additive decreased the fatigue life of gears 75%.

It is interesting to note that AW additive has a significant effect on the surface fatigue life of gears especially at load stage nine. At load stage eleven, it is suggested that the increased mechanical stress may have decreased the effectiveness of the AW additive.

3-2. Surface Morphology and Surface Chemistry

The even numbered figures (Fig. 4-10) are optical and scanning electron micrographs of the drive side surfaces of representative teeth from each gear. The major surface fatigue modes observed on each gear are detailed below.

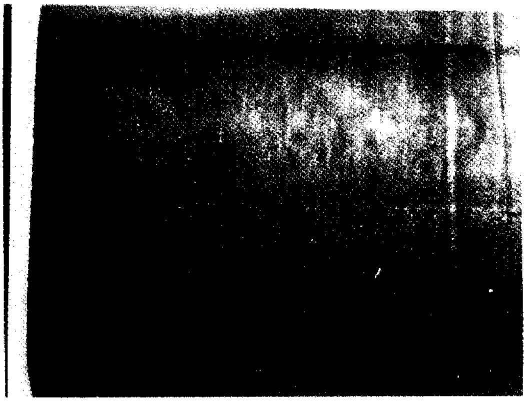

Fig. 4a. Optical micrograph (10x) of gear tooth tested with fluid 1.

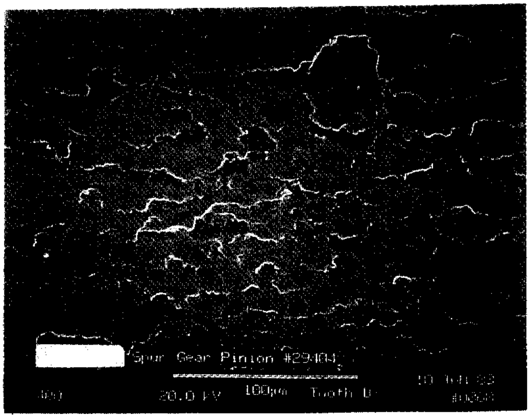

Fig. 4b. SEM micrograph of gear tooth tested with fluid 1.

The odd numbered figures (Fig. 5-11) are SAM depth profiles for intact film areas on a representative drive side gear surface. The profiles of carbon, oxygen, phosphorous, sulfur, and iron are included; however, other elements may have been observes in small amounts as noted in the text.

3-2-1. Test Fluid 1 (GL-5 formulation)

Micropitting is the dominant surface fatigue mode in the drive side dedendum of the FZG gears tested with fluid 1. To the unaided eye, the surface appears smooth but divided into gray and bright regions. Grindine/machining marks are plainly visible in the bright regions. However, optical and electron micrographs reveal the micropitting responsibe for the gray regions (Fig. 4a and 4b).

Fig. 5a shows the SAM depth profile for a flat area within the micropitted region of the FZG gear tested with fluid 1. Phosphorous and oxygen concentrations reach a maximum near the surface (at approximately 25 Å) and gradully reach a minimum at

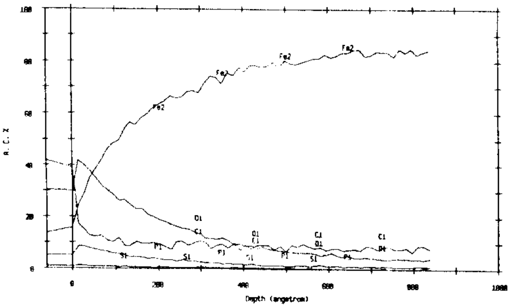

Fig. 5a. SAM depth profile from gear tooth tested with fluid 1.

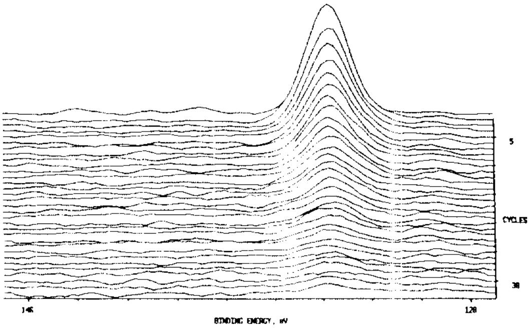

Fig. 5b. XPS spectra of P 2p peak as a function of depth from gear tooth tested with fluid 1.

approximately 600 Å. The phosphorous and oxygen profiles have similar profiles suggesting that they are chemically related in the surface film. The absolute oxgen concentration is approximately 5 time that of phosphorous at given depth suggesting a mixture of phosphates/phosphites and iron oxides. An elemental depth profile of a micropitted region acquired by consistent with that obtained by SAM. (23). Fig. 5b shows the P2p peak positions as a function of sputter cycles. The phosphorous main peak positions (~133.5 eV) are consistent with that of phosphate or phosphite species throughout the entire depth profile. Very little sulfur is observed on the surface with the maximum sulfur concentration no more than 1 or 2 atom percent near the surface. Carbon is present near the surface reaching a minimum concentration by 50 Å. The iron concentation rises steadily reaching a maximmum concentation by 50 Å. The iron concentration rises steadily reaching a maximum concentration at 750 Å.

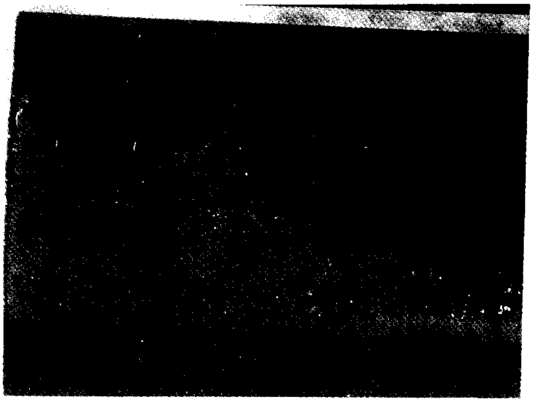

Fig. 6a. Optical micrograph (10x) of gear tooth tested with fluid 2.

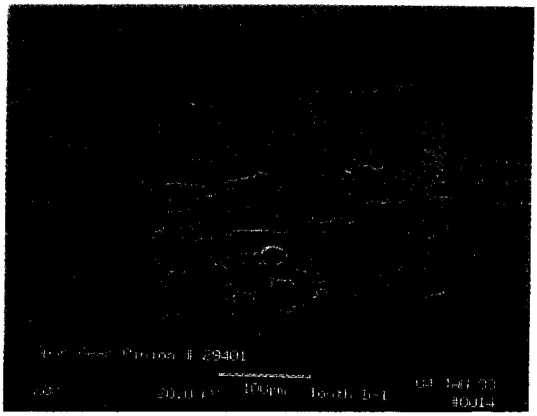

Fig. 6b. SEM micrograph of gear tooth tested with fluid 2.

3-2-2. Test Fluid 2 (GL-5 formulation less EP)

The major surface fatigue mode is again micropitting in the dedendum of the FZG gear tested with fluid 2. The characteristic graying is shown by optical microscopy (Fig. 6a), and Fig. 6b shows the many small pits observed by SEM.

Fig. 7 shows the SAM depth profile for a flat area within the micropitted region of the FZG gear tested with fluid 2. Several similarities exist between this profile and that of Fig. 5. Aphosphorous and oxygen containing layer is present on the surface; however, the phosphorous profile has two distinct regions which are not mirrored in tee oxygen profile. The phosphorous concentration decreases more rapidly between 50 Å and 300 Å compared to its of decrease between 300 Å and 1100 Å. At 50 the oxygen concentration is roughly five time the phosphorous concentration, and at 300 Å the oxygen to phosphorous ratio is closer to seven. Thus, the oxygen and phosphorous containing layer is richer in oxide compared to that seen for fluid 1. The sulfur profile shows a peak in sulfur concentration between 100 Å and 200 Å decreasing to a minimum at 700 Å; nevertheless, the absolute sulfur conentration is never more than approximately 2 atom percent. It is important to note that the AW component, corrosion inhibitors, and the base oil should be the only contributors of sulfur in the absence of the EP component. The carbon concentration reaches a minimum at 50 Å as it dose with fluid 1. The iron concentration does not reach a maximum until 1100 Å

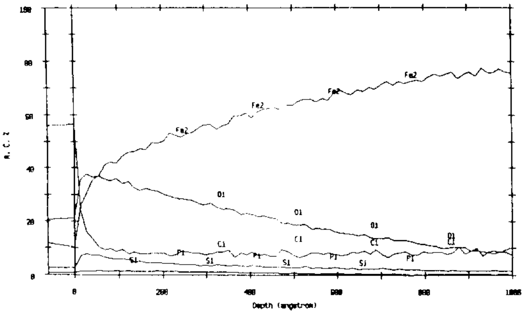

Fig. 7. SAM depth profile from gear tooth tested with fluid 2.

as a result of the thicker O and P layer.

3-2-3. Test Fluid 3 (GL-5 formulation less AW)

Spalling is the dominant wear mode obsered in the dedendum of the gear tested with fluid 3. Micropitting is also observed on teeth where pitting has not progressed to catastrophic levels. In the addendum, abrasive wear is observed. Fig. 8a is an optical micrograph showing the spalls and abrasion tracks. Fig. 8b is an SEM micrograph of the larger pits.

Fig. 9 shows the SAM profile for a flat area on the surface of the gear tested with fluid 3. The surface is almost entirely composed of iron oxides. The oxygen concentration reaches a maximum of 40 atom percent at 50 Å and decreases to a minimum at approximately 1000 Å. The iron profile increases rapidly to 50 atom percent at 50 Å, and then gradually rises to a maximum as oxygen reaches its minimum concentration. The sulfur concentration reaches a maximum of approximately 2.5 atom percet at 25 Å but decreases rapidly to ≤ 1 atom percent by 100 Å. Between 100 and 700 Å, the sulfur concentration decreases gradually to baseline.

3-2-4. Test Fluid 4 (GL-5 formulation less AW and EP)

Spalling is the dominant wear mode in the dedendum of the gear tested with fluid 4. It is more severe than with fluid 3. Abrasive wear in present in the addendum. As expected, it is more severe than in the preceding pinion. Fig. 10a is an optical micrograph showing spalls abrasive wear grooves. Fig. 10b is a SEM micrograph showing some of the large pits. Fig. 11 shows the SAM profile for a flat area on the surface of the gear tested fluid 4. The surface is almost entirely composed of iron oxides

Fig. 8a. Optical micrograph (10x) of gear tooth tested with fluid 3.

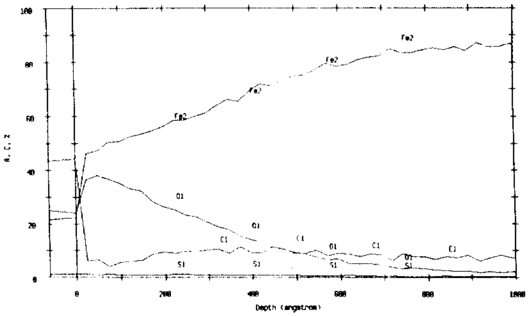

Fig. 9. SAM depth profile from gear tooth tested with fluid 3.

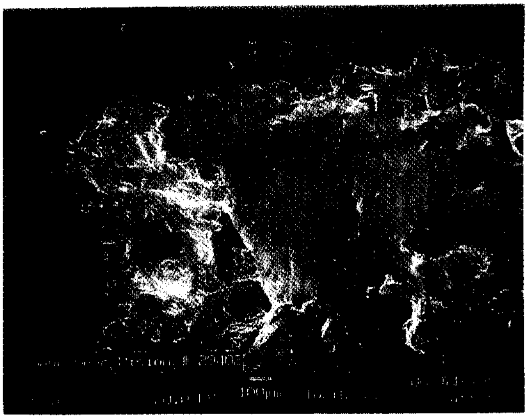

Fig. 8b. SEM micrograph of gear tooth tested with fluid 3.

Fig. 10a. Optical micrograph (10x) of gear tooth tested with fluid 4.

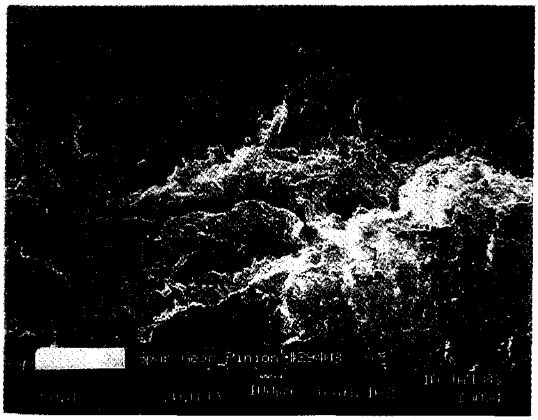

Fig. 10b. SEM micrograph of gear tooth tested with fluid 4.

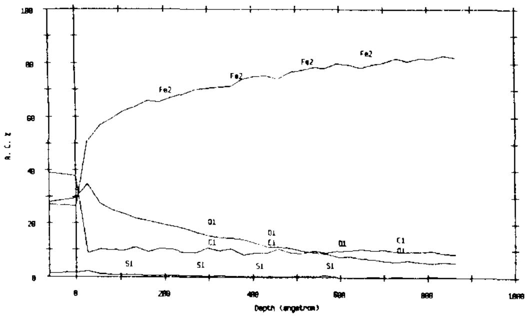

Fig. 11. SAM depth profile from gear tooth tested with fluid 4.

with the sulfur concentration reaching a maximum of approximately 2 atom percent at 50 Å.

4. Conclusions

The stress-fatigue life portion of this study showed that the effect of additive on the surface fatigue life of gears can be investigated at load stages nine through eleven. At load stage nine, the removal of EP additive from the fully formulated gear oil resulted in a slight decrease in the fatigue life of gears, removal of the AW additive decreased the fatigue life of the gears significantly. At load stage eleven, removal of the EP additive from the fully formulated gear oil decreased the fatigue life of the gears 25%, however, the removal of AW additive resulted in a significant of fatigue life of gears.

Micropitting is the dominant fatigue mode at load stage eleven for fluids containing an AW component in the presence or absence of an EP component, whereas spalling is the dominant fatigue mode in the absence of an AW component. Surface analyses of the end-of-test gears suggest that formation of a phosphate/phosphite-oxide layer is key to long FZG gear fatigue life using a simple API GL-5 grade gear oil.

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